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DESIGN OF A TRITIUM PELLET INJECTOR FOR TFTR*

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ABSTRACT

The TFTR tritium pellet injector (TPI) is designed to provide a tritium pellet fueling capability with pellet speeds in the 1- to 3 km/s-range for the TFTR D-T phase. The existing TFTR deuterium pellet injector (DPI) is being modified at Oak Ridge National Laboratory (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. The pipe gun concept has been qualified for tritium operation by the tritium proof-of-principle (TPOP) injector experiments conducted on the Tritium Systems Test Assembly (TSTA) at Los Alamos National Laboratory. In these experiments, tritium and D-T pellets were accelerated to speeds near 1.5 km/s. The TPI is being designed for pellet sizes in the range from 3.43 to 4.0 mm in diameter in arbitrarily programmable firing sequences at speeds up to approximately 1.5 km/s for the three single-stage drivers and 2.5 to 3 km/s for the two-stage driver. Injector operation will be controlled by a programmable logic controller (PLC).

1. INTRODUCTION

The TPI is a cryogenic pellet injector to be used prior to and during the D-T phase of TFTR. The injector shown in perspective in Fig. 1 will replace the eight-shot DPI¹ at Bay T but will retain much of the injector facility currently in place. While the DPI formed pellets by an extrusion process, the TPI will form its four cylindrical pellets by the in situ condensation process. Two of these pellets will have diameters of 3.43 mm; the other two, diameters of 4.0 mm. The nominal aspect ratio is 1.25. One of the 4-mm guns will be equipped with a two-stage light gas gun driver, while the remaining three guns will operate with fast-acting electromagnetic propellant valves developed at ORNL.² In the configuration described here, the single-stage guns are capable of producing velocities of 1.8 km/s in deuterium and 1.5 km/s in tritium.³

Use of the TPI on TFTR will permit access to both a regime suitable for initial alpha particle physics studies and a regime suitable for studies of particle and energy confinement in high-density D-T plasmas ($n_e(0) = (1-5) \times 10^{20} \text{ m}^{-3}$). It will provide the capability for extending the supershot regime to density suitable for high- Q operation and provide access to both the peaked-density-profile, pellet-fueled PEP regime⁴ and a regime of sustained high-density operation using

multiple tritium pellets and ion cyclotron range of frequencies (ICRF) heating. The project is divided into two phases. Phase I activities allow the deuterium fueling capability to be used during 1992 operations, while the Phase II activities incorporate systems required for tritium operation and include an extended period of testing at the TFTR site, ending with the formation and acceleration of tritium pellets in 1993.

2. TPI SYSTEM DESIGN

The TPI consists of several subsystems, which are shown in Figs. 1 and 2 and described below.

2.1 Injector

The injector has a liquid-helium-cooled cryostat that provides cooling for pellet formation. The injector is located within the guard vacuum subsystem, and its design is based on the so-called "pipe-gun" concept, in which hydrogenic (H, D, T) pellets are formed by direct condensation in the gun barrel, a segment of which is held below the hydrogen triple-point temperature by contact with a liquid-helium-cooled block. Pellet length is controlled both by regulating the gas fill pressure and by establishing temperature gradients along the barrel tube with auxiliary heating collars.⁵ This design is ideal for tritium service because there are no moving parts inside the gun and because little additional tritium is required in the pellet production process. The injector uses four independent 1-m-long gun barrel assemblies mounted around the perimeter of a single cryostat. The cryostats shown in Fig. 2 are based on designs used for injectors built for the Advanced Toroidal Facility and the Princeton Beta Experiment.⁵

Three of the barrel assemblies are coupled to an ORNL-designed fast propellant valve (single-stage driver). This valve develops full pressure within 300 μs and will operate with a supply pressure of up to 138 bar. The remaining barrel assembly is connected to the two-stage driver.

Experiments at the TSTA using a prototype tritium pellet injector have shown that the presence of noncondensable helium-3 at levels above 0.005% prevents pellet formation by blocking the condensation of tritium in the pipe-gun freezing cell.³ Since helium-3 occurs as a by-product of tritium decay, specific removal of residual helium-3 from the tritium feed gas to this level of purity is required. This removal is accomplished using a cryogenic separator that is also located in the guard vacuum enclosure.

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Fig. 1. Perspective view of the TPI installation on TFTR.

The tritium is purified by circulating the fuel charge through the separator, which freezes only the hydrogenic isotopes and leaves the noncondensable helium-3 to be removed from the loop by a mechanical vacuum pump.

2.2 Two-Stage Driver

The two-stage driver subsystem provides the high-pressure, high-temperature drive gas required to accelerate pellets to near 3 km/s. In the two-stage driver, moderate-pressure helium propellant gas accelerates a piston to velocities in the range of 100–200 m/s in a thick-walled (1.25-cm) pump tube. The piston in turn compresses adiabatically low-pressure, room-temperature hydrogen propellant gas initially at about 1 bar. This hydrogen gas becomes the driving gas for the cryogenic pellet. At the high pressure reached following compression, the mechanical strength of the hydrogenic pellet becomes a design constraint and determines the maximum muzzle velocity, which is of order 2.5–3 km/s.

The TPI two-stage driver as shown in Fig. 2 consists of:

1. The 0.64-L first-stage reservoir, containing helium gas at a pressure up to 35 bar.

2. A 2.2-cm-diam orifice, pneumatically actuated valve to accelerate the piston by releasing gas from the first-stage reservoir.
3. A 25- to 50-g titanium piston.
4. A cylindrical, 0.9-m-long, 2.54-cm-ID pump tube (the second stage), filled initially with hydrogen propellant gas at a pressure of 0.5–1 bar.
5. A high-pressure section that provides additional strength at the end of the pump tube.
6. A bellows that isolates the two-stage driver and the guard vacuum chamber.

2.3 Pellet Injection Line and Vacuum Systems

The barrel isolation valve subsystem links the injector with the primary vacuum subsystem. It consists of four vacuum valves and four double-wall bellows units, one assembly per barrel. The valves, when closed, isolate the injector from the primary vacuum subsystem.

The primary vacuum subsystem links the injector with the high-vacuum subsystem. It consists of a stainless steel injection line containing an array of four 8.0-mm-ID, 1.1-m-

long pellet guide tubes, four fast-acting (25-ms cycle time) conductance-limiting valves, a pellet diagnostic station, an isolation valve at the connection to the high-vacuum subsystem, and a 0.71-m³ stainless steel chamber. When pellets are fired, the primary vacuum subsystem absorbs most of the propellant gas used to accelerate the pellet.

The high-vacuum subsystem links the primary vacuum subsystem to the TFTR vacuum vessel through a region of high vacuum. The high-vacuum subsystem consists of a stainless steel injection line containing four 14.8-mm-ID, 1.0-m-long pellet guide tubes, a pellet diagnostic station for photography and pellet mass measurements, a system isolation valve and bellows, and a ceramic break.

This portion of the subsystem ends with a connection to the pellet injector torus interface valve (TIV). The subsystem also contains a 0.265-m³ stainless steel chamber that absorbs most of the residual propellant gas used to accelerate the pellet which is not absorbed by the primary vacuum system.

The TPI pumping subsystem links the various TPI vacuum subsystems to the TFTR vacuum exhaust system, and, for Phase II tritium operations, to the gas holding tanks. The guard vacuum, primary vacuum, and high-vacuum subsystems are pumped by separate vacuum pumping systems, which sustain base pressures and provide pumping speeds appropriate to the different systems. Pumping for the guard vacuum subsystem is provided by a small turbopump backed by a rotary pump. Pumping for the primary vacuum subsystem is provided by a Roots blower backed by a rotary pump maintaining a base pressure of approximately 10⁻³ torr. Pumping for the high-vacuum subsystem is provided by a turbopump backed by a rotary pump maintaining a base pressure of approximately 10⁻⁷ torr. Exhaust from the two rotary pumps connected to the primary and high-vacuum subsystems is routed to a single vacuum line linked directly to the TFTR gas holding tanks (Phase II). Exhaust from the guard vacuum is routed to the diagnostic vacuum exhaust and through this system to the gas holding tanks (Phase II).

Fig. 2. The TPI injector and two-stage light gas gun assembly

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Fig. 3. Firing sequence for the two-stage light gas gun prototype and typical pressure response at several locations in the gun.

The performance of the two-stage driver has been modeled using the QUICKGUN code.⁷ The results are shown in Fig. 4 for a case in which a 20-mg tritium pellet is accelerated to a velocity of 2.7 km/s in a path length of 1 m for an initial reservoir pressure of 16.6 bar. The relevant system parameters are plotted for times after release of the pellet, which is assumed to occur when the breech pressure reaches 48 bar (as determined from tests of the TPOP device). This case exhibits relatively low piston velocities and moderate conditions at the breech. Moreover, the acceleration is gradual, as indicated by the moderate and relatively constant pressure predicted at the pellet base.

DISCLAIMER

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Fig. 4. Predicted performance of the two-stage light gas gun for 20-mg tritium pellet. 1 ksi = 68.95 bar.

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