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PELLET INJECTOR DEVELOPMENT AT ORNL*

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Plasma fueling systems for magnetic confinement experiments are under development at Oak Ridge National Laboratory (ORNL). ORNL has recently provided a four-shot tritium pellet injector with up to 4-mm-diam capability for the Tokamak Fusion Test Reactor (TFTR). This injector, which is based on the in situ condensation technique for pellet formation, features three single-stage gas guns that have been qualified in deuterium at up to 1.7 km/s and a two-stage light gas gun driver that has been operated at 2.8-km/s pellet speeds for deep penetration in the high-temperature TFTR supershot regime. Performance improvements to the centrifugal pellet injector for the Tore Supra tokamak are being made by modifying the storage-type pellet feed system, which has been redesigned to improve the reliability of delivery of pellets and to extend operation to longer pulse durations (up to 400 pellets). Two-stage light gas guns and electron-beam (e-beam) rocket accelerators for speeds in the range from 2 to 10 km/s are also under development. A repeating, two-stage light gas gun that has been developed can accelerate low-density plastic pellets at a 1-Hz repetition rate to speeds of 3 km/s. In a collaboration with ENEA-Frascati, a test facility has been prepared to study repetitive operation of a two-stage gas gun driver equipped with an extrusion-type deuterium pellet source. Extensive testing of the e-beam accelerator has demonstrated a parametric dependence of propellant burn velocity and pellet speed, in accordance with a model derived from the neutral gas shielding theory for pellet ablation in a magnetized plasma.

1. INTRODUCTION

In the past few years, steady progress has been made at ORNL in the development and application of pellet injectors for fueling present-day and future fusion reactors based on the magnetic confinement concept. The recent emphasis has been in the areas of (1) tritium injector development [1.5–3 km/s, in support of the TFTR deuterium-tritium (DT) phase of operation], (2) repeating two-stage light gas guns (for anticipated higher speed ITER applications at 2.5–5 km/s), (3) the e-beam rocket accelerator concept for future ultrahigh-speed applications (>5 km/s) and (4) long-pulse centrifuge development (for Tore Supra and ITER high-throughput applications). We describe recent developments in the ORNL program with emphasis on items 1–3. A program to upgrade the present ORNL centrifuge injector to longer pulse operation (from the present 100-pellet capability to 300–500 pellets) is described in a paper by Foster et al., "ORNL Centrifuge Pellet Fueling System." A collaboration between ORNL and ENEA-Frascati in the development of a repeating two-stage light gas gun based on an extrusion-type pellet feed system is described by Frattolillo et al. in the paper "High-Speed Repetitive Pellet Injector Prototype for Magnetic Confinement Fusion Devices."

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2. TRITIUM INJECTOR DEVELOPMENT

2.1 Tritium Pellet Injector for TFTR

The tritium pellet injector (TPI) for TFTR will provide a tritium pellet fueling capability with pellet speeds in the 1- to 3-km/s range for the TFTR DT phase. The TFTR deuterium pellet injector was modified at ORNL to provide a four-shot, tritium-compatible, pipe-gun configuration with three upgraded single-stage pneumatic guns and a two-stage light gas gun driver (refs. 1, 2, 3). The pipe-gun (in situ condensation) design is ideal for tritium service because there are no moving parts inside the gun and because less tritium is required in the pellet production process. Two guns have diameters of 3.4 mm; the other two, diameters of 4.0 mm. The nominal pellet aspect ratio is 1.25, but pellets can be formed with aspect ratios of 1.0 to ≥1.5. The injector, Figs. 1 and 2, has gaseous-helium-cooled cryostats that provide cooling for pellet formation and, for DT pellets, cooling for cryogenic He^3 separation. The barrel assemblies are located around the gun cryostat. Three of the barrel assemblies are coupled to an ORNL-designedfast propellant valve (single-stage driver); the fourth is connected to the two-stage driver.

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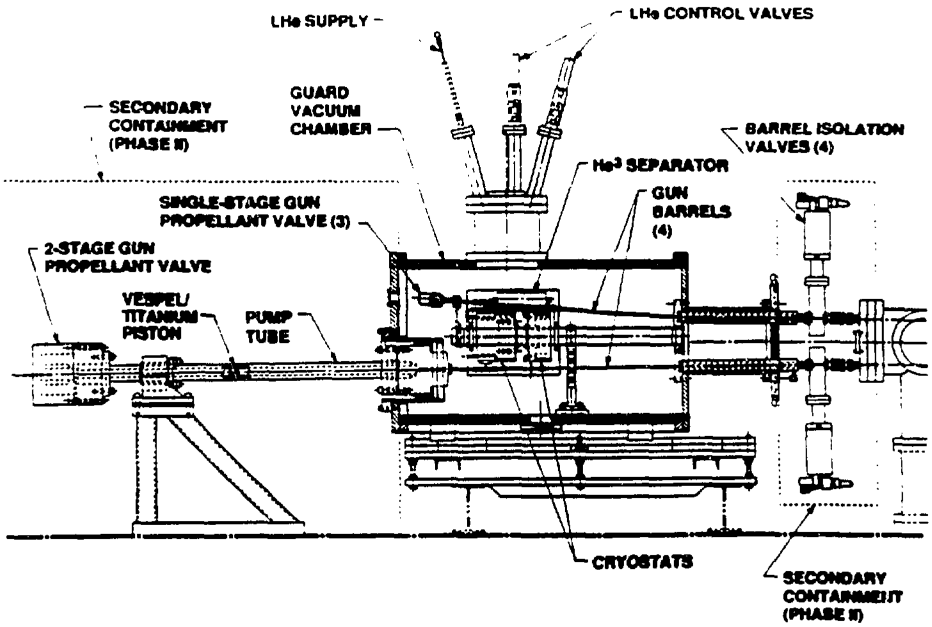

Fig. 1. The TPI injector and two-stage light gas gun assembly.

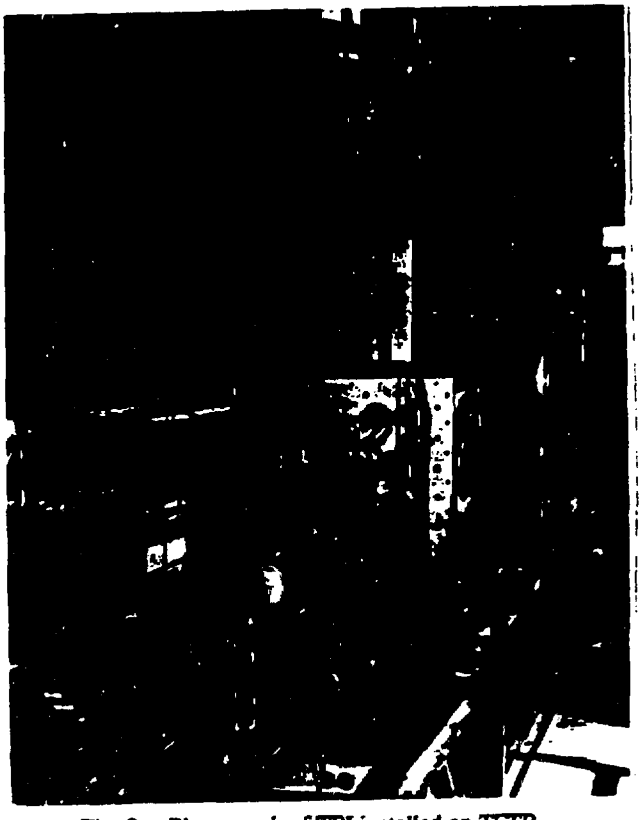

Fig. 2. Photograph of TPI installed on TFTR.

The two-stage driver system provides the high-pressure, high-temperature drive gas required to accelerate pellets to the 2.5- to 3-km/s range. It is based on development of two-stage light gas guns at ORNL (refs. 4, 5) and in Europe (refs. 6, 7). In the two-stage driver, moderate-pressure (20- to 58-bar) helium propellant gas initially in a 0.64-L first-stage reservoir accelerates a 25.4-mm-OD Vespel® or titanium piston in a 0.9-m-long, thick-walled 4130 carbon steel pump tube. The reservoir is connected to the pump tube by a 1.9-cm-diam orifice, pneumatically actuated fast valve. A bellows isolates the two-stage driver and the guard vacuum chamber. The high-pressure end of the pump tube is enclosed in a 4340 carbon steel head assembly. The accelerating piston compresses low-pressure (initially 1- to 2-bar), room-temperature hydrogen propellant gas that becomes the driving gas for the cryogenic pellet.

The pellet injection line provides differential vacuum pumping of the propellant and contains diagnostics to measure the pellet speed (two light gate stations), determine the pellet relative mass (microwave cavity), photograph the pellet and measure the pellet ablation (H_α diagnostics). The injection line primary vacuum system links the injector with the high-vacuum system. It contains an array of four 8.0-mm-ID, 1.1-m-long guide tubes. The injection line high-vacuum system links the primary vacuum system to the TFTR vacuum vessel through a region of high vacuum. The high-vacuum system contains four 14.8-mm-ID, 1.0-m-long guide tubes. This portion of the system ends with a connection to the pellet injector torus interface valve.

The three TPI single-stage gas guns were commissioned on TFTR in August 1992. The injector is controlled by an Allen-Bradley programmable logic controller (PLC), and the operator interface consists of multiple mimic panels. The three single-stage light gas guns can make 3.4-mm and 4-mm deuterium pellets at aspect ratios of 1, 1.25, and 1.5. Each single-stage gun was tested at hydrogen propellant supply pressures in the range from 69 to 138 bar, and deuterium pellet muzzle velocities over 1.7 km/s were achieved. One major goal was to verify that the helium gas cooling circui had a sufficiently low pressure drop to allow operation with a closed cryogenic helium system used for the TFTR neutral beam injector cryopumps. The main gun copper cryostat was maintained at temperatures as low as 8 K at a system pressure drop of ~0.1 bar. The TPI two-stage driver has accelerated deuterium pellets to 2.8 km/s with a 25-g Vespel® piston. Peak head pressures are estimated at <1000 bar. The gun performance is shown in Fig. 3 as a function of the first-stage pressure for constant initial second-stage fill pressure (H_2 at 1.97 bar). Shown also are the piston time-of-flight measurement and theoretical calculations from the QUICKGUN (ref. 8) and TRUCCO (ref. 9) interior ballistics codes. While QUICKGUN solves only approximately for the nonsteady gas dynamic conditions inside the gun barrel, it includes a model for the first-stage propellant valve. TRUCCO approximates the first-stage propellant valve as a rupture disk but uses the full method of characteristics to compute the gasdynamic conditions and includes a model for gas leakage across the piston. Good agreement for QUICKGUN was obtained by assuming that the pellet releases at a pressure of 20.7 bar, while the results shown for TRUCCO were obtained by assuming pellet breakaway at 34.5 bar. Both values are within the range of the measurements for deuterium pellets of similar size (see below). In QUICKGUN, the propellant valve was modeled as an orifice of 1.9 cm with a discharge coefficient = 0.7 and an opening time of 3.5 ms. In TRUCCO, the first-stage reservoir was adjusted downward so as to match the experimentally measured piston transit times.

The TPI system, as installed on TFTR for the 1992 deuterium experimental run, is fully tritium-compatible and radiation hardened for TFTR DT operations in 1993–94. Ongoing design and fabrication activities will provide a DT gas manifold and two secondary containment structures. These components, when retrofitted on TPI in 1993, will provide full tritium pellet capability.

2.2 Studies of Tritium Properties

The tritium proof-of-principle (TPOP) apparatus was built by ORNL to demonstrate the formation and acceleration of tritium pellets in support of the TPI project (ref. 10). Many parameters measured during the course of the experiment have been used to evaluate the physical properties of solid tritium. One parameter needed to model two-stage gun performance is the "breakaway pressure" of the pellet, which is the minimum propellant pressure required to shear the pellet from the barrel wall. To observe the breakaway pressure, propellant gas flow was restricted by using an ordinary solenoid valve with a needle valve in series to launch the pellet. The propellant gas was helium, which does not condense and change the pellet size. In these experiments, the propellant pressure was slowly increased until the pellet broke away from the wall.

The shear strength of the pellet can be calculated by setting the breakaway force exerted on the rear of the pellet equal to the shear force at the wall, $\sigma = (P_b D_p)/4L_p$, where P_b is the breakaway pressure, D_p is the pellet diameter, and L_p is the pellet length. Values of the shear strength inferred in this way are presented as a function of temperature in Fig. 4. Also shown are the ultimate tensile strengths of hydrogen (ref. 11) and deuterium (ref. 12). Strictly speaking, the shear strength and tensile strength of a material are not necessarily equal. However, the shear strength and tensile strength of deuterium have similar magnitudes and temperature dependences. The shear strength for tritium is about twice that for deuterium at 8 K.

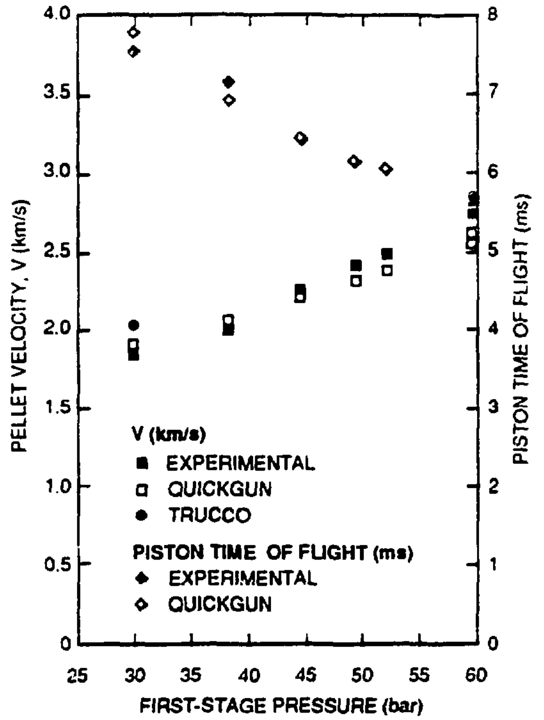

Fig. 3. TPI two-stage gas gun performance measurements and calculations.

3. REPEATING TWO-STAGE LIGHT GAS GUN

A schematic of the ORNL repeating two-stage light gas gun is shown in Fig. 5. The device consists of some standard components for two-stage light gas guns: a 2.2-L first-stage reservoir, a pump tube (27.0 mm ID and 1.0 m long), and a gun barrel (4.0 mm ID 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 (Vespel®). Plastic pellets (nylon, polypropylene, polycarbonate, acetal, etc.) with a 4-mm diameter were used in this study, including right circular cylinders and spheres. 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.

The operating sequence is as follows. (1) A pellet is 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; the fast valve then automatically switches back from pressure to vacuum and dumps the remaining gas to the vacuum system (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. An Allen-Bradley PLC (Model 5-25) and a MicroVax II–based CAMAC data acquisition system are the central components of the control and data acquisition system.

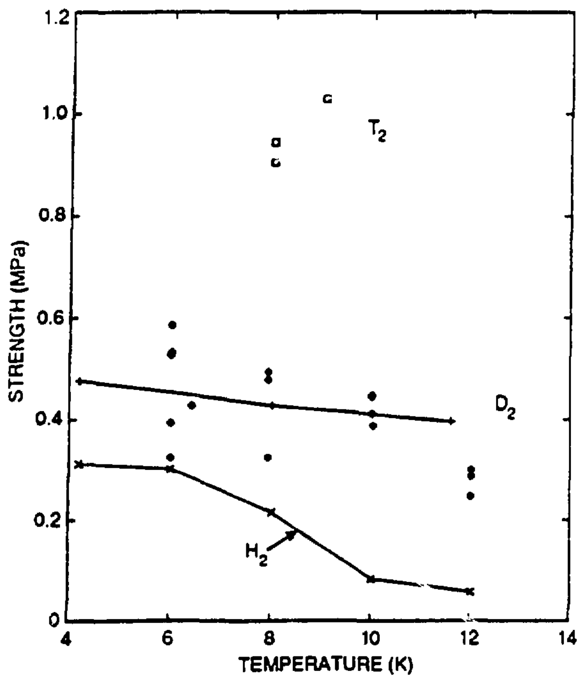

Fig. 4. Measurements of the shear strength of solid tritium.

Small plastic projectiles (4-mm nominal size) and helium gas have been used in the prototype device to demonstrate repetitive operation. In a typical ten-pellet sequence, polypropylene spheres (29 mg) were accelerated to an average speed of 3 km/s with a piston mass of 30 g and first- and second-stage propellant gas fill pressures of 100 bar and 0.8 bar, respectively (ref. 13). The highest experimental velocity is twice that available from conventional repeating single-stage pneumatic injectors that accelerate hydrogen pellets. Pellets composed of light hydrogen ice can easily be accelerated to close to 3 km/s (refs. 4,5); however, protective shells (or sabots) will be required to protect the relatively weak ice from high acceleration forces and temperatures in order to achieve higher velocities. The pellet test repetition rate of 1 Hz is relevant for fueling applications on future large fusion research devices.

The next step in developing a functional high-speed repetitive hydrogen pellet injector is to combine this acceleration technology with the cryogenic extruder technology for supplying hydrogen ice (e.g., ref. 14). Sabots could be used to attain even higher velocities. The present design can, however, be readily integrated into a pellet injection system, with or without sabot-handling capability.

4. ELECTRON-BEAM ACCELERATOR

A method of accelerating deuterium pellets using a high-power, magnetically compressed electron beam is under development at ORNL. A payload is accelerated by ablating gas from a hydrogen ice propellant "stick" with an electron beam. The "rocket effect" has been observed on the trajectory of hydrogenic pellets injected into several tokamaks. Since the neutral shielding model of pellet ablation in a plasma treats the plasma as an equivalent electron beam incident on the pellet surface, it has been modified and employed as the physics model for the e-beam rocket.

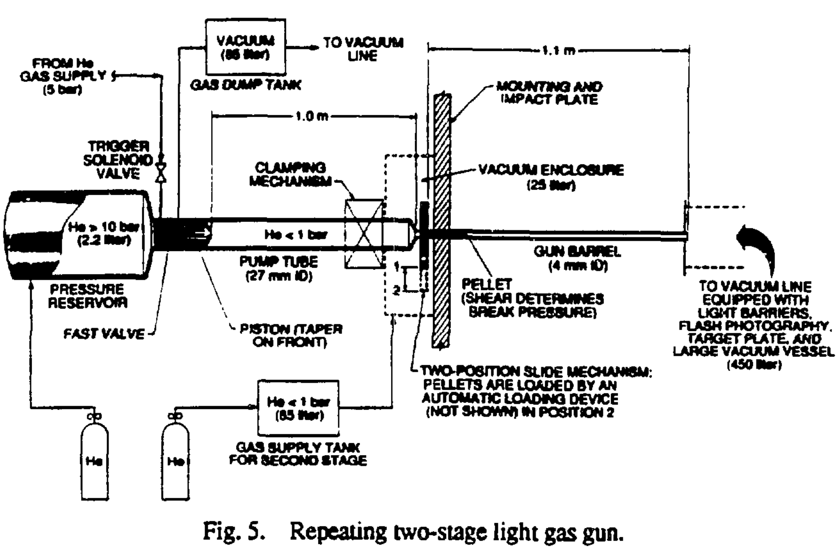

Fig. 5. Repeating two-stage light gas gun.

An apparatus consisting of an electron gun and a 50-cm acceleration column enclosed in a 1-T solenoid magnet was constructed to test this principle. Cryogenic hydrogen pellets (ϕ = 4 mm, l = 12 mm) have been accelerated to 500 m/s. In Fig. 6, the measured velocities as a function of e-beam current are compared with a theory adapted from the neutral gas shielding model (ref. 15). The beam voltage increases systematically from 4.5 kV to 14 kV as the current increases. Good agreement with the theory is obtained if it is assumed that two-thirds of the beam power is absorbed in the expanding gas and one-third of the exhaust gas velocity contributes to directional acceleration of the pellet. In these experiments, the limits of the acceleration for hydrogenic pellets are found to correspond to an effective acceleration pressure of 0.2 MPa. To overcome this limitation, a higher strength material such as lithium or lithium hydride has been proposed as the propellant material. A parametric analysis of systems capable of accelerating pellets to 10 km/s has been made. The accelerator characteristics are shown as a function of beam voltage in Fig. 7 for a constant perveance ($I/V^{3/2}$) of 12 µP. The symbols L_0, P_0, and S correspond to initial pellet length, acceleration pressure, and accelerator length, respectively. Two design points are indicated (DP1, DP2), corresponding to acceleration lengths of 2 m and 12 m and beam currents of 100 A and 38 A, respectively. The difference represents a trade-off between accelerator length and acceleration pressure.

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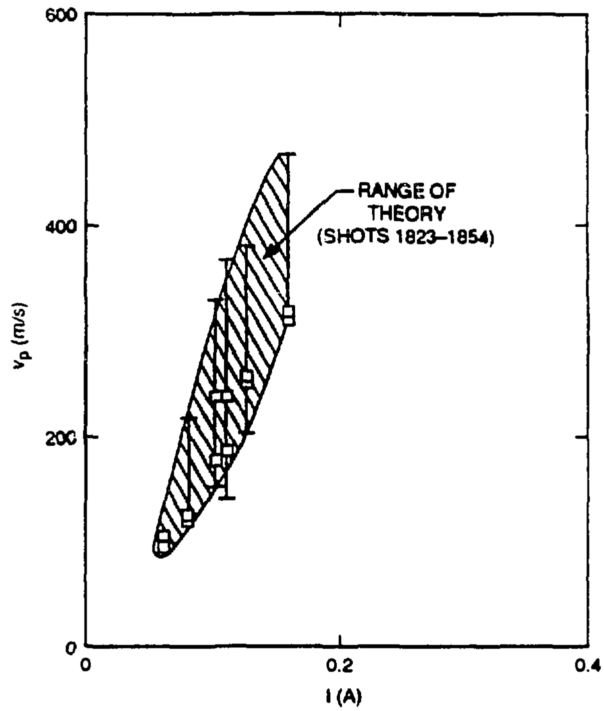

Fig. 6. Proof-of-principle electron-beam rocket accelerator performance.

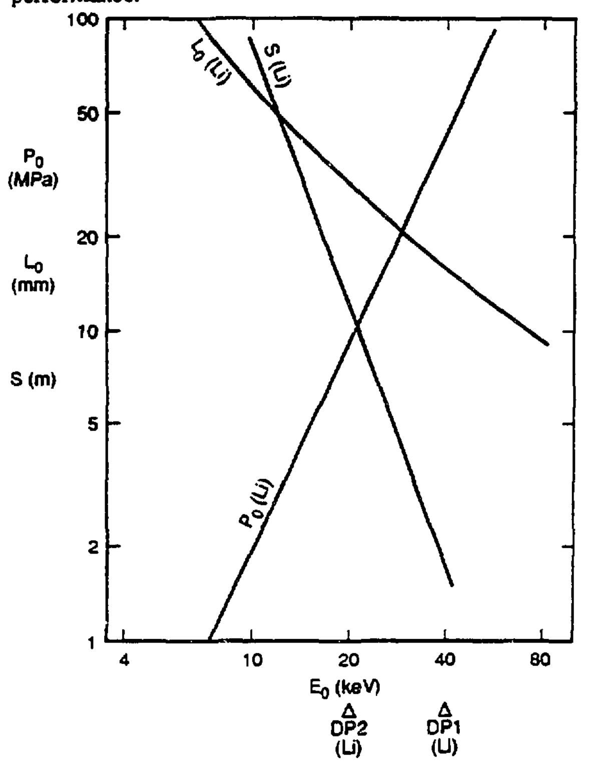

Fig. 7. Projected 10-km/s electron-beam rocket accelerator parameters for lithium pellets and beam perveance = 12 µP.