A three-barrel repeating pneumatic pellet injector for plasma fueling of the Joint European Torus*

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A three-barrel repeating pneumatic pellet injector has been developed for plasma fueling of the Joint European Torus (JET) tokamak. The versatile device consists of three independent machine gun–like mechanisms that operate at cryogenic temperatures (10–20 K). Individual extruders provide a continuous supply of solid hydrogen isotope to each gun assembly, where a reciprocating breech-side cutter forms and chambers cylindrical pellets from the extrusion; the deuterium pellets are then accelerated in the gun barrels with compressed hydrogen gas (pressures up to 105 bar) to velocities $\leq$ 1.5 km/s. The injector features three nominal pellet sizes (2.7, 4.0, and 6.0 mm) and repetitive operation (5 Hz, 2.5 Hz, and 1 Hz, respectively) for quasi-steady-state conditions (>10 s). The design allows the gun barrels to be mechanically aligned for accurate aiming. A remote, stand-alone control and data acquisition system is used for injector operation. The injector system has been installed on JET. The design features, operation, and performance characteristics of the injector are described.

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I. INTRODUCTION

Pellet fueling,[1,2] the injection of frozen hydrogen isotope pellets at high velocity, has been used to improve plasma performance in various tokamak experiments.[3–7] In one recent experiment,[5,6] the repeating pneumatic hydrogen pellet injector[8,9] was used on the Tokamak Fusion Test Reactor (TFTR). This machine gun–like device, which was developed at the Oak Ridge National Laboratory (ORNL) with an objective of steady-state fueling applications, was characterized by a fixed pellet size and a maximum repetition rate of 4–6 Hz for several seconds. It was used to deliver deuterium pellets at speeds ranging from 1.0 to 1.5 km/s into TFTR plasma discharges. In the first experiments, injection of single, large (nominal 4-mm-diam) pellets provided high plasma densities in TFTR (1.8×10^{14} cm^{-3} on axis). After a conversion to smaller (nominal 2.7-mm-diam) pellets, the pellet injector was operated in the repeating mode to gradually increase the plasma density, injecting up to five pellets on a single machine pulse. This resulted in central plasma densities approaching 4×10^{14} cm^{-3} and $n\tau$ values of 1.4×10^{14} $cm^{-3}s$.

For plasma fueling applications on the Joint European Torus (JET), a pellet injector fashioned after the prototype repeating pneumatic design has been developed. The versatile injector features three repeating guns in a common vacuum enclosure; the guns provide pellets that are 2.7, 4.0, and 6.0 mm in diameter and can operate independently at repetition rates of 5, 2.5, and 1 Hz, respectively. The injector has been installed on JET. A description of the equipment is presented, emphasizing the differences from the original repeating device. Performance characteristics of the three pneumatic guns are also included.

II. EQUIPMENT

A. Injector

The injector, shown in Fig. 1, is a three-barrel machine gun–type device that operates on a pneumatic principle.[10] As shown in Fig. 1, three separate cryogenic extruders are used; each supplies a continuous stream of frozen hydrogen isotope to one gun section, where individual pellets are repetitively formed, chambered, and accelerated. The cryogenic extruders and the gun assemblies are housed in a high-vacuum enclosure to provide thermal isolation. The operation of these components is illustrated in Fig. 2. Since the operation of the prototype repeating injector and of similar cryogenic extruders has been described elsewhere,[8,9,11] only a brief description is presented here.

Each extruder consists of a motor-driven screw press that activates a piston running in a brass sleeve. Each sleeve is brazed at both ends to OFHC copper blocks that are convectively force-cooled by liquid helium flowing through cooling channels on their exteriors. One central inlet distributes coolant flow to the nine copper blocks (three per gun) that serve as heat exchangers, as shown in Fig. 1. The deuterium gas enters the top of each extruder, and the liquid reservoirs fill automatically as the deuterium condenses on the subcooled walls of the liquefiers ($\approx$19 K). When the pistons are fully retracted, the condensate drains through channels machined in the top of the brass sleeves and fills the cylindrical cavities in the second set of heat exchangers. The liquid freezes in these regions, which are maintained at the operating point of $\approx$14 K.

The third copper block of each gun assembly (Fig. 1) accommodates a fast propellant valve and a pellet chambering mechanism. Like the second blocks, they are maintained at solid deuterium temperature ($\approx$14 K). Individual extrusion nozzles (Fig. 2) provide for transition and reduction in extrusion cross section from inside the brass cylinder to the gun feed (rectangular-type cross section). The pellet diameter of each gun assembly is established by the inside diameter of the stainless steel tubing for the gun barrel. The width of the extrusion exiting the nozzle determines the length of the chambered pellet. During operation, the extrusions can be viewed through windows located below the gun mechanisms. For the JET application, gun barrel diameters of 2.7, 4.0, and 6.0 mm are provided with a gun barrel length of 0.8 m for the two smaller sizes and 1 m for the largest pellet size (center barrel in Fig. 2). Nominal pellet dimensions are listed in Table I.

The main difference between this design and the original repeating one is the scheme used for the punch-type pellet chambering mechanisms. In the prototype repeating injector, the gun barrel served as the active mechanism; however, in the new design a short (≈13.8-cm-long) section of stainless steel tube is brazed directly to a solenoid plunger and is located on the breech side of the gun, between the propellant valve and the copper block. When the solenoid is activated, the knife-edge end of the tube, which acts as the punch, is driven into the extrusion, punching out and chambering a pellet (a shock accelerometer mounted on each mechanism housing indicates chambering action). This design change allows the gun barrels to be aimed and positioned (fixed) accurately, as required for the JET installation.

While the punch mechanism is engaged, the hydrogen propellant is admitted to the gun breech by a fast-opening magnetic valve. The valves for the two smaller guns are of a standard ORNL design[12] used on previous pellet injectors[8,9,13,14] and are equipped with a 5-mm orifice and a 10-cm^3 storage reservoir (in addition to the internal valve volume of ≈5 cm^3). For the 6-mm gun, a special valve was fabricated with a larger (6-mm-diam) orifice and a larger volume (20-cm^3 storage reservoir). A piezoelectric pressure transducer mounted at the outlet of the fast solenoid valve measures the gun breech pressure. The low-inductance solenoids used for both the valves and the chambering mechanisms are powered by a capacitive discharge circuit that provides up to 40 A of drive current. Current pulses of only a few milliseconds are required to fully open the valves; current pulses of 5–10 ms are adequate for activation of the pellet chambering mechanisms.

B. Control and data acquisition system

A stand-alone control and data acquisition system is used for injector operation. The system is based on an Allen-Bradley Model 2/30 programmable logic controller (PLC) and a Digital Equipment Corporation MicroVAX II computer. The PLC performs all of the control functions and is interfaced to the VAX for remote operation via a color graphic display. Local operation of the injector is provided by an intelligent panel system that has a keypad and push-button module programmed from the PLC. The VAX has a CAMAC serial highway interface that drives color graphic status displays, data acquisition from transient recorders, and the serial communications link with the PLC. The VAX also has a serial communications link to the JET pellet firing sequencer, which interfaces to the JET central timing system and synchronizes the actual triggering of the pellet injectors with the JET pulse. The system is operated remotely through a combination of track-ball and keyboard commands that the VAX processes and sends to the PLC. The VAX acquires both transient data from pellet shots and trend data from the PLC during operation of the pellet injector. The transient diagnostic information is analyzed to determine pellet speed and is archived with the JET experimental data. The design of the system is based on previous systems used at TFTR and has been described by Baylor[15] and Burris.[16]

C. Operation

With a 2.0-mm-i.d., ≈3-m-long line for the transfer of liquid helium, the time required to cool down the cryostats (nine copper blocks for operation of all three guns) to operating temperatures was <1 h during testing at ORNL, where liquid helium coolant was supplied from a 500-L storage dewar pressurized to ≈1.5 bar (7 psig). The total consumption of liquid helium was ≈340 L for a typical test day, including ≈100 L for the cooldown and another ≈240 L for 8 h of standard operation. This translates to coolant flow rates of 30 L/h total or 10 L/h per gun for routine operation after the cooldown phase. The injector has been tested only with the deuterium isotope, but experience with the original repeating pneumatic injector,[8] in which hydrogen was also tested, suggests that hydrogen operation should be straightforward. Operation of similar ORNL pellet injectors has been described previously.[9,11,13]

III. INJECTOR PERFORMANCE

In laboratory operation at ORNL, the injector was used to accelerate deuterium pellets to speeds of 1.0–1.5 km/s (operating range of 70–105 bar for hydrogen propellant valves). Nominal physical properties of the pellets are listed in Table I. To verify pellet integrity and size, pellets were photographed at the muzzle of each gun, as shown in Table I. Accurate pellet velocity measurements were obtained from the data acquisition system by measuring the time of flight between a light barrier and a target plate (equipped with a shock accelerometer).

The pellet speed data for the three-barrel injector are similar to those previously reported for the prototype repeating gun (Fig. 4 of Ref. 9); in general, speeds are slightly lower, but fall within 5–10% of the original data when compared at the same operating pressure. This decrease is probably due to the higher aspect ratio (length/diameter) of the present pellets, which retards the acceleration slightly. The highest speeds measured in the tests at ORNL were 1.47 km/s for both the 2.7- and 4-mm pellets at operating pressures of 105 bar (1500 psi). The larger-orifice propellant valve would not open reliably at the higher pressure with the standard ORNL power supply; thus, for the large pellets the highest velocity recorded was 1.40 km/s at an operating pressure of 70 bar (1000 psi). The 6-mm gun speed information extends the ORNL data base to larger pellet sizes. To achieve these highest velocities, the holding time (or current pulse length) of the propellant solenoid valves was sufficently long to ensure that the valves fully opened. However, for repetitive testing (which is discussed next), the holding time was reduced to limit the gas loading and thermal effects on the gun cryostats. The highest measured gas loads were 1600, 900, and 650 Torr·L for the 6.0-, 4.0-, and 2.7-mm guns, respectively.

Table II summarizes the maximum repetitive performance obtained in laboratory tests for each gun. These values represent an improvement over the performance previously reported for the prototype repeating injector,[8,9] especially with regard to total number of smaller pellets per pulse (previously limited to only five pellets at a frequency of 4 Hz). At repetition rates in the range from 1 to 5 Hz, the present device approaches steady-state conditions. The pulse length (≈10–20 s) is limited only by the volume of deuterium ice available from the batch-type freezing process (≈4 cm^3). The enhanced performance is attributed to improvements in the thermal and mechanical designs of the gun assemblies and extrusion nozzles. Since the guns operate independently, the data indicate that the injector can deliver over 100 pellets in pulses of <20 s. The highest repetition rates listed in Table II (5, 2.5, and 1 Hz for the small, medium, and large pellets, respectively) exceed the requirements for JET, and no attempt has yet been made to extend these parameters.

Finally, several tests were conducted to simulate an aggressive experiment on JET. The results of three 25-pellet sequences with all three guns operating in the repeating mode are listed in Table III. The frequencies of the guns were 3, 2, and 1 Hz for the 2.7-, 4.0-, and 6.0-mm guns, respectively. These data give some indication of the reproducibility and reliability of the injector. The average pellet speed in Table II is 1.22 km/s; all speeds in these repetitive tests fall within ±10% of this average value.

During testing at ORNL, soft aluminum targets located ≈2.6 m downstream of the gun muzzles were used to intercept the pellets. The pellets made distinct craters or, in many cases, penetrations in the target plates; from this information the angular dispersion of pellets fired from the guns was determined. The dispersion was always within ±0.33° for each gun. In one test, a one-cent piece was attached to the target plate, and the 6-mm gun was aimed by adjusting the barrel alignment until the pellets hit near the center of the penny. A few shots were sufficient to penetrate the metal (Fig. 3). This test demonstrated the aiming capability of the guns and indicated the accuracy with which the injector can deliver pellets, as well as the kinetic energy associated with the large, high-speed pellets ($\approx$0.1 kJ).

IV. CONCLUSIONS

The three-barrel repeating pneumatic pellet injector has been installed on JET. The injector can deliver over 100 deuterium pellets (in three sizes: 2.7, 4.0, and 6.0 mm) within 10 to 20 s at speeds in the range of 1.0 to 1.5 km/s. This application will extend previous pellet fueling results to the larger plasma volume and longer pulse length associated with JET. The largest pellet size supplied by the three-barrel repeating injector also represents an extension of previous experience.

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Table I. Physical pellet parameters.

	Pellet size		
	Small	Medium	Large
Photograph[a] (scale: mm)			
Nominal size[b]			
Diameter (mm)	2.7	4.0	6.0
Length (mm)	2.7	4.0	6.0
Pellet load[c]			
Volume (mm^3)	15	50	170
Weight (mg)	3	10	34
PV (torr L)	12	42	130
N (D^O)	9×10^{20}	3×10^{21}	1×10^{22}

[a]Photographs were taken within 20 mm of gun muzzles; the housing for the light fibers used in detecting the pellet can be seen in the 6-mm photograph.
[b]Determined by gun barrel bore (diameter) and extrusion width (length).
[c]Based on nominal sizes; the density was taken as 0.2 g/cm^3 for solid deuterium.

TABLE II. Maximum repetitive performance for guns (pellet velocities were similar to those listed in Table III; supply pressure of 70 bar for hydrogen propellant values)

Gun size (mm)	Frequency (Hz)	Pulse length (s)	Pellets per pulse
2.7	4	21.25	85
2.7	5	13.00	65
4	2	21.00	42
4	2.5	12.40	31
6	1	11.00	11

TABLE III. Velocity measurements for three 25-pellet sequences; three guns operating in repeating modes at 3 Hz (2.7-mm pellets), 2 Hz (4.0-mm pellets), and 1 Hz (6.0-mm pellets). Initial hydrogen supply pressure of 70 bar, falling gradually to 56 bar at end of test

Pellet number	Pellet size (mm)			Time (ms)	Pellet velocity (m/s)		
	2.7	4	6		Test 1914	Test 1020	Test 1025
1	x			0.333	1175	1154	1164
2	x			0.667	1164	1314	1174
3	x			1.000	1154	1314	1171
4	x			1.333	1144	1327	1185
5	x			1.667	1115	1289	1196
6	x			2.000	1175	1314	1164
7	x			2.333	1134	1301	1164
8	x			2.667	1105	1314	1134
9	x			3.000	1125	1301	1144
10	x			3.333	1144	1185	1144
11		x		4.500	1264	1134	1264
12		x		5.000	1301	1164	1327
13		x		5.500	1327	1106	1264
14		x		6.000	1276	1088	1276
15		x		6.500	1276	1115	1301
16		x		7.000	1314	1134	1276
17		x		7.500	1327	1134	1264
18		x		8.000	1289	1154	1301
19		x		8.500	1301	1144	1264
20		x		9.000	1288	1185	1289
21			x	10.500	1240	1327	1327
22			x	11.500	1115	1196	1229
23			x	12.500	1097	1240	1218
24			x	13.500	1125	1276	1207
25			x	14.500	1106	1218	1218

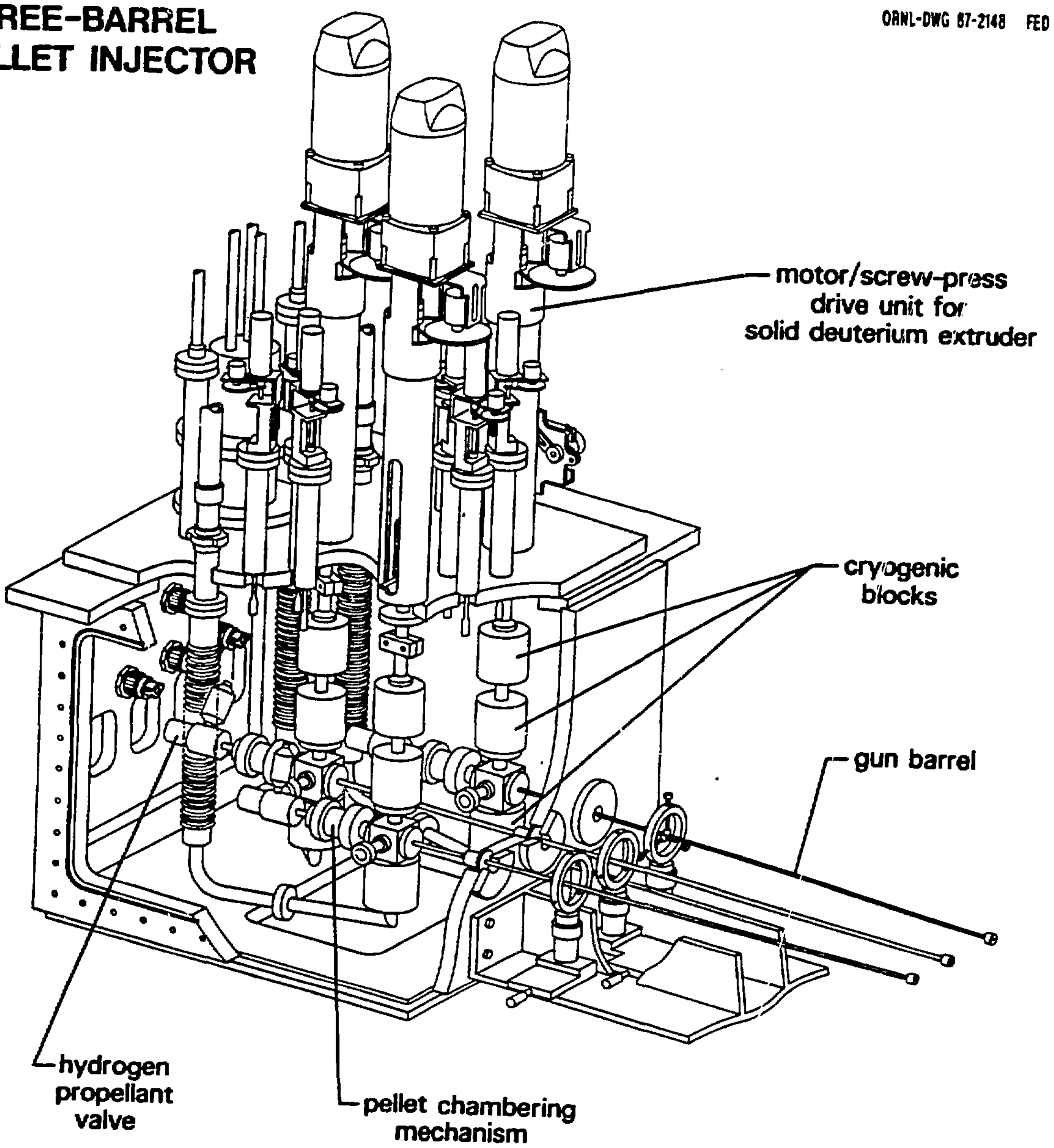
FIGURE CAPTIONS

FIG. 1. Three-barrel repeating pneumatic pellet injector.

FIG. 2. Schematic of a cryogenic extruder and a gun assembly; firing sequence includes (1) activation of punch-type mechanism to chamber pellet and (2) opening of fast magnetic valve to admit hydrogen propellant that accelerates pellet in gun barrel.

FIG. 3. Impact damage of large (6-mm), high-speed ($\approx$1.4-km/s) deuterium pellets on a target.

REPEATING THREE-BARREL PELLET INJECTOR



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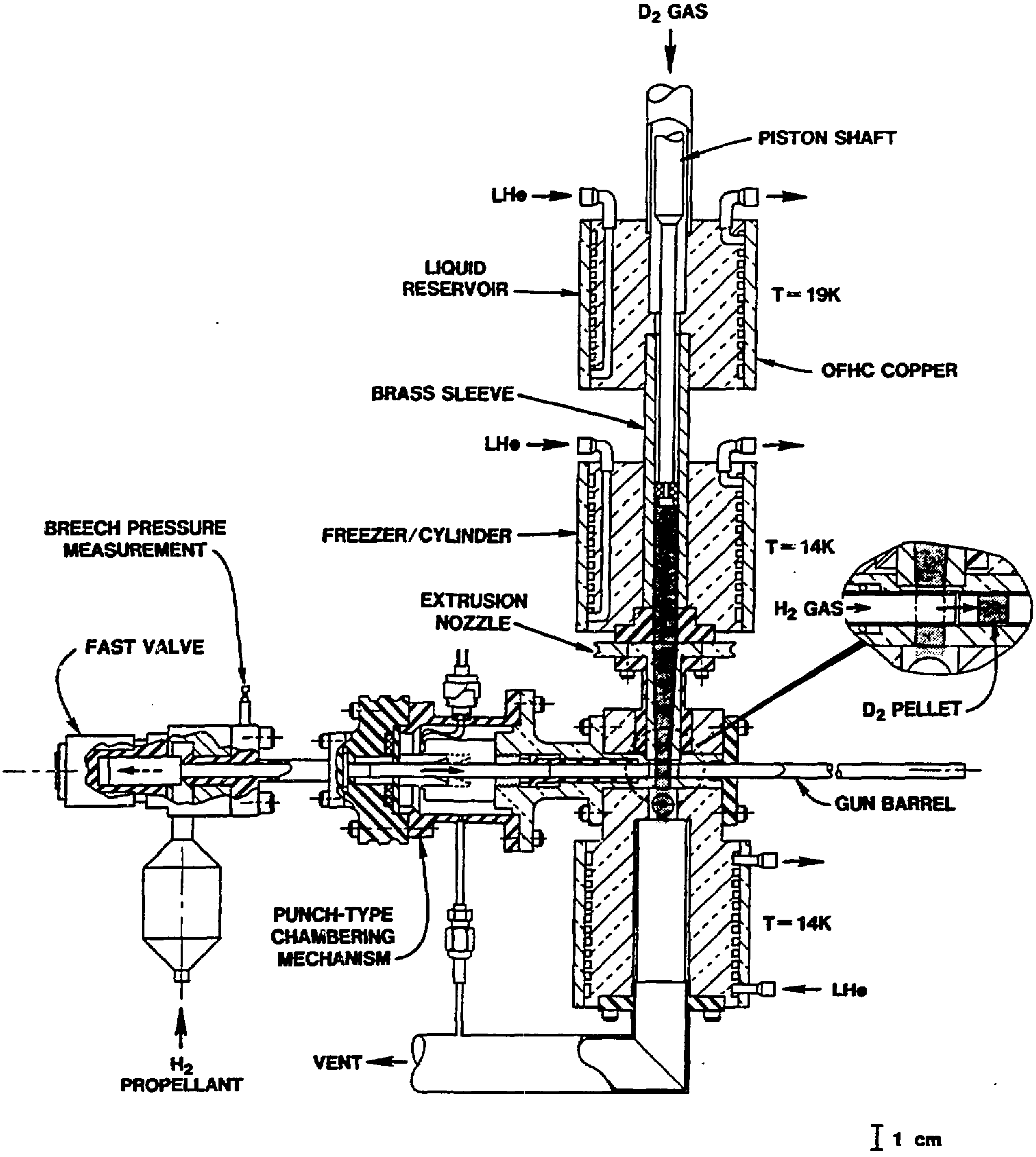


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