Conf-9110244--1

CONF-9110244--1

DE92 001970

REPETITIVE, SMALL-BORE TWO-STAGE LIGHT GAS GUN*

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A repetitive two-stage light gas gun for high-speed pellet injection has been developed at Oak Ridge National Laboratory. In general, applications of the two-stage light gas gun have been limited to only single shots, with a finite time (at least minutes) needed for recovery and preparation for the next shot. The new device overcomes problems associated with repetitive operation, including rapidly evacuating the propellant gases, reloading the gun breech with a new projectile, returning the piston to its initial position, and refilling the first- and second-stage gas volumes to the appropriate pressure levels. In addition, some components are subjected to and must survive severe operating conditions, which include rapid cycling to high pressures and temperatures (up to thousands of bars and thousands of kelvins) and significant mechanical shocks. Small plastic projectiles (4-mm nominal size) and helium gas have been used in the prototype device, which was equipped with a 1-m-long pump tube and a 1-m-long gun barrel, to demonstrate repetitive operation (up to 1 Hz) at relatively high pellet velocities (up to 3000 m/s). The equipment is described, and experimental results are presented.

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

I. INTRODUCTION AND BACKGROUND

At last year's meeting, a paper that described the development of single- and two-stage repeating pneumatic pellet injectors at Oak Ridge National Laboratory[1] (ORNL) was presented. These devices are used to launch solid hydrogen, deuterium, and tritium pellets with diameters of 1 to 6 mm at speeds of greater than 1000 m/s; the application of this technology is plasma fueling by the injection of frozen pellets of hydrogen isotopes into magnetically confined plasmas for controlled thermonuclear fusion research. The process and benefits of plasma fueling by this approach have been demonstrated conclusively on a number of toroidal magnetic confinement configurations, including tokamaks, stellarators, and reversed-field pinches; this specific area of research and development has been summarized in review papers (e.g., Refs. 2–4). For many experiments over the last ten years, single-stage light gas guns operating with helium and hydrogen propellant have been used as drivers for plasma fuel injection systems (e.g., Refs. 5–12). In general, there appear to be no significant obstacles associated with reliable, steady-state operation of such systems to produce pellets at speeds up to about 1500 m/s (see, e.g., Ref. 13). However, higher pellet velocities are desirable for more demanding applications on reactor-scale fusion devices, since faster pellets can penetrate more deeply into large, hot plasmas and deposit atoms of fuel directly in a larger fraction of the plasma volume.

One fundamental technique to achieve higher pellet speeds uses a two-stage light gas gun as the driver in place of the single-stage light gas gun. With lighter and more fragile projectiles such as hydrogen ice (densities of 0.087, 0.20, and 0.32 g/cm^3 for H_2, D_2, and T_2, respectively, and yield strengths of only several bars), the driving pressures on the pellet must be limited to prevent fracturing of the pellet in the gun barrel during the acceleration process. (The use of sabots to encase the cryogenic pellets and protect them from the high-pressure hot gas provides a mechanism to overcome this limitation.) Even with these constraints, present development systems have already been used to accelerate single deuterium pellets to speeds of about 3000 m/s at ORNL[14,15] and at European research facilities.[16–18] Even speeds above 4000 m/s have been attained when the deuterium ice is protected from the high-pressure, hot propellant gas by a sabot.[16] However, before any pellet injection device can be considered a viable plasma fueling system, it must be able to operate repetitively for long pulse lengths (hundreds of seconds to steady state). For example, a pellet frequency of about 0.7 Hz (with 8-mm-diam pellets) is the design repetition rate for the baseline high-speed pellet fueling system for the proposed

International Thermonuclear Experimental Reactor (ITER).[19] In general, applications of the two-stage light gas gun have been limited to only single shots, with a finite time needed for recovery and preparation for the next shot (anywhere from minutes to days, depending on gun size and operating conditions). Previous papers[14,15,20] describe initial results of ORNL experiments using two-stage light gas guns. In the previous conference paper,[1] a repetitive two-stage light gas gun under development at ORNL for high-speed pellet injection was described briefly and some preliminary data were presented. In the present paper, the equipment is described more thoroughly, and the most recent experimental test results are presented.

II. EQUIPMENT AND OPERATING FEATURES

A. Two-stage light gas gun

A schematic of the repetitive two-stage light gas gun and key subsystems is shown in Fig. 1, and physical parameters of the gun and operating test ranges are listed in Table I. The actual layout of most key components is shown in Fig. 2. The device comprises several components (and features) that must interact precisely to accomplish repetitive operation. The repetitive device consists of some standard components for two-stage light gas guns: a first-stage reservoir for high-pressure gas (2.2-L internal volume), a pump tube (27.0 mm i.d. and 1.0 m long), and a gun barrel (4.0 mm i.d. and 1.1 m long). The typical piston was ≈40 mm long (with a 45° taper on the front) and weighed 25–30 g; it was constructed of polyimide with 15% graphite filler by weight (supplied as Vespel® by E. I. du Pont de Nemours & Co., Inc.). Typically, a piston survived for up to hundreds of shots without excessive wear/damage or significant effects on gun performance. Various plastic pellets (nylon, polypropylene, polycarbonate, acetal, etc.) with a 4-mm diameter were used in this study, including two geometric forms (right circular cylinders and spheres). The 4-mm-diam pellet size was chosen for the gun because it is applicable to large, present-day tokamak fueling experiments.[10,21] Special components developed for repetitive operation include a fast valve, mechanisms for automatic pellet loading, and a pneumatic clamping device for sealing the pump tube/gun barrel interface. Necessary techniques for rapid filling and evacuation of gases and control of pressure levels were also developed. The key components and features are described in some detail below; fine details (e.g., descriptions of the numerous seals) are omitted. Operational information is also presented.

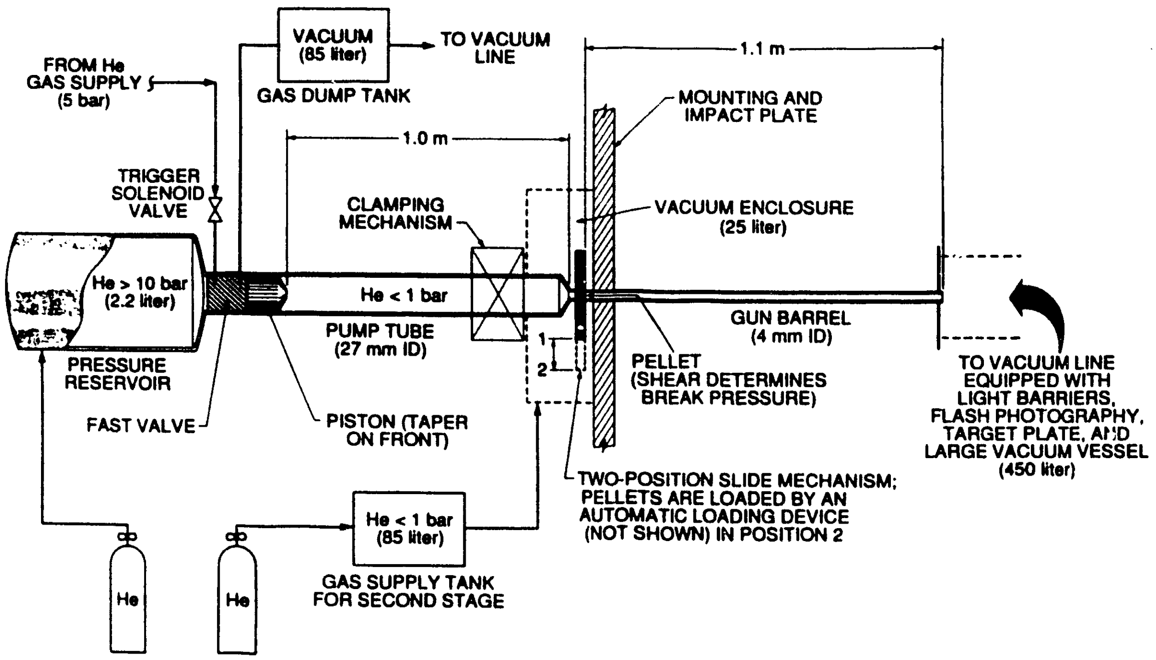

FIG. 1. Schematic of ORNL repetitive two-stage light gas gun.

1. Fast valve

A pressure/vacuum valve-type controller (or fast valve), shown in Fig. 3, is used in place of the standard rupture disk and initiates the acceleration process of the piston in the first stage. The controller executes several functions in a synchronized sequence to accomplish pneumatic actuation of the piston and to control the environment behind it. In its normal position, the valve is in the vacuum mode, in which the pump tube is exposed to the system vacuum (≈10 mbar). The vacuum provides the force to move (and return) the piston and seal the back of the piston against an O-ring provided on the valve output port. The device is triggered pneumatically by a gas pulse (typically helium at 40–90 psi) that is regulated by a solenoid valve. When the trigger is applied, the center throttle of the apparatus is moved outward (away from the piston), which exposes a port through which high-pressure gas is transported from the high-pressure compartment to the primary side of the internal actuator compartment.

Table I. Parameters for repetitive two-state light gas gun

First stage	
Material	304 stainless steel
Volume (cm^3)	2250
Length (m)	≈0.42
Inside diameter (mm)	≈82
Gas	Helium
Initial pressure (bar)	>10 (typically 50–100)
Activation mechanism	Fast valve
Second stage[a]	
Pump tube material	4130 carbon steel
Volume (cm^3)	585
Length (m)	1.02
Inside diameter (mm)	27.0
Wall thickness (mm)	5.6
Gas	Helium
Initial pressure (bar)	<1 (typically 0.8)
Piston	
Material	Plastic
Geometry	Solid cylinder with tapered front
Diameter (mm)	27.0
Mass (g)	25–30
Gun barrel	
Material	4130 carbon steel
Length (m)	1.14
Inside diameter (mm)	4.0
Wall thickness (mm)	2.8
Pellet	
Material	Plastic
Geometry	Solid cylinders, spheres
Diameter (mm)	4
Mass (mg)	29–55

[a]Includes small section (4.0 mm i.d., ≈38 mm long) between end of pump tube and base of projectile.

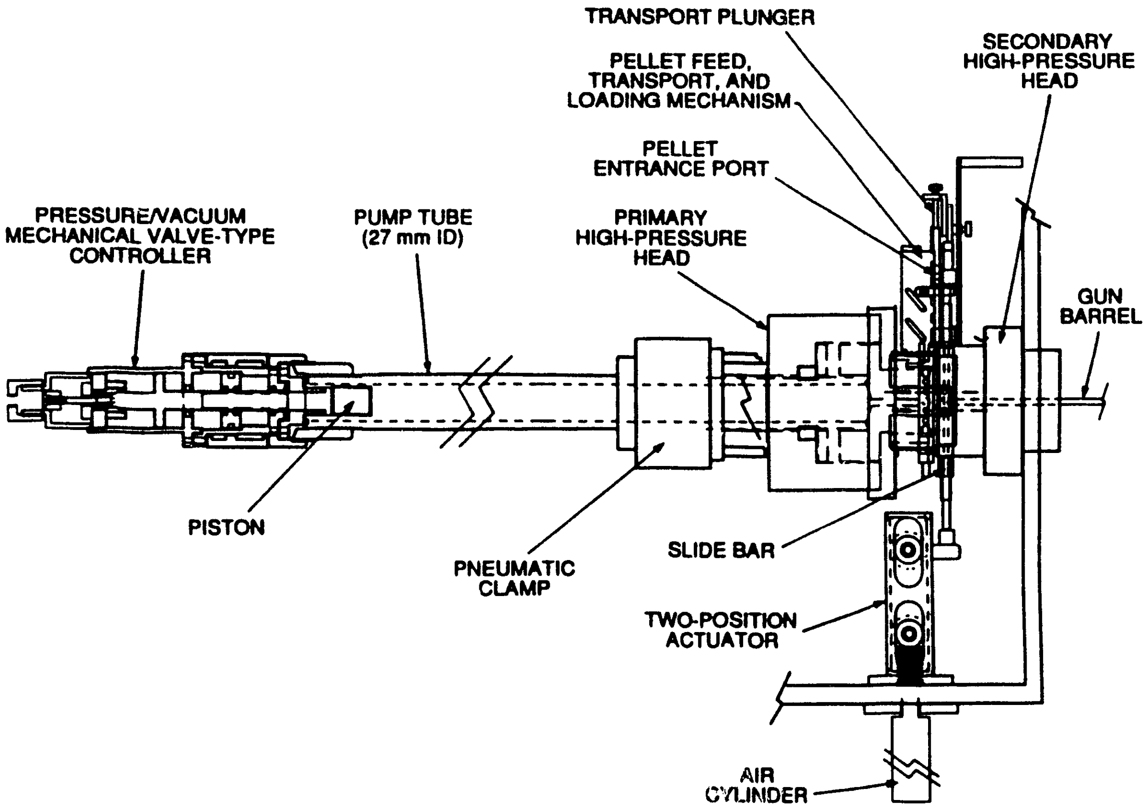

FIG. 2. Assembly drawing of ORNL repetitive two-stage light gas gun.

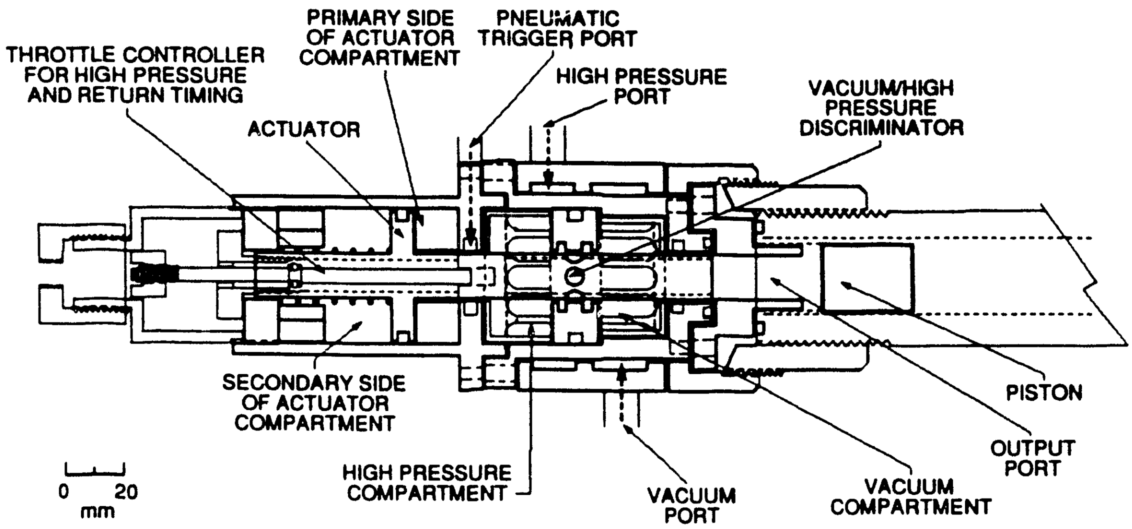

FIG. 3. Pressure/vacuum mechanical valve-type controller.

With the pressure force, the internal actuator moves to shift output from vacuum mode to high-pressure mode by means of a vacuum/high-pressure discriminator (which connects the valve output to the high-pressure gas supply). When the output shifts into the pressure mode, high-pressure gas is released to actuate (or drive) the piston. The high-pressure gas also shifts the internal actuator from the high-pressure mode back to vacuum mode; this is accomplished through a small flow passage. The flow area of the passage can be adjusted mechanically. This precisely controls the timing of the actuator to change the output from pressure to vacuum and thus controls the total gas throughput. This also automatically dumps the remaining high-pressure gas through the vacuum chamber and, thus, returns the piston to its home (or seated) position. The valve-like device is capable of independently operating at frequencies of ≥10 Hz.

2. Mechanisms for automatic pellet loading

A two-position slide mechanism that is pneumatically activated (driven by an air cylinder) is used to remotely load a pellet into the gun breech. The slide bar of the mechanism essentially separates the pump tube and the gun barrel. When the slide bar is in position 1 in Fig. 1, the open cylindrical cavity in the slide bar is accurately aligned with the gun barrel. Thus, a single projectile can be loaded into the hole when the slide bar is in position 2, and the projectile is transported to the gun breech and properly aligned with the gun barrel when the slide bar returns to position 1. To accomplish these actions automatically, a loading mechanism (Fig. 2) is used. This mechanism (not clearly visible in Fig. 2) carries out several events in a mechanically synchronized sequence to feed, transport, and load pellets into the slide bar. The pellets are introduced vertically through an entrance port and accumulated in a single file against a set of mechanical picks. Here the pellets are separated and fed individually. The mechanical actions of this automatic loading mechanism are driven and synchronized with the same two-position actuator used for moving the slide mechanism. When the actuator is shifted to the bottom position in Fig. 2 (position 2 in Fig. 1), the pellet in the loading position is loaded into the cylindrical chamber of the slide bar, and the picks inject one pellet into an accumulating and transporting chamber. When the actuator returns to the top position in Fig. 2 (position 1 in Fig. 1), the pellet in the accumulating and transporting chamber is transported into the loading position by a transporting plunger. At this point, the pellet in the slide bar is accurately aligned with the gun barrel. The cycle is then repeated. These components can be used to load cylindrical or spherical pellets and can operate independently at rates of ≥5 Hz.

3. Other components and operating features

Figures 1 and 2 also show most other key components of the device. The downstream end of the pump tube mates with and is enclosed within a thick-walled, high-pressure primary head; this allows a safety margin for operation at the high pressures generated in that region during compression. The gun barrel mounts to and is supported by a secondary high-pressure head. O-ring type seals and a pneumatic clamp are used to seal the interface between the pump tube, the slide mechanism, and the gun barrel during the firing phase, when high peak pressures (up to thousands of bars) are generated in the gun. For firing of the gun, the pump tube and attached components are actually driven forward slightly (≈5 mm) and held by pneumatic means to make satisfactory seals; return of the apparatus to the normal or unclamped position is also pneumatically controlled. The slide bar is only moved in the unclamped position to minimize the possibility of damage to the O-rings. In addition to providing satisfactory seals at high pressure while accommodating a sliding component, this clamp/sealing technique provides for rapid refilling of the pump tube through the clearances between the O-rings and mating surfaces in the normal position. That is, after firing and releasing the clamp, the pump tube is refilled automatically with the cover gas surrounding the pump tube/gun barrel interface. This interface section is enclosed in a relatively large vessel (≈25 L, as compared to the 0.6-L internal volume of the pump tube) and is directly coupled to an even larger vessel (≈85 L) as shown in Fig. 1. This section is fed directly from a helium gas cylinder (≈44 L at 125 bar for a full cylinder) through a gas regulator that is set to maintain the desired pump tube operating pressure (typically 0.8 bar absolute). With this large relative volume, the supply gas pressure feeding the pump tube is essentially constant, with a negligible pressure loss for a gas fill of the pump tube. Thus, the pump tube is automatically refilled with gas and maintained at the proper pressure as the clamping mechanism cycles. In a similar manner, the first-stage reservoir (volume of 2.2 L) is fed directly by a helium gas cylinder (≈44 L at 125 bar for full cylinder) through a pressure regulator, as shown in Fig. 1.

The operating sequence consists of the following cycle (see Fig. 1). (1) A pellet is automatically loaded into the slide bar when it moves to position 2 (initially the valve output is connected to the vacuum system and the clamp is disengaged). (2) After the slide bar returns to position 1, the pneumatic clamp is engaged and held. (3) While clamped, the fast valve is triggered. This switches the valve output from vacuum to high pressure to drive the piston and shoot the pellet; the controller-type fast valve then automatically switches back from pressure to vacuum and dumps the remaining gas to the vacuum system after a finite time. (4) The clamp is released; this automatically starts the refill of the pump tube with gas, which also ensures that the piston returns to its home position (where it seals against an O-ring). The cycle is repeated for each shot. Electrical limit switches are used to indicate position or status of key components; these include the slide position (load or fire) and the status of the pneumatic clamp (engaged or disengaged), as well as that of several valves (open or closed). The programmable logic controller (PLC) that is used to control the operations (see Sec. II B) monitors this information and shuts the system down safely if the proper criteria are not met throughout the operating sequence. A few important safeguards have been incorporated for automatic repetitive operation. First, the slide mechanism will not operate unless the clamp is disengaged. Second, the gun will not fire unless three criteria are met: the slide mechanism is in the fire position, the clamp is engaged, and the downstream valve in the injection line is opened. Third, a new cycle for the next pellet is not started unless the previous pellet was fired; this is detected by a shock accelerometer mounted on a target plate at the end of the injection line and monitored by the PLC. These restrictions minimize the possibility of damage to the equipment during operation. Manual operation of individual components is also possible, including actual firing of pellets with all actions controlled by push buttons on the PLC. The PLC logic is described in Sec. II B, and timing data for mechanical actions during repetitive operations are presented in Sec. III.

B. Instrumentation and control/data acquisition systems

In addition to standard pressure/vacuum gauges for monitoring initial conditions before a test shot, the experiment is equipped with instrumentation for tracking fast transients during gun firings. A pressure transducer is located on the upstream end of the pump tube (and slightly in front of the piston), and a shock accelerometer is positioned at the downstream end of the pump tube. Instrumentation in the vacuum injection line provides velocity and photographic information to thoroughly document each pellet shot. Light barriers through which pellets pass supply timing data for accurately evaluating pellet speeds. At the end of the injection line, a target plate intercepts the pellets and indicates pellet dispersion and integrity; this target also provides timing data for velocity measurements, since it is equipped with a shock accelerometer.

An integrated control and data acquisition system (Fig. 4) is used for repetitive operation of the two-stage light gas gun. An Allen Bradley PLC (Model 5-25) and a MicroVax II–based CAMAC data acquisition system are the central components of the system. All variable control parameters such as valve open/close sequences are controlled via a parameter screen on an Allen Bradley Panel View operator interface. After initial setup, automatic pellet firing is initiated by depressing a push button on the Panel View screen, which causes the PLC to trigger a CAMAC Jorway 221 sequencer.

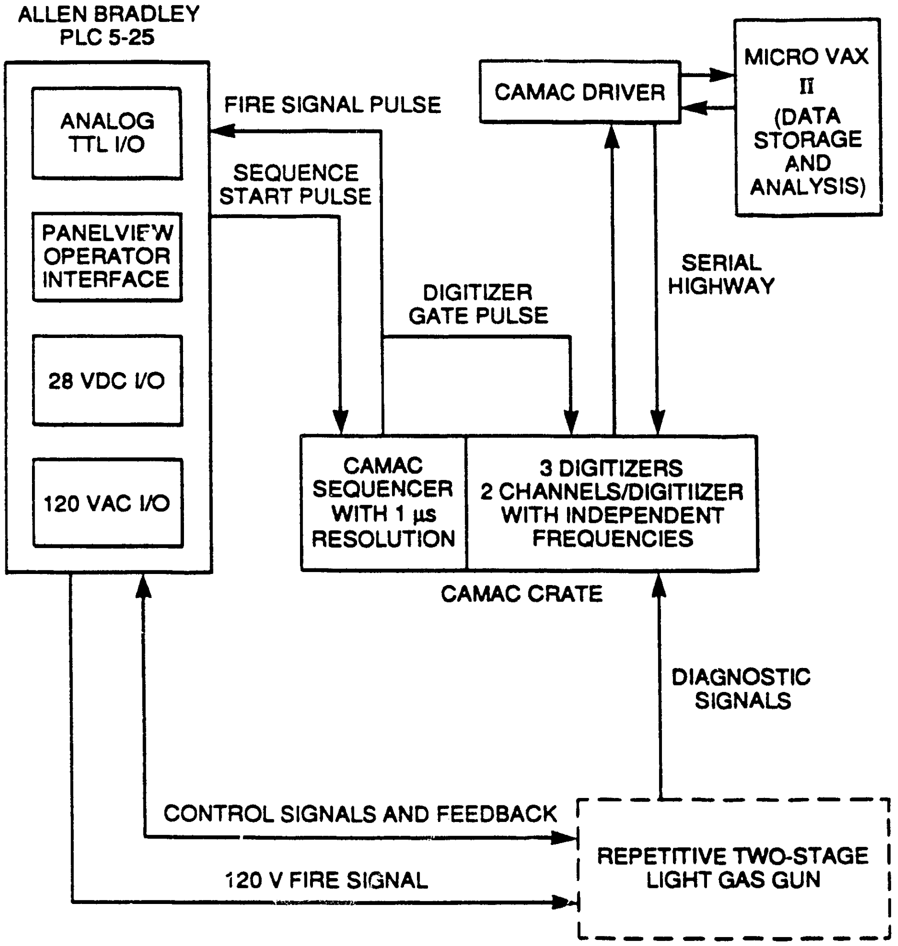

FIG. 4. Schematic diagram of control/data acquisition system.

The sequencer controls the timing of pellet firing and the corresponding data acquisition for multiple pellets by feeding trigger pulses to TTL input modules of the PLC and of the CAMAC digitizers, respectively. Upon completion of setup and loading permissives along with the sequencer input pulse, the PLC pulses a solenoid valve (120 V ac), which in turn pneumatically triggers the fast valve on the pump tube, thus activating the piston (similar to the action of a burst disk). This system has a firing resolution of about 10 ms (the PLC scan time) and is adequate for demonstrating repetitive operation at frequencies of ≈1 Hz. Handling the pellet firing sequence in this manner has the advantages of prohibiting firing until all PLC permissives are met and of making it easy to incorporate interlocks to prevent actions that could damage the equipment. The PLC also records timing information of selected permissive signals in internal memory to provide diagnostic capabilities; mechanical actions can thus be timed and adjusted to optimize performance. Typical information from the diagnostic timers for a repetitive 10-pellet sequence is presented in Sec. III.

The MicroVAX-based CAMAC data acquisition system is gated to provide maximum data for each individual pellet. The data window size is totally dependent on the individual digitizer frequency and the number of pellets to be fired. A typical test in this study included firing multiple pellets consecutively at a frequency of up to 1 Hz; up to six channels of transient data for each pellet were recorded and archived with three CAMAC digitizers (two signals per digitizer) sampling at individual frequencies of 200, 100, and 50 kHz. The fastest rate corresponds to a 5-μs resolution and was used for sampling the photodiode output signals that monitor the light intensity transmitted across the light barriers (which intercept the pellet flight path). This resolution is adequate to accurately detect the time at which the high-speed pellets pass through the light barriers, as determined by an abrupt drop in light intensity on the photodiode detector. The other two sampling frequencies correspond to resolutions of 10 and 20 μs and are sufficient for analyzing the additional transient data.

III. EXPERIMENTAL DATA AND RESULTS

In laboratory tests with this device exhausting into a 450-L vacuum vessel, the gun was operated using helium gas in both stages and plastic pellets of 4-mm nominal diameter. To demonstrate repetitive operation of the two-stage light gas gun, experiments were carried out in which pellets were fired consecutively at frequencies of up to 1 Hz. Typical timing data for individual component operation during repetitive tests at 1 Hz are listed in Table II; these data are for test sequence 1056, in which ten pellets were fired. The data were recorded by the PLC and include the relative times at which the clamp and slide mechanisms cycle and the on/off times for the trigger pulse that initiates the actuation of the fast valve. The timing information shows that the mechanical actions are consistent in time and fast enough to accomplish operation at 1 Hz, with potential for slightly higher pellet test frequencies.

Table II. Timing data of key actions during 1-Hz operation of two-stage light gas gun (test sequence 1056)

	Relative time (s) as recorded by PLC[a]					
Pellet number	Clamp disengaged	Slide in load position	Slide in fire position	Clamp engaged	Start of fire pulse to trigger valve	End of fire pulse to trigger valve
1	0.01	0.16	0.41	0.61	0.63	0.67
2	0.88	1.05	1.29	1.49	1.63	1.67
3	1.88	2.08	2.36	2.56	2.62	2.66
4	2.88	3.09	3.34	3.53	3.63	3.66
5	3.85	4.03	4.28	4.47	4.62	4.66
6	4.87	5.02	5.28	5.48	5.63	5.67
7	5.86	6.04	6.28	6.48	6.62	6.67
8	6.87	7.05	7.30	7.49	7.62	7.66
9	7.88	8.04	8.29	8.52	8.63	8.67
10	8.88	9.08	9.33	9.53	9.62	9.66

[a]Time resolution of 10 ms for data recorded by PLC.

Experimental data for two ten-pellet test sequences (1056 and 1109) are summarized in Table III; solid plastic cylinders weighing 55 mg were used in sequence 1056, and spheres weighing 29 mg were used in sequence 1109. Examples of the transient data recorded by the CAMAC digitizers for an individual pellet (fifth pellet of test sequence 1109) are shown in Figs. 5 and 6. All times are relative to the start of the initial fire pulse from the PLC, which serves as the zero time reference. A software program used to generate the data plots also provides analysis and was used to precisely identify event times; the program also automatically configures the time divisions for the axes of the plots (and explains the noninteger values). The left-hand traces in Figs. 5 and 6 include all of the data collected during the time window allocated for the fifth pellet; data acquisition windows were synchronized with the fire pulses. Data sampling was delayed 30 ms since there was a time lag between the start of the fire pulse and the opening of the solenoid trigger valve and, thus, the fast valve; this provided the proper time windows to capture the data for all pellets and explains why data plots for the fifth pellet start at 4.03 s.

Table III. Experimental data for two 10-pellet test sequences with repetitive two-stage light gas gun operating at 1 Hz

Pellet number	Transient timing data[a] (s): Gun muzzle light gate	Transient timing data[a] (s): Target plate accelerometer	Flight time[b] (μs)	Pellet velocity (m/s)
Test sequence 1056				
First-stage pressure: 62 bar; Second-stage pressure: 0.8 bar		Piston mass: 25 g; Pellet mass: 0.055 g		Pellet material: acetal; Pellet shape: solid cylinders
Pellet size: 4.0 mm diam × 3.5 mm long				
1	0.071106	0.071811	705	2130
2	1.0737659	1.0745409	775	1935
3	2.0740361	2.074781	745	2015
4	3.074631	3.075371	740	2030
5	4.075336	4.0760708	735	2040
6	5.0758257	5.076561	735	2040
7	6.076481	6.077211	730	2055
8	7.0688057	7.069541	735	2040
9	8.077776	8.078511	735	2040
10	9.070187	9.070921	734	2045
				Avg = 2040
Test sequence 1109				
First-stage pressure: 100 bar; Second-stage pressure: 0.8 bar		Piston mass: 30 g; Pellet mass: 0.029 g		Pellet material: polypropylene; Pellet shape: solid spheres
Pellet size: 4.0 mm diam				
1	0.051846	0.052321	475	3160
2	1.0476309	1.0481009	470	3190
3	2.0481758	2.048681	505	2970
4	3.0510309	3.0515509	520	2885
5	4.048901	4.0494113	510	2940
6	5.049611	5.0501113	500	3000
7	6.0423713	6.042881	520	2885
8	7.0497513	7.050221	470	3190
9	8.050951	8.05148	529	2835
10	9.051056	9.051620	564	2660
				Avg = 2970

[a]Taken as time of abrupt change in instrument signals as determined by software code that analyzes raw transient data.

[b]Separation distance of 1.5 m between muzzle light gate and target plate.

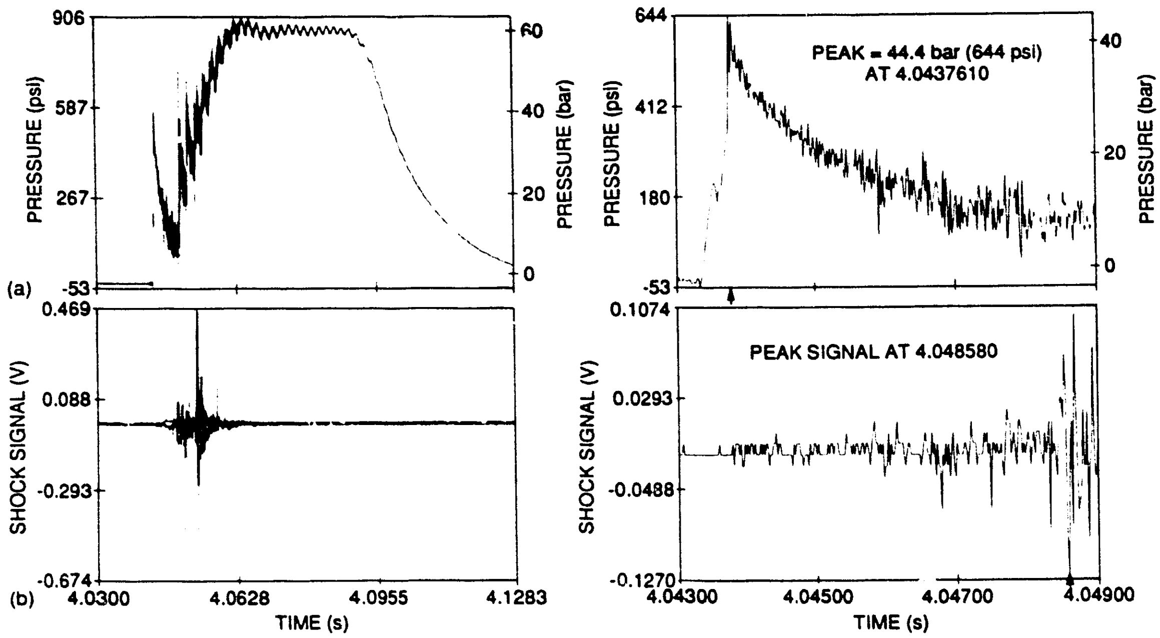

FIG. 5. Experimental data for fifth pellet of test sequence 1109: (a) pressure in upstream end of pump tube and (b) output signal from shock accelerometer located at downstream end of pump tube (data sampling rate of 50 kHz).

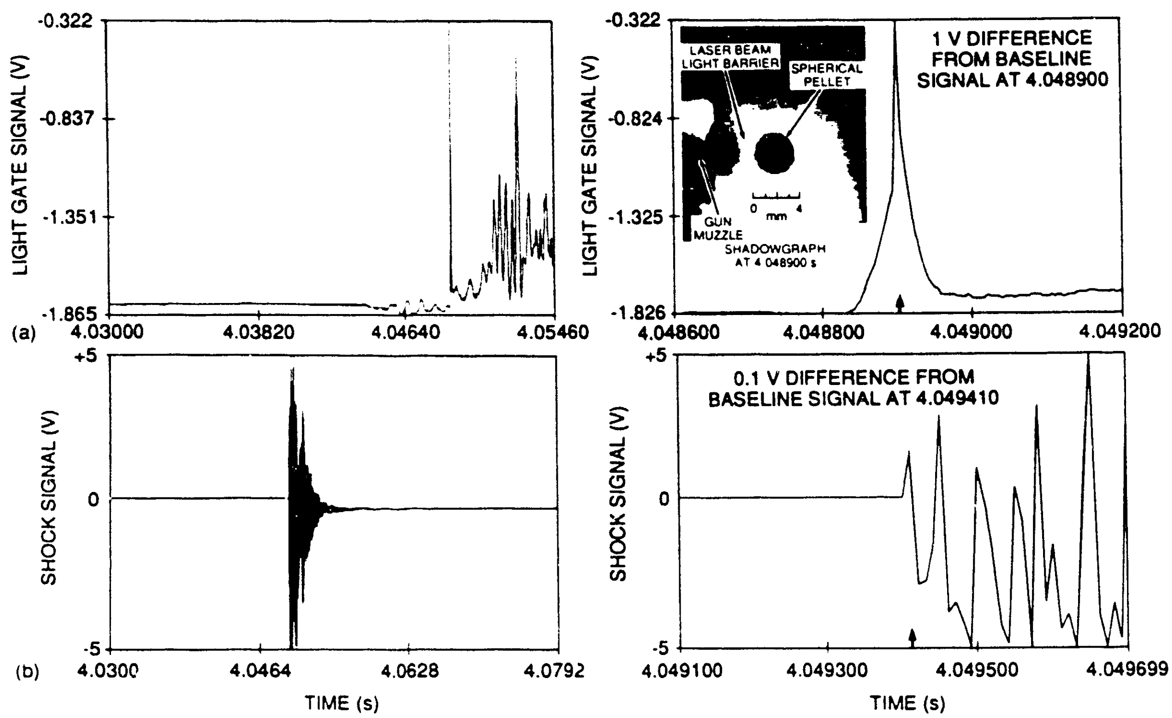

FIG. 6. Experimental data for fifth pellet of test sequence 1109: (a) output of diode that monitors light intensity at gun muzzle light barrier and (b) output signal from shock accelerometer located on target plate (data sampling rates of 200 kHz and 100 kHz, respectively).

In Fig. 5, the top trace is the pressure at the upstream end of the pump tube (values shown were obtained by multiplying the voltage signal from the pressure transducer by its calibration constant). The pressure, which is initially subatmospheric (0.8 bar absolute), suddenly increases to ≈45 bar as the transducer is exposed to the first-stage gas upon the piston transit; the piston actually oscillates back and forth in the pump tube after the pellet is shot, as indicated by the cyclic nature of the signal. The decay of the pressure toward the end of the data trace corresponds to the switching of the fast valve output back to the vacuum mode and the dumping of the remaining gas from the pump tube. The bottom trace in Fig. 5 is the output of the shock accelerometer mounted at the downstream end of the pump tube. Although there is some uncertainty, the data provided by these transducers can be used to estimate the flight time for the piston to travel the ≈1-m length during the initial compression. As shown in the expanded traces on the right-hand side of Fig. 5, the time for the piston to travel from the transducer (peak pressure at 4.0438 s) to the end of the pump tube (shock signal peak at 4.0486 s) is estimated as 4.8 ms. The time at which the piston reaches the downstream end should be (and is) close to the time that the pellet exits the barrel (which is 4.0489 s, as illustrated in Fig. 6). This travel time is in reasonable agreement with calculated values, as discussed in Ref. 22.

Accurate pellet velocities were determined using timing data from instruments located in the pellet injection line downstream of the gun barrel. The standard velocity in this study was based on the time of flight between the light barrier located at the gun muzzle and the shock target plate (1.5-m separation distance). Also, a light barrier located about 1 m downstream of the gun muzzle provided a third timing signal and means to check the projectile velocity. Pellet speeds based on different timing combinations always agreed to within a few percent of the standard velocity. An example of the experimental transient data used to evaluate pellet velocity is shown in Fig. 6. The top left-hand trace is the output of the photodiode detector at the gun muzzle light barrier; the abrupt decrease in signal magnitude (actually negative going toward zero) corresponds to the pellet transit. The signal level decreased abruptly (1-V decrease from baseline value) at precisely 4.048900 s. This is more clearly shown on the right-hand trace, in which data for a 600-μs window are plotted. Mechanical shock can cause a similar response on the photodiode output, so a photograph that was triggered at the same time (within a few microseconds) was used to verify the timing data. A ≈10-ns flash from a nitrogen/dye laser was used to freeze the in-flight pellet in a shadowgraph, which was monitored and stored by a standard video camera and recorder; the shadowgraph for the test shot is shown in the inset of Fig. 6(a). Only test sequences with photographs for all pellets are reported in this study, and this guarantees that the correct times for these events were selected. In nearly all shots, the pellet interrupted the light barrier before the mechanical shock significantly affected the diode output, as shown in the left-hand trace of Fig. 6(a). The bottom left-hand trace in Fig. 6 is the output of the shock accelerometer attached to the target plate at the end of the pellet injection line. The impact of the pellet is clearly identified by the gross change in the signal signature that occurred at 4.049410 s and is evident in the right-hand trace of Fig. 6(b) (again, a 600-μs window is plotted). Thus, the pellet traveled the 1.5-m separation distance between the light gate and the target plate in 510 μs, corresponding to a velocity of 2940 m/s. Transient data as shown in Figs. 5 and 6 were recorded for each individual pellet and were used to obtain the data in Table III.

As noted previously, Table III summarizes the experimental data for two ten-pellet test sequences (1056 and 1109). The key differences in input parameters for the data sets were the type and mass of the pellets and the first-stage pressure. In test sequence 1056, solid 4-mm-diam, 3.5-mm-long cylinders of acetal plastic were used for the pellets, and the first-stage pressure was regulated at 62 bar. For this test, the average pellet velocity is 2040 m/s with all pellets falling within 5% of the average; examining only the last eight pellet speeds indicates a maximum variation of only 30 m/s (or 1.5%) from the average. This reproducibility would be excellent for a single-stage gun and is outstanding for a two-stage prototype device. It also indicates that the techniques used to automatically refill the first- and second-stage volumes are functioning properly; otherwise, the gun could not produce such consistent pellet velocities. For the higher-performance test sequence 1109, solid 4-mm-diam spheres of polypropylene were used for the pellets, and the first-stage pressure was maintained at 100 bar. For this ten-shot sequence, the average pellet velocity is 2970 m/s with all pellets falling within about 10% of the average. Although the speeds vary more than for test sequence 1056, the reproducibility is still noteworthy considering the high speed and severe mechanical shock associated with this operating regime. Also, the differential pressure between the helium supply cylinder and the first stage was lower at the higher operating pressure of test sequence 1109, with the supply pressure approaching the operating pressure by the end of the the test sequence; this may have affected the performance slightly.

In Fig. 7, we show data for all ten pellets of test sequence 1109 by plotting the data over the entire time window of data acquisition (data were actually collected for only a small time window for each pellet, as shown in Figs. 5 and 6, with the time interval between pellets void in Fig. 7). The top trace is the pressure in the upstream end of the pump tube, and the bottom trace is the output of the target shock accelerometer. The peak driving pressure for the piston is essentially the same for each pellet with almost identical pulse shapes. In fact, even when comparing the data on the same time scale as in Fig. 5, the signatures of the pressure traces for the other nine pellets were almost indistinguishable from that shown for the fifth pellet, even with an equal number of pressure oscillations (other data not shown). This essentially guarantees consistent projectile speeds throughout the test sequence. The top and bottom traces in Fig. 7 indicate a 1.0-Hz test frequency, which is the rate at which pellets were fired and delivered to the target plate. Thousands of pellets have been fired in this study, including hundreds of multiple pellet sequences. The data presented here are typical, with test sequence 1056 representative of modest operating parameters and test sequence 1109 exemplifying the highest performance parameters observed to date for repetitive operation. No more than ten pellets were fired in standard test sequences; the number was limited by the capability of the original data acquisition system. Also, some gun components were exposed to high-temperature gases during operation, and active cooling will probably be required for test durations much longer than ≈10 s. However, ten-pellet sequences were sufficient to demonstrate the feasibility of repetitive two-stage gun operation.

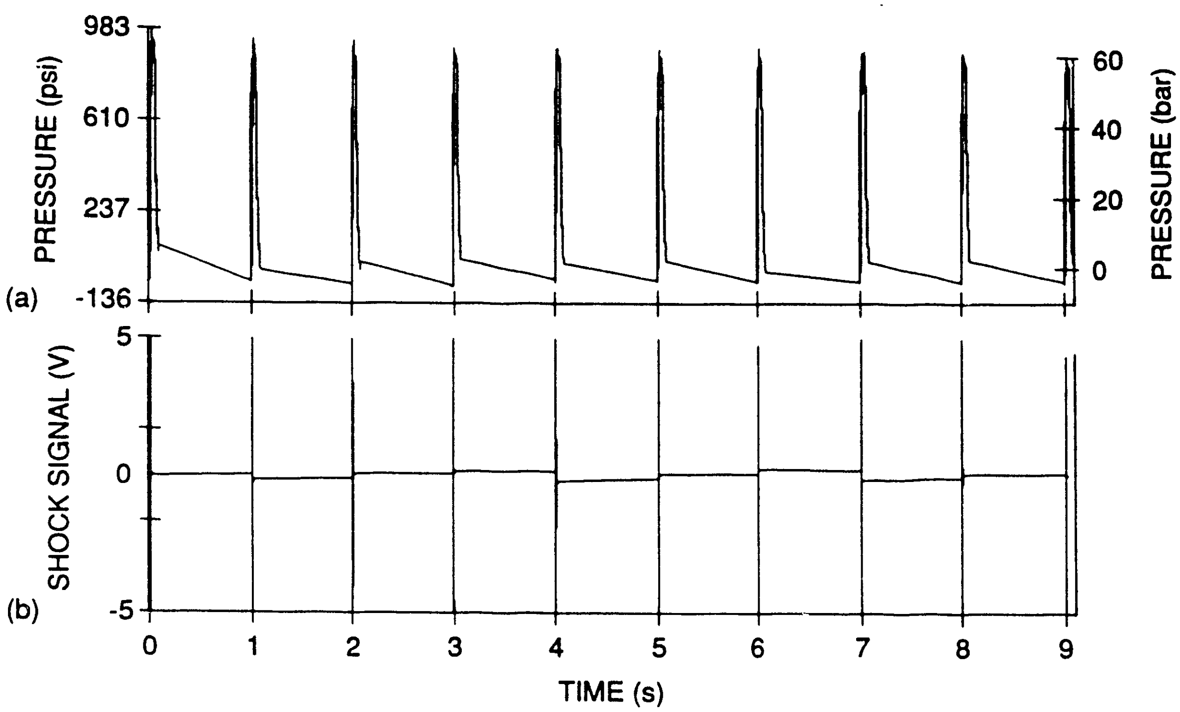

FIG. 7. Experimental data for test sequence 1109: (a) pressure from transducer located in upstream end of pump tube and (b) output signal from shock accelerometer located on target plate (data sampling rates of 50 kHz and 100 kHz, respectively).

The temperature and pressure at the downstream end of the pump tube were not measured in the downstream end of the pump tube; however, computer codes[23,24] that model the gas dynamics in the pump tube and gun barrel have been used to estimate these values. For the test conditions in this study, the codes indicate maximum gas temperatures in the range from ≈3000 to 4000 K and peak pressures in the range from ≈300 to 1000 bar (the models and results relative to this study are thoroughly documented in Ref. 22).

IV. DISCUSSION

The prototype device described here has been used to demonstrate the capability of the two-stage light gas gun to operate repetitively at relatively high pellet velocities (up to 1 Hz at 3 km/s). The performance parameters are encouraging and relevant for future pellet injection systems. The pellet velocities are twice those available from conventional repeating single-stage pneumatic injectors.[6,10] Also, the test pellet frequency of 1 Hz exceeds the design goal of 0.7 Hz for the proposed ITER baseline pellet fueling system.[19]

Since this is a prototype device developed for demonstrating the feasibility of the technique, further improvements in performance are likely with additional development efforts. The next step in developing a functional high-speed repetitive hydrogen pellet injector is to combine the acceleration technology described here with the cryogenic extruder technology for supplying hydrogen ice previously developed at ORNL (see, e.g., Ref. 6). The use of sabots could be incorporated to allow even higher velocity limits; however, such a system would be more complicated and would have to operate under more severe conditions (higher gas pressures and temperatures with increased mechanical shock). The key elements of the present design can, however, be readily integrated into a pellet injection system, with or without sabot-handling capability.

Other key development issues for applying this technique to plasma fueling include the piston design, incorporation of active cooling for long-pulse operation, and sabot configurations including separation techniques. Even though a single standard plastic piston used in these experiments was often employed for up to hundreds of shots, a piston will require longer lifetimes (at least tens of thousands of shots) in a practical plasma fueling system. Also, with the present design a significant amount of black soot-like material from the piston is dispersed in the driving gas that propels the pellet; this contamination is not compatible with clean plasmas. To solve these problems, improved piston designs, probably using metal or metal alloys, need to be developed and experimentally evaluated. Active cooling of some of the gun components will probably be required to limit the exposure of bulk materials to elevated temperature during long-pulse operation. Reliable techniques to continuously supply sabots to the gun and to accomplish the stripping action near the gun muzzle are yet to be demonstrated. It is no simpie task to separate the pellet from the sabot at high speeds and to deliver only the pellet to the plasma. In general, the designs of all components need to be reexamined with respect to materials and operating lifetime. In summary, a significant development effort is still required before a practical plasma fueling system based on the two-stage light gas gun can demonstrate reliability approaching that attained by present pellet injection systems (see, e.g., Ref. 13).

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.

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12/02/91