OPERATION AND RELIABILITY OF A PNEUMATIC HYDROGEN PELLET INJECTION SYSTEM ON THE JOINT EUROPEAN TORUS

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ABSTRACT

A pneumatic-based, hydrogen isotope pellet injector that was developed at the Oak Ridge National Laboratory for the plasma fueling application on the Joint European Torus (JET) was described at the last Symposium on Fusion Engineering (1987). The injector was installed on JET during 1987 and has since been used in plasma fueling experiments. The injector consists of three independent machine-gun-like mechanisms (nominal pellet sizes of 2.7, 4.0, and 6.0 mm in diameter), and it features repetitive operation (1–5 Hz) for quasi-steady-state conditions (>10 s). An extensive set of injector diagnostics permits evaluation of parameters for each pellet shot, including speed, mass, and integrity. Pellet speeds can be varied but typically range from 1.0 to 1.5 km/s. Over 5000 pellets have been fired with the equipment at JET, including about 2000 pellets shot for plasma fueling experiments. In recent experiments, the system performance has been outstanding, including excellent reproducibility in pellet speed and mass and a reliability of $>98\%$ in delivery of pellets to the plasma.

Fig. 1. Three-barrel repeating pneumatic injector.

INTRODUCTION

High-speed injection of frozen pellets (millimeter size) composed of the isotopes of hydrogen is the leading technology for fueling magnetically confined plasmas for controlled thermonuclear fusion research.¹ A pellet injector design that is likely to prove useful for future fusion research experiments is the repeating pneumatic gun. The prototype repeating pneumatic injector was first described² in 1985. This single-barrel machine-gun-type injector was used in the first pellet fueling experiments on the Tokamak Fusion Test Reactor (TFTR).³ More recently, a three-barrel version of the device^{4,5} was developed and installed on JET in 1987. The versatile device (Fig. 1) consists of three independent machine-gun-like mechanisms that operate at cryogenic temperatures (14–20 K). Individual high-speed extruders (Fig. 2) provide a continuous supply of solid deuterium to each

gun assembly, where a reciprocating cutting mechanism forms and chambers cylindrical pellets from the extrusion. The deuterium pellets are then accelerated in the gun barrels with controlled amounts of compressed hydrogen gas (pressures up to 100 bar) to velocities of <1.5 km/s. The injector features three nominal pellet sizes (2.7, 4.0, and 6.0 mm in diameter) and has been tested at repetition rates of 5 Hz for the 2.7-mm gun, 2.5 Hz for the 4.0-mm gun, and 1 Hz for the 6.0-mm gun. The three pellet sizes correspond to nominal deuterium masses of 3 mg (9×10^{20} D⁰/pellet), 10 mg (3×10^{21} D⁰/pellet), and 34 mg (1×10^{22} D⁰/pellet). Each gun can operate (individually or simultaneously) at the design repetition rate for 15-s pulses (limited only by the capacity of the extruder supply system).

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Fig. 2. Schematic of a cryogenic deuterium extruder/gun assembly.

This paper concentrates on the performance of the injector at JET during testing (injection into an intermediate vacuum chamber) and plasma fueling experiments. Examples of JET plasmas fueled by pellet injection are shown in Fig. 3, where the line-averaged electron density ($\bar{n}_e$) is plotted as a function of time for two discharges with 3-MA plasma current. For the JET shot in Fig. 3(a), six 4-mm pellets were injected at a rate of 1 Hz. For the shot in Fig. 3(b), a 4-mm pellet was injected at time $t = 3$ s, followed by an 8-s pulse of 2.7-mm pellets fired at a rate of 4 Hz. Most of the data discussed here were taken during repetitive operation of the injector. Key parameters in evaluating injector performance include reproducibility of pellet speed and mass (or size) and reliability in delivering pellets to the plasma. The first pellets produced with the three-barrel plasma gun at JET were fired in August 1987; from that time through August 1989 (two years), more than 5000 pellets were fired, including over 2000 pellets shot during plasma operation.

Fig. 3. Density evolutions for two 3-MA JET plasma discharges with pellet fueling. (ICRF = ion cyclotron range of frequencies.)

From this large database, selected data representing the injector capabilities are presented. Only results for the 2.7- and 4.0-mm guns are presented, however, since these two guns have been used extensively in plasma fueling experiments. At this time, only a few 6-mm pellets have been injected into plasmas.

SYSTEM DESCRIPTION

Before discussing the test results, we briefly describe the installation at JET and the diagnostics available for evaluating the injector performance. Figure 4 is a schematic of the injector installation on JET. A large (50-m^3) vacuum chamber equipped with a high-throughput ($8 \times 10^6 \text{ L/s}$) cryocondensation pump serves as the interface between the injector and the torus vacuum and provides efficient differential pumping of propellant gas and unused deuterium fuel. This chamber is also an integral part of the support structure and provides a platform for the pellet injector. The injector (identified as "pellet launcher" in Fig. 4) is equipped with pellet diagnostics along each pellet trajectory, which allow for accurate velocity measurements, relative mass determinations, and in-flight photographs of all pellets at the gun muzzles. First, a fiber-optic pellet detection system is used at the muzzle of each barrel to provide a timing pulse for velocity measurements and photographs; a photographic station provides a picture

of each pellet, which can be stored on an optical disk. Next, the pellets pass through the JET microwave interferometer, which consists of two cavities located in each gun line at two intermediate locations (0.6 and 1.0 m from the muzzle). In addition to providing timing information for velocity measurements, the microwave output signals are a function of the pellet mass. Signals obtained at the first stations are used to estimate the relative mass of the pellets. The ratio of the signal outputs from the first and second microwave stations is useful in evaluating the aim of the gun; lower ratios indicate that the pellet is near the center of the second cavity and that the flight of the pellet is near the ideal trajectory. All of this information is available for each pellet. Also, an instrumented target developed by JET can be used for active gun alignment and aiming. With this destructive diagnostic, the target is moved into the pellet's flight path to intercept it ($\approx 3 \text{ m}$ from the muzzle) immediately downstream of the 1-m-long gas flow restrainer tubes (Fig. 4). The target is equipped with pressure sensors to yield an accurate two-dimensional position of the pellet impact on the target plate. Thus, the effect of corrective steering (slight changes in the gun barrel alignment) is monitored, allowing active aiming to provide the optimum pellet trajectory. The total distance that the pellets travel from the gun muzzle to the plasma is approximately 7.4 m. If the gun is ideally aimed, the pellet dispersion at the gun muzzle must be within $\pm 0.4^\circ$

Fig. 4. Schematic of injector installation on JET (top plan view).

to keep the pellets away from obstacles and ensure their entry into the plasma vacuum chamber. Complete descriptions of the installation and pellet diagnostics have been published elsewhere.^{6,7}

PERFORMANCE DATA

Selected performance data are summarized in the histograms in Fig. 5, which show measured velocity and relative mass for pellets from the 2.7- and 4.0-mm guns. The number of pellets is plotted versus the percent deviation from the average in 5% data bins. In Figs. 5(a) and 5(b), the sample sizes for the velocity data are large (922 and 736 pellets, respectively) and include all data taken from March through September 1988. This time frame was chosen because at this point the operating staff had been trained and the operating conditions standardized for optimum performance. All of the velocity data are for an operating pressure (hydrogen supply) of about 70 bar (1000 psi) at the propellant valves; however, the pressure was not controlled precisely and was allowed to drop slightly during repetitive sequences. As shown in the figure, the average velocities (1225 and 1230 m/s) are essentially the same for both guns; the standard deviation is slightly higher for the 4-mm gun (62 m/s versus 40 m/s for the 2.7-mm gun). The velocities are quite consistent; for the 2.7-mm pellets, over 90% have a velocity within $\pm 5\%$ of the average, and 99.2% have a velocity within $\pm 10\%$ of the average. The 4-mm data show a little more scatter, but more than 95% of the pellets still have velocities within $\pm 10\%$ of the average.

The information summarizing the relative mass measurements in Figs. 5(c) and 5(d) is for smaller samples (79 and 156 pellets, respectively) and includes data taken over a shorter testing period (1–3 days). Since the mass measurement is relative (a voltage output based on the pellet perturbation to a tuned microwave cavity),⁷ it tends to be affected by systematic changes (e.g., temperature), thus, measurements over a short time period are more representative of the gun capability. Theory and calibration tests indicate that, for the 4-mm pellet size, the voltage output varies as the mass raised to the 1.4 power (or $m \propto V^{0.71}$) and, for the 2.7-mm pellet size, the signal varies as the mass raised to the 2.2 power (or $m \propto V^{0.45}$). Thus, the voltage signal raised to the appropriate power was used as the relative mass measurement in Figs. 5(c) and 5(d). Since the measurements are relative for each data set, a comparison of the magnitude between data sets is not meaningful. As shown in the mass plots, the average relative mass is 1.71 for the 2.7-mm pellets and 2.89 for the 4-mm pellets, with standard deviations of 0.06 and 0.13, respectively. For the data presented in Figs. 5(c) and 5(d), over 80% of the pellets have a relative mass within $\pm 5\%$ of the average, and over 95% of the pellets have a relative mass within

$\pm 10\%$. Physical pellet size was also determined from video recorder images taken at the gun muzzle location with a 10-ns flash illumination system. Within the accuracy of the measurements, the diameters and lengths of pellets from each gun were consistent and agreed with the expected values (i.e., the diameters closely matched the gun barrel inner diameter, and the lengths checked approximately with the width of the deuterium extrusion). Thus, in general, the physical observations verified the reproducibility in pellet size.

The most important performance parameter of a pellet injection system is its reliability in delivering pellets to the plasma. In some early fueling experiments on JET, it was observed that a significant fraction of the pellets did not reach the plasma. Later, during a shutdown period in May 1988, we discovered that an obstruction had been inadvertently intercepting some of the missing pellets downstream of the flow restrainer tubes (Fig. 4). During the three-month period after this problem was corrected (July–September 1988), the 2.7-mm gun successfully delivered to the plasma 237 pellets out of 238 that were fired; the 4-mm gun delivered 115 pellets out of 119 that were fired. This corresponds to $>98\%$ reliability in delivery of pellets (352 out of 357) and is representative of the capability of this type of injector design. Recently (May–June 1989), the system was used to inject 555 pellets into plasmas; the delivery of pellets to the plasma was essentially 100%. It should also be pointed out that this installation did not make extensive use of guide tubes to direct the pellets along the correct path, as in most previous pellet fueling applications, but relied on accurate gun alignment and low dispersion. This is a more stringent requirement; thus, the reliability of the injector in delivering pellets is noteworthy. The single-barrel prototype device used in fueling experiments on TFTR also performed at a high level of reliability during a test period lasting about one year (1985–1986).³

The overall system reliability, including mechanical failures of the equipment, cannot be assessed on the basis of the present data. After the commissioning period, no mechanical failures that prevented routine operation were experienced. More operating time is required before a thorough reliability analysis can be performed. However, given recent performance and past experience, the repeating pneumatic injector design provides pellets of consistent mass and speed and offers a high reliability in delivering pellets to the plasma.

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Fig. 5. Histograms of velocity and relative mass measurements for 2.7- and 4.0-mm pellets. (a) Data from JET shots 14937-18774 (773 pellets) and injector tests 2768-3094 (149 pellets), between 1 March 1988 and 30 September 1988. (b) Data from JET shots 14937-18774 (220 pellets) and injector tests 2768-3094 (516 pellets), between 1 March 1988 and 30 September 1988. (c) Data from JET shots 17662-17750 (75 pellets) and injector test 3078 (4 pellets), between 17 August 1988 and 19 August 1988. (d) Data from injector tests 3021-3040 (156 pellets), 23 June 1988.

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