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Design of a Repeating Pneumatic Pellet Injector for the Joint European Torus

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A three-barrel pneumatic pellet injector has been developed for plasma fueling of the Joint European Torus (JET). The versatile device consists of three independent machine-gun-like mechanisms that operate at cryogenic temperatures (14 K-20 K). Individual high speed extruders provide a continuous supply of solid deuterium to each gun assembly, where a reciprocating breech-side cutting mechanism forms and chambers cylindrical pellets from the extrusion; deuterium pellets are then accelerated in the gun barrels with controlled amounts of compressed hydrogen gas (pressures up to 100 bars) to velocities ≤1.5 km/s. The injector features three nominal pellet sizes (2.7 mm, 4.0 mm, and 6.0 mm) and has been tested at repetition rates of 5 Hz, 2.5 Hz, and 1 Hz, respectively. Each gun is capable of operating (individually or simultaneously) at the design repetition rate for 15-second duration pulses (limited only by the capacity of the extruder feed system). A remote, stand-alone control and data acquisition system is used for injector operation.

1 Introduction

A repetitive, long-pulse hydrogen pellet injection system based on the repeating pneumatic type[1] has been developed at ORNL. As shown in Fig. 1 the pellet injector features three separate solid hydrogen extruder/gun mechanism subassemblies in a common high vacuum chamber. Individual solid hydrogen extruders feed the 2.7mm, 4mm and 6 mm diameter gun chambers independently. *In situ* formation and chambering of pellets is accomplished by a hollow, cylindrical, reciprocating die that is driven by an electromagnetic actuator. Pellet acceleration is provided by timed short bursts of high pressure hydrogen gas admitted to the breech of the gun mechanism by programmable solenoid valves developed at ORNL[2] for this application. In addition to the pellet injector, the ORNL pellet injection system consists of:

1) an instrumented propellant and fuel gas feed system with components that can be controlled and monitored remotely.

2) a complete set of injector diagnostics including pressure, temperature and mass flow sensors, a fiber-optic pellet detection system and optical systems for remote monitoring of solid hydrogen extrusions and high speed flash photography of pellets at the muzzle location.

3) a data acquisition and remote control system consisting of a programmable logic controller(PLC) and a computer/CAMAC based operator interface and data acquisition system.

The balance of the installation at JET consists of the following JET supplied components and subsystems:

1) support structure and mechanical interface to the torus.

2) a liquid helium storage, delivery and recovery system.

3) vacuum services including a cryopump with a pumping capacity of 10^6 l/s for rapid removal of the hydrogen propellant gas and vacuum isolation of the torus.

4) a fire control sequencer that provides timed trigger pulses for initiation of the extrusion process and programmable firing of pellets.

5) a microwave based pellet mass detection system and an instrumented target array to facilitate aiming of all three guns.

6) fuel and propellant gas distribution systems.

7) a PLC based control system and computer operator interface for the above systems.

The design and performance of the JET subsystems are described in the paper by Kupschus et. al. [3] at this conference. In the present paper the design features, operation, and performance parameters of the ORNL pellet injector are described.

2 Pellet Injector Design

2.1 Chambering Mechanism

The basic design features and operating characteristics of a repeating pneumatic injector(RPI) are described elsewhere[1],[4]. The present design differs from the prototype version which was used on the Tokamak Fusion Test Reactor(TFTR)[4], [5] in that the chambering mechanism has been relocated to the breech side of the gun. This is illustrated in Fig. 2 where the basic extruder/gun mechanism is shown in cross section. A ribbon of solid deuterium is extruded between the gun barrel on the right and the chambering mechanism on the left. The punch type chambering mechanism consists of a thin wall(0.4 mm) in-line stainless steel tube of the same internal diameter as the gun barrel. The punch is attached to the armature of an electromagnetic actuator; the assembly is free to move axially(inside the solenoid coil housing) between the gun barrel and the propellant valve internal stops.Close fitting(0.08 mm diametric clearance) brass bushings at the ends of the chambering mechanism housing serve as low friction bearing surfaces and low leakage seals for the propellant gas. When the solenoid coil is energized, the tube is driven across the extruded deuterium ribbon and penetrates 2.2 mm into a chamber behind the gun barrel as shown in the insert of Fig.2. The leading edge of the punch tube is sharpened in order to facilitate cutting of the deuterium ice.

The chambering mechanisms of the 2.7mm, 4mm and 6mm guns are provided with a stroke of 5.4 mm, 6.9 mm and 8.6 mm respectively. The actuators typically engage 5-7ms after the low inductance ($L \approx 1mH$, $R \approx 1\Omega$) solenoid coils are energized. A capacitive discharge circuit provides up to 40A of drive current with a rise time of <0.5ms. The mechanisms can be held in the chambered position for an arbitrary time by extending the current pulse length. The punch tubes are returned to the unchambered position by internal springs in 10-20ms after the drive current is interrupted.

2.2 Propellant Valve

The high pressure (100 bar) fast solenoid type propellant valves are based on the design described by Milora et. al. [2]. It is provided with a polyimide stem tip (hard seal), a low inductance solenoid coil (of similar design to that used for the chambering mechanism), and a large orifice (5mm for the 2.7 and 4 mm guns and 6 mm for the 6 mm gun), for fast opening and high throughput. The valves are energized by programmable power supplies similar to the units used for the chambering mechanisms. In typical operation, the valve begins to open 1.6 ms after the coil is energized and peak pressure is delivered 0.6 ms later. The pellet residence time in the gun barrels (80cm for 2.7 and 4mm guns; 100 cm for the 6 mm gun) is typically ≈ 1ms. The valves can be programmed for partial (< 1ms bursts) or complete opening by varying the duration of the drive current pulse from 1.4- 2.2 ms. In this way the propellant gas load can be controlled to vary pellet speed and limit the heat load to the cryostats during repetitive long pulse operation. Precise timing pulses for the chambering mechanism and propellant valve power supplies including relative delays and drive current durations are issued by the JET supplied CAMAC based fire control sequencer. In typical operation, the propellant valve pressure burst is delayed 1-2 ms after the chambering mechanism is engaged.

2.3 Extruders and Cryogenic System

Three high speed motor driven extruders provide a continuous supply of solid deuterium to the gun mechanism. In design and operation, the extruders are similar to the apparatus described by Combs et. al. [1]. The design of the extruder cryogenic stage is illustrated in Fig. 2. It consists of a liquid reservoir positioned above a cylindrical freezing chamber which is fitted at its outlet with a tapered copper extrusion nozzle. A programmable motor driven screw press activates a piston that moves vertically inside the cylindrical bore of the freezing chamber where the solid deuterium charge is located. The extrusion nozzle which terminates just above the chambering mechanism position provides a smooth transition from the 10.5 mm cylindrical extruder bore to a rectangular like cross section whose length is larger than the punch tube diameter and whose width determines the length of the pellet. The dimensions of the extrusion at the point where pellets are chambered are 9.3x6.2mm, 6.6x4mm, and 5.4x2.7mm for the 6, 4 and 2.7mm guns respectively. The extruders are equipped with a fiber optic imaging system for monitoring the quality of the extrusions at viewports located below the chambering mechanism.

The extruder reservoirs and gun sections are convectively forced cooled with liquid helium flowing through 0.3 cm channels located on the periphery of the copper heat exchangers. Temperature regulation of the nine cryogenic zones is achieved by feedback heat and individual motor controlled helium throttle valves. All of the cryogenic components are located within a single high vacuum chamber. Thermal isolation is maintained by a 50 l/s turbomolecular pump. Excess extrudate and propellant gas blow-by is vented to a separate vacuum system.

3 Control and Data Acquisition System

A stand-alone control and data acquisition system is used for operation of the pellet injector. The system is based on an Allen-Bradley 2/30 programmable logic controller(PLC) that is interfaced via RS-232 to a Digital Equipment Corporation MicroVAX II computer. The PLC performs control functions from commands that it receives from the MicroVAX which has an operator interface consisting of a color graphic mimic with a track ball and keyboard. The MicroVAX is equipped with a CAMAC serial highway that drives the color graphic mimic displays, acquires data from high speed transient recorders, and communicates via RS-232 with the PLC. The CAMAC interface also connects the MicroVAX to the pellet timing system of JET for actual triggering of pellet injection(the fire control sequencer). The transient data acquired is analyzed to determine pellet speeds from time-of-flight measurements and is archived with JET experimental data. Breech pressure measurements and chambering mechanism vibration signals are stored for each pellet. Trend data of the injector performance is also archived for later analysis. Included in the data set are cryostat temperatures, extrusion pressures and extruder piston positions. The design of the control system is described in detail by Baylor[6] and Burris[7].

4 Results

4.1 Velocity

With respect to velocity the performance of the injector is comparable to previous results achieved at ORNL with several pneumatic type injectors. With the propellant valves fully open, and at a working pressure of 100 bars, a maximum velocity of 1470 m/s was recorded for the 2.7 mm and 4 mm guns with deuterium pellets. The 6 mm gun achieved a maximum velocity of 1400 m/s at 70 bars. In the repeating mode with the propellant valves partly throttled to limit the gas loading on the vacuum system, the injector typically produces velocities in the range of 1150-1350 m/s.

4.2 Repetition Rate and Pulse Length

To date, the 2.7 mm gun has been operated at a maximum repetition rate of 5 Hz. This rate was maintained for a pulse duration of 13 seconds which was limited by the volume of material in the extruder and not by any discernable degradation in the quality of the extrusion or temperature instabilities in the cryostats. The extended pulse operation is a substantial improvement over the performance of the prototype device[1] and is likely due to changes made in the chambering mechanism, the extrusion nozzle design and the gun block cooling efficiency. The 4 mm and 6 mm guns have been operated at repetition rates of 2.5 Hz and 1 Hz respectively for pulse durations in the 11-12 second range. These results were also limited by the extruder volume, and longer pulses were achieved at lower repetition rates. The fueling rates and pulse lengths achieved exceed the fueling requirements of JET and no attempt has been made to extend the performance. Simultaneous operation of all three guns has been achieved and, taken together, the three guns should be capable of delivering a fuel charge of up to 2.5×10^{23} D^0 within a 15 second burst.

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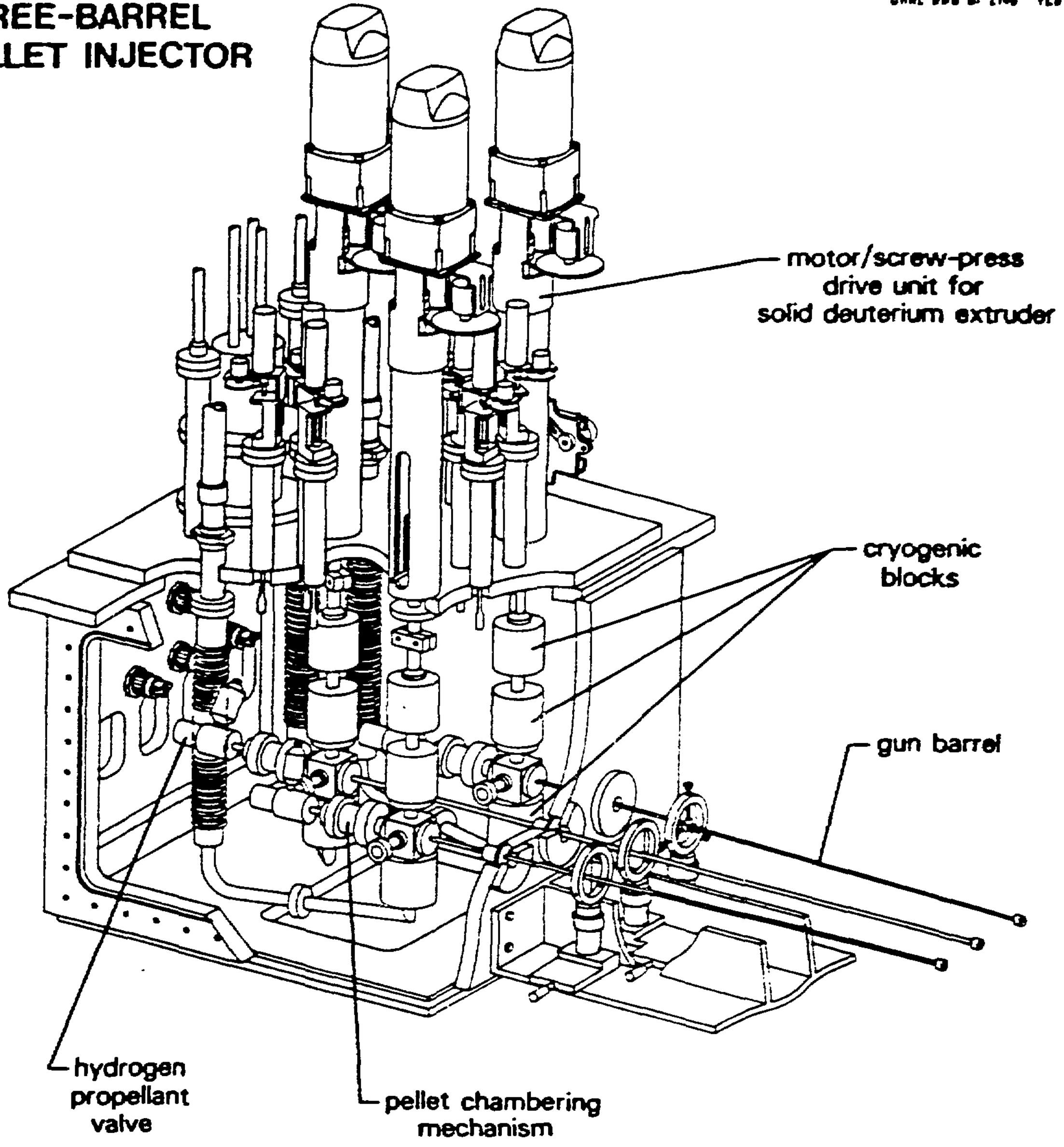
REPEATING THREE-BARREL PELLET INJECTOR



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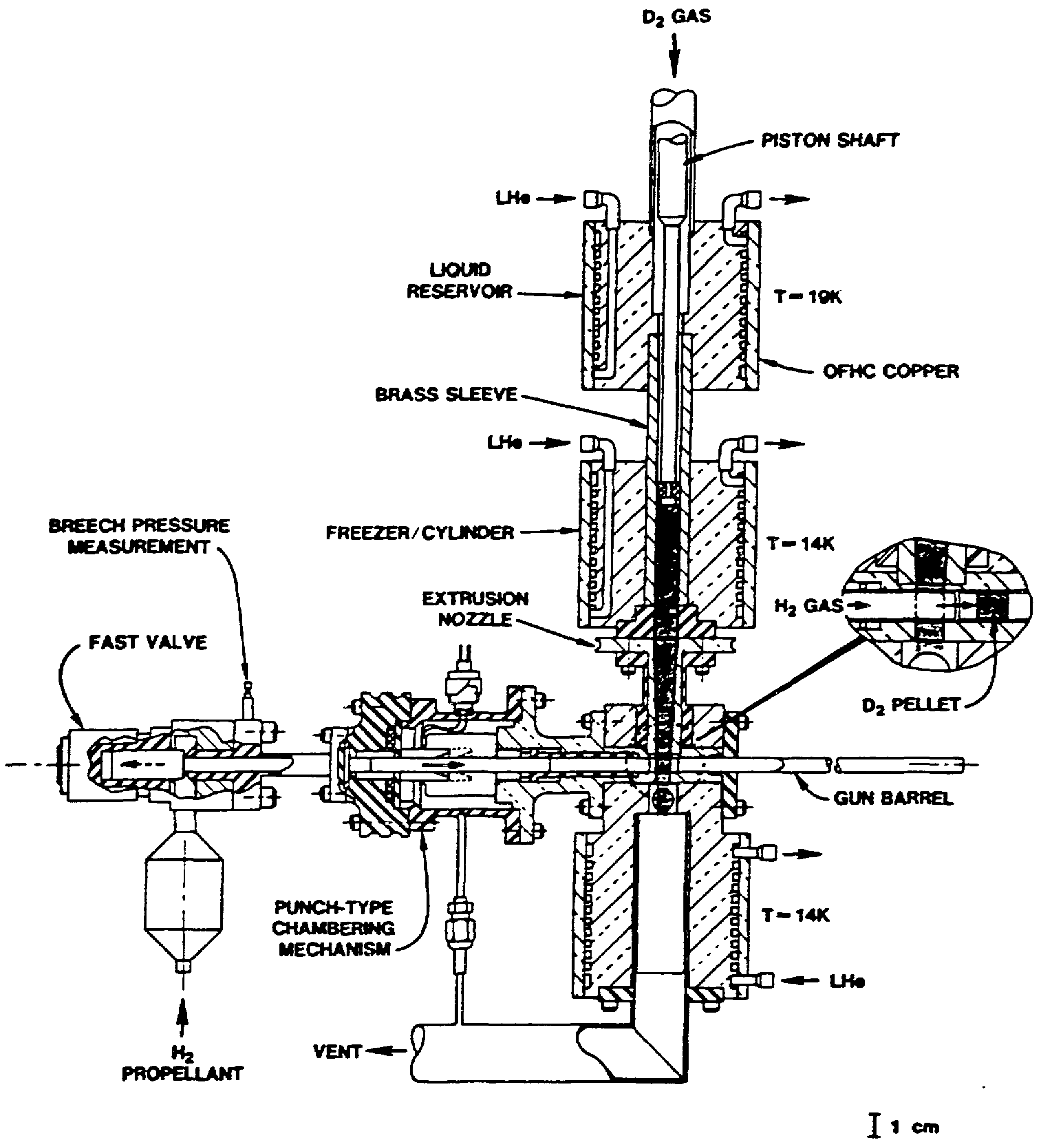

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