HIGH-FIELD-SIDE PELLET INJECTION TECHNOLOGY

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ABSTRACT

High-speed injection of pellets, composed of frozen hydrogen isotopes and multimillimeter in size, is commonly used for core fueling of magnetically confined plasmas for controlled thermonuclear fusion research. Straight guide tubes have typically been used to transport/deliver pellets from the acceleration device to the outside, or magnetic low-field side, of the torus/plasma (distance of ~5 to 10 m for most installations). Recently, alternative pellet injection schemes have been used in plasma fueling experiments, including inside launch from the magnetic high-field side on ASDEX-U and top launch (vertically downward) on Tore Supra and DIII-D. These schemes require the use of curved guide tubes in which the pellets are subjected to stresses from centrifugal and impact forces. Thus, with curved guide tubes the speed at which intact pellets can be delivered reliably to the plasma is limited. In impact experiments on flat plates, it was found that deuterium (D_2) pellets can survive single collisions at normal velocities in the range 20 to 35 m/s. Several series of tests with various curved guide tube configurations have been carried out, showing that intact pellets can be reliably delivered at speeds of several hundreds of meters per second. The experimental data are summarized and discussed. Also, a model is under development at Tore Supra for predicting these phenomena, and preliminary comparisons with the data are discussed.

I. INTRODUCTION

The process and benefits of plasma fueling by pellet injection have been thoroughly documented in the literature.[1,2] In the recent high-field-side (HFS) pellet injection experiments on ASDEX-U,[3] improvements in pellet penetration (factor of 2) and fueling efficiency (factor of 4) were attained. Other pellet research groups have conducted experiments with top or vertical launch (DIII-D[4] and Tore Supra[5]); DIII-D is also planning for HFS launch experiments in the near future. The International Thermonuclear Experimental Reactor (ITER) has adopted the HFS approach for the baseline pellet injection design. Thus, research and development is in progress at the Oak Ridge National Laboratory (ORNL) to develop pellet launch and transport systems that can deliver intact pellets to the low-field-side (LFS) or HFS of the plasma via assemblies of curved guide tubes. For LFS injection with straight guide tubes, pellet speeds of about 1 to 2 km/s are routinely achieved, with intact pellets almost always delivered to the plasma; very high speeds (up to 5 km/s) are feasible with LFS injection and straight guide tubes. However, with HFS injection using curved guide tubes, the speed at which intact pellets can be delivered reliably to the plasma is limited. Centrifugal and impact forces can result in pellet fractures, depending on the experimental parameters of the pellet and guide tube geometry. For the pellet, the key parameters include size, speed, and strength; the strength varies inversely with temperature and may depend somewhat on the formation technique. The geometry of the guide tube installation can be quite complex for HFS or other alternative injection schemes, requiring multiple bends and long runs. The key parameters for each bend are the radius of curvature and inside tube diameter; tube material and surface roughness are also variables, though probably less significant. To provide some baseline data for this phenomenon, laboratory experiments have been carried out, and the test results provide the operating regimes for some specific pellet parameters and guide tube geometries. The initial results from this experimental study were previously reported.[6] In this paper, some new results from pellet impact tests are presented, as well as additional results from curved guide tube experiments. Key objectives of this study are to gather enough experimental data to permit the development/validation of a model for predicting pellet survival for any guide tube configuration and then explore techniques to optimize performance. A model under development at Tore Supra[7] could be a key step in achieving this objective.

II. EXPERIMENTAL EQUIPMENT AND OPERATIONS

Two pneumatic pellet injector facilities were used for this study: (1) a repeating pneumatic injector (RPI)[8,9] and (2) a pipe-gun injector.[10,11] With the RPI, D_2 ice is provided to the acceleration section by a cryogenic extruder,

and pellets are punched and accelerated in the gun assembly. For this study, the injector was equipped with a punch/barrel combination with a 2.7-mm bore. This pellet size is relevant for most present large tokamak experiments such as DIII-D, which is equipped with a multibarrel RPI of that size. A new pipe gun injector was fabricated specifically for this study. The pipe gun is a technique in which a single D_2 pellet is frozen in situ in the gun barrel. The cryostat can accommodate any practical barrel size, and barrels with bores of 2.7 and 10 mm have been tested. The 10-mm size is more applicable for fueling ITER-size plasmas.[12] Different pellet speeds were obtained in the experiments by adjusting the gas supply pressure and the total gas flow through the ORNL propellant valve.[13] Helium and hydrogen gases at supply pressures of ~5 to 70 bar were used for propellants. It proved surprisingly difficult to reliably attain moderate speeds (100 to 500 m/s) with both injector types. This was particularly the case for pipe guns because of the inherent high breakaway pressures (=20 bar vs ~5 bar for RPI) associated with pipe gun pellets. In some experiments, the pipe gun cryostat was warmed before introducing the gas, which lowered the breakaway pressure and allowed slower pellet speeds. This technique was employed for all of the impact data, and pellet speeds <100 m/s could be reliably attained. For even better control, a mechanical punch was added to the breech-side of the pipe-gun injector, which effectively broke the pellet loose from its initial freezing position (eliminating the need to warm the cryostat); small bursts of gas could then be applied to aid acceleration. With the punch and no propellant gas, the pellets exited the gun barrel at ~100 m/s.

The basic experimental configurations are shown in Fig. 1. For the impact tests, a stainless steel plate was used for the target; it could be rotated from 0 to 90° relative to the pellet flight path. For the curved guide tube tests, the standard tube included a single curved

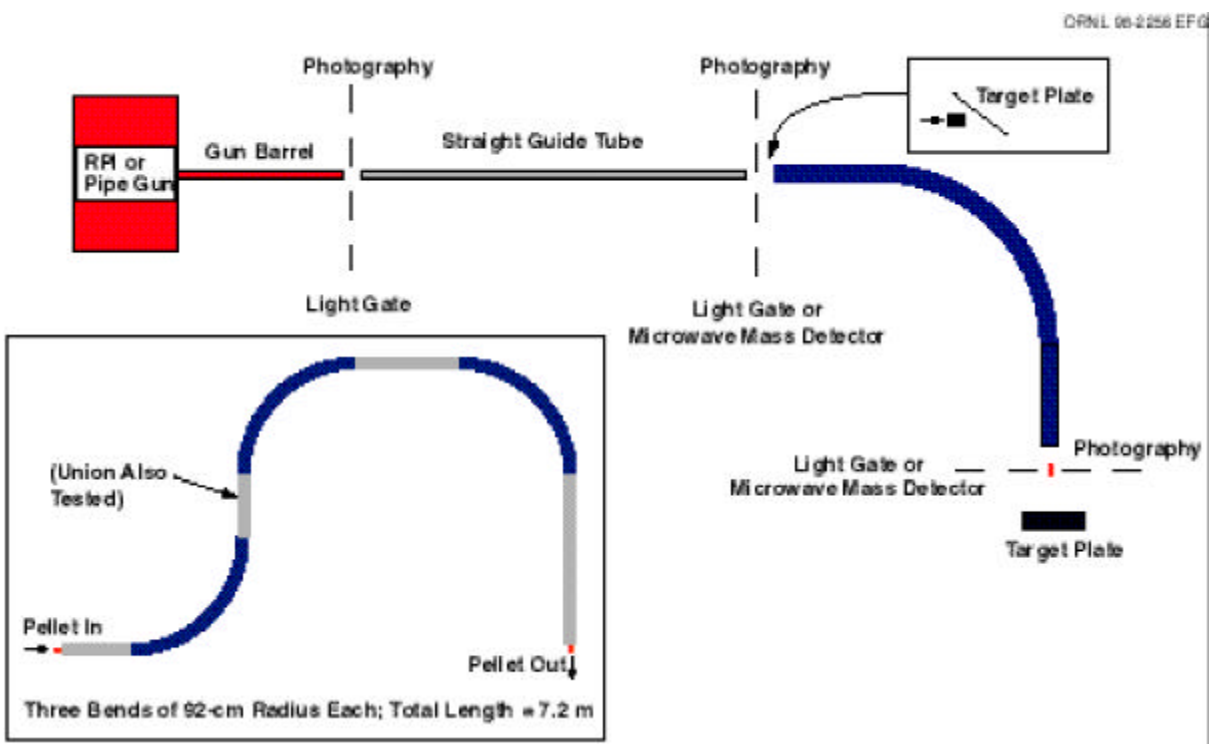

Figure 1. Test configurations for experiments with RPI and pipe gun; insets show special setups for multiple bends and impact tests (pipe gun only).

section of 90°. The materials used for the guide tubes were standard commercial tubes, and no special surface finish was specified. Tests with multiple curved sections (three sections of 90° each) were also carried out and are described in the next section. The pellet speeds were obtained by measuring the time of flight between light barriers, and it is estimated that the accuracy is typically within a few percent. In some tests, a third light barrier and/or target plate provided checks on the speed measurement (always in agreement within a few percent). Using strobe lamps, photographs were recorded at the gun barrel exit and downstream at the guide tube exit (or on the target plate for impact tests). This verified that observed pellet damage was attributed to the curved guide tube (or collision on target for impact tests).

III. TEST RESULTS

A. Impact Tests

The data for the impact tests on a flat stainless steel plate are shown in Fig. 2 (*a*) and (*b*) for nominal 2.7-mm and 10-mm pellets, respectively. The abscissa is the velocity component normal to the plate; the ordinate value is the pellet condition (0 or 1), with 0 signifying broken pellets and 1 intact pellets. The impact angles in the experiments ranged from 15° to 90°. For both sets of data, the velocity transition range in which intact and broken pellets were observed is ~20 to 35 m/s. Below 20 m/s, all pellets were intact; and above 35 m/s, all pellets were broken. Some typical photographs of the 10-mm pellet impacts are shown in Fig. 3; the pellet speed, normal velocity, and impact angle are also listed. The strobe flash was triggered by the shock on the target plate, and it was necessary to delay the flash an appropriate amount of time to verify the pellet condition after impact. For the 10-mm pellets in Fig. 3, the optimum delay was 80 µs. With shorter delay times, cracks in the pellet interior were sometimes observed; however, the final pellet condition could not always be verified. In recent centrifuge experiments at ORNL,[14] the normal velocity limit for impacts on a flat guide tube surface was estimated to be ~20 m/s (for 2.3-mm pellets), which corresponds to the lower limit in Fig. 2. Fundamental information such as this should prove useful in design and modeling efforts.

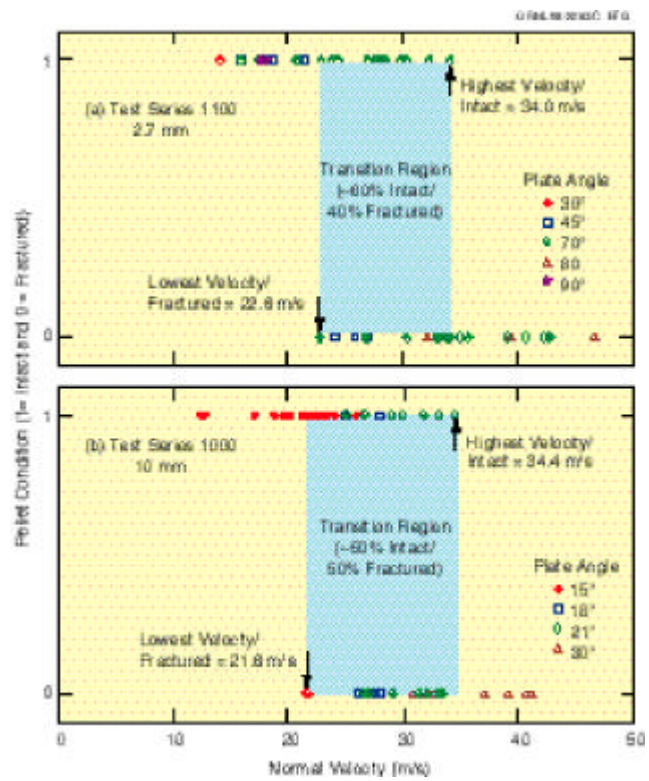

Figure 2. Impact test results for D_2 pellets on inclined flat plate; normal velocity transition region is identified for each data set: (*a*) 2.7 mm and (*b*) 10 mm.

B. Curved Guide Tube Tests

The data for all test series with curved guide tubes (90° sections) are summarized in Table 1 and Fig. 4. The data for test series A, B, C, D, E, and F were presented in Ref. 6 and are included for completeness and comparison. In Fig. 4, the radius of curvature is plotted as a function of pellet speed, and a transition region is shown for each test series. At pellet speeds below the transition region, pellets were always found to be intact; at speeds above the region,

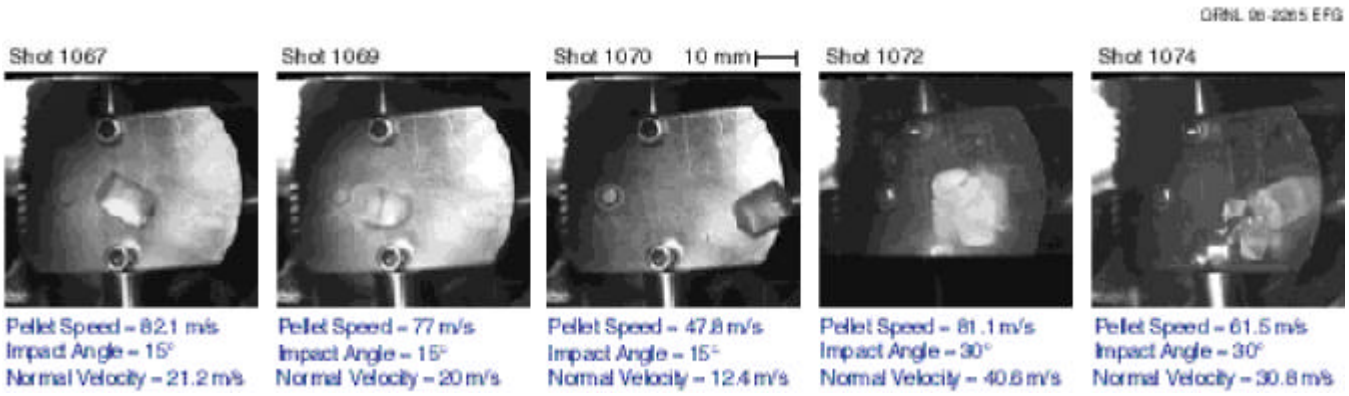

Figure 3. Photographs of 10-mm D_2 pellets after impact on inclined flat plate.

Table 1. Summary of parameters for curved guide tube tests (D_2 pellets shot through 90° sections)

Test series	Guide tube parameters: Curve radius (cm)	ID (mm)	Material	Pellet parameters: Diameter[a] (mm)	Length/ diameter	Temperature (K)	Speed: Transition range[b] (m/s)
			RPI				
A	5	7.9	Stainless steel	2.7	1 to 2	12	200 to 250
B	20	7.9	Stainless steel	2.7	1 to 2	12	380 to 480
C	40	7.9 and 8.5	Stainless steel	2.7	1 to 2	12	300 to 440
D	92	8.5	Stainless steel	2.7	1 to 2	12	400 to 500
E	92 (×3)	8.5	Stainless steel	2.7	1 to 2	12	400 to 450
			Pipe gun				
F	80	22.0	Stainless steel	9.7	1	8[c]	280 to 300
1200	40	9.1	Teflon	2.7	1	9[d]	330 to 370
1300	92 (×3)	8.5	Stainless steel	2.7	1	9[d]	350 to 410
1400	40	4.0	Carbon steel	2.7	1	9[d]	480 to 530
1500	40	8.5	Stainless steel	2.7	1	9[d]	380 to 480
1600	80	10.9	Stainless steel	9.7	1	8[d]	330 to 410
1700	80	9.7	Stainless steel	9.7	1	8[d]	370 to 430

[a]Nominal pellet diameter is taken as the gun barrel ID.
[b]In the transition range, intact and fractured pellets were observed; below the minimum velocity, pellets were always intact; and above the maximum velocity, pellets were always fractured or severely eroded.
[c]Pellet was frozen at 8 K; however, cryostat was warmed up to ~15 K to attain slower speeds.
[d]Punch was used to initiate pellet motion.

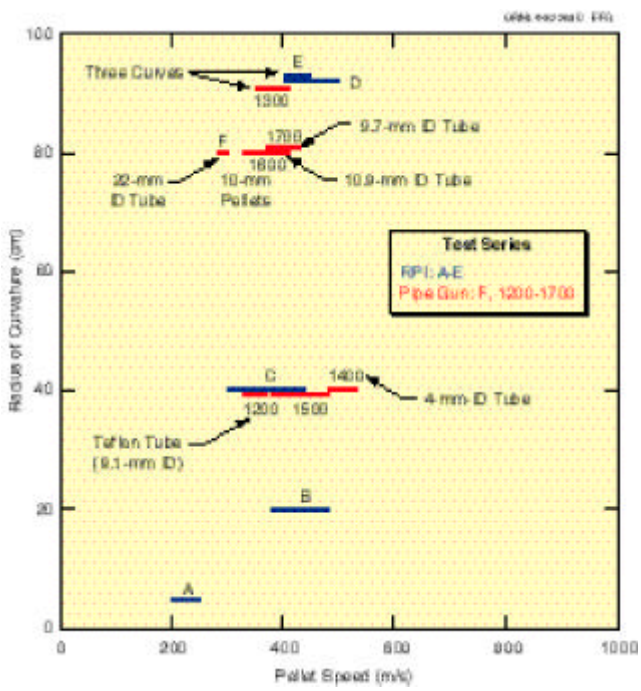

Figure 4. Test results for D_2 pellets shot through curved guide tubes (90° sections); speed transition region is identified for each test series (unless marked, pellet size is 2.7 mm, and tube ID is ~8mm).

pellets were always found to be fractured. In the transition region, both intact and fractured pellets were observed. Hundreds of pellets were fired in the experiments, and most experiments were carried out in or near the transition regions. At speeds below 200 m/s, intact pellets were always observed at the downstream end of the guide tube; and no intact pellets were observed at speeds above 530 m/s. The transition range varies somewhat for each test series. The majority of the experiments was with 2.7-mm pellets and stainless steel guide tubes of ~8-mm inside diameter (ID). If different from that, key parameters for that test series are identified in Fig. 4.

Four test series were carried out with guide tubes of 40-cm curve radius, with the data sets overlapping in general. A test series with a teflon tube was conducted, and no advantage was identified. A distinct improvement was observed with a 4-mm-ID tube (series 1400). Comparing test series 1500 and 1400 (both pipe gun pellets at same conditions except different tube IDs), the lower speed limit increased by ~25% (380 to 480 m/s); and the upper speed limit increased by ~10% (480 to 530 m/s). The improvement is attributed to the smaller ID tube (4 vs 8 mm). The model discussed in the next section suggested that smaller tubes would improve guide tube performance and provided motivation for test series 1400.

Three test series (D, E, and 1300) were carried out with guide tubes of 92-cm curve radius, including two tests (E and 1300) with three curved sections as shown in Fig. 1. In general, the data sets overlap, with intact pellets at speeds of up to 500 m/s with a single bend and 450 m/s with three bends. For test series 1300, a data set was collected with a single continuous tube; the tube was cut and a union added as shown in Fig. 1; and then a second data set was collected. The addition of the union had no discernible effect on the tube performance. This demonstrates that long runs with multiple tubes are practical.

Three test series (F, 1600, and 1700) were done with the 10-mm pellet and guide tubes with an 80-cm radius of curvature. This curvature was chosen because it is the tightest radius of curvature planned for the pellet line installation for HFS injection on ITER. The initial test series (F) was done with a relatively large 22-mm-ID tube, and the speed limit was ~300 m/s. Test series 1600 was done with a 10.9-mm-ID tube. As for the 2.7-mm pellet case, improvement was observed with the upper speed limit increased by almost 40% (300 to 410 m/s) and the lower speed limit increased by ~20% (280 to 330 m/s). In test series 1700, the guide tube ID was the same as the gun barrel bore (9.7 mm). A special union was fabricated and used to connect/align the gun barrel and guide tube; it was equipped with slots to vent the propellant gas. The speed transition range was 370 to 430 m/s, which is only a slight improvement over the 10.9-mm case. This may correspond to the centrifugal force limit, since effects of pellet impacts should be minimal for this case.

Note that some minor variation observed in the data may be attributed to systematic differences in the operating parameters/procedures and measurement techniques.

IV. MODELS

In the previous paper on this experimental study,[6] the RPI data series was compared to a simple model proposed by Büchl and Sandmann;[15] the model only considered centrifugal forces and was not adequate to predict guide tube performance for the parameter range. It was apparent that a practical model needed to account for the pellet/tube surface collisions. Such a model is under development by Artaud and Géraud[7] at Tore Supra and is based on the deformation strength of the D_2 ice, assuming that pellets have a ballistic propagation in a guide tube or funnel. A funnel is often used to collect pellets. In the model, equations are derived for treating elastic and plastic collisions and used to estimate the pellet propagation within the guide tube (or funnel). From impact to impact, the pellet accumulates strain when the stress is above the elastic limit. When the strain limit for the D_2 ice pellet is reached, breakage should occur. A paper describing the model is in preparation,[7] and it will compare some of the data sets reported here. In a preliminary comparison, the model appeared to predict the RPI data trends shown in Fig. 4 quite well, indicating about ten collisions or bounces for the largest radius of curvature (test series D) and only 2 bounces for the smallest radius of curvature (test series A). The model was also consistent with the impact data presented in Fig. 2. In addition, the model predicts a higher pellet speed limit for curved guide tubes with smaller IDs. As pointed out earlier, this was a motivation for test series 1400, 1600, and 1700, and improved performance was observed with the smaller tube IDs.

V. APPLICATIONS

This experimental study was in support of the pellet fueling application on DIII-D and the proposed application on ITER. In Fig. 5, the installation of the ORNL pellet injector on DIII-D is depicted, and three injection schemes are shown. The outside launch has been used reliably to inject pellets (1.8, 2.7, and 4.0 mm) for many experiments during the last few years; the top launch[4] was recently implemented and is now operating reliably with 2.7-mm pellets; and the inside launch is planned for the near future. The proposed pellet injection system for ITER includes an inside launch scheme. Based on the results of this study, pellets can be delivered reliably to the plasma for any curved guide tube installation as long as the pellet speed is maintained below a threshold limit. This limit will probably be in the range of ~200 to 500 m/s, depending on the

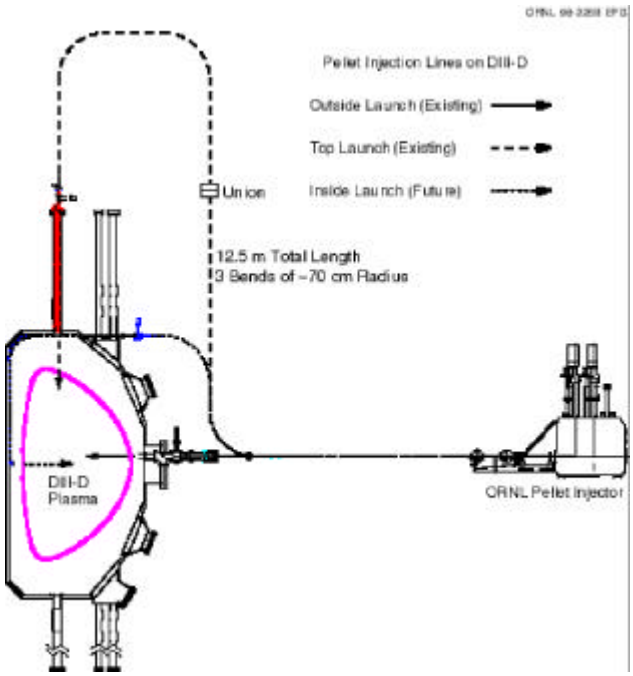

Figure 5. Pellet injection schemes on DIII-D.

specific pellet and guide tube parameters. The use of curved guide tubes with smaller ID promises performance improvement. However, more experimental data are needed to confirm and quantify the effect for different pellet parameters and guide tube configurations.

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