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PELLET DELIVERY AND SURVIVABILITY THROUGH CURVED GUIDE TUBES FOR FUSION FUELING AND ITS IMPLICATIONS FOR ITER*,†

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Pellet delivery and survivability through curved guide tubes for fusion fueling and its implications for ITER

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Abstract

Injection of solid hydrogen pellets from the magnetic high-field side will be the primary technique for depositing fuel particles into the core of International Thermonuclear Experimental Reactor (ITER) burning plasmas. This injection scheme will require the use of curved guide tubes to route the pellets from the acceleration devices to the inside launch locations. Experimental pellet studies with curved guide tubes have been carried out for several years at the Oak Ridge National Laboratory (ORNL), including mock-up tests of guide tube installations for several fusion experiments. In general, the tightest bend radius of the guide tube is the key parameter in limiting pellet speed, and for inside launch the pellet speed is typically limited to a few hundreds of meters per second for reliable delivery of intact pellets. Recently, an experimental mock-up of the proposed ITER curved guide tube for inside pellet launch was set up in the lab and tested with nominal 5.3-mm D_2 pellets. For this mock-up, the pellet speed had to be limited to ≈300 m/s for reliable delivery of intact pellets. Also, microwave cavity mass detectors located upstream and downstream of the test tube indicated that ≈10% of the pellet mass was lost in the guide tube at 300 m/s. The test results from the previous mock-ups will be summarized in the paper, and the new data from the ITER mock-up will be presented and discussed.

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1. Introduction

High-speed injection of pellets, composed of frozen hydrogen isotopes and multimillimeter in size, has commonly been used for core fueling of magnetically confined plasmas for controlled thermonuclear fusion research [1,2]. For the proposed ITER experiment, the traditional gas fueling technique is calculated to have much lower fueling efficiency than for present day experiments; thus, pellet fueling will be particularly important. For many years, pellets have commonly been injected from the outside midplane of experimental fusion devices (magnetic low-field side for tokamaks), and researchers strived for high pellet speeds (up to ≈4 km/s) [3] to achieve deep pellet penetration and better fueling efficiency. In the past several years, pellet technology development and experiments have concentrated on pellet fueling from the magnetic high-field side for tokamaks [4,5], with significantly deeper mass deposition and improved fueling efficiency observed at relatively low pellet speeds (<300 m/s). These injection schemes require the use of curved guide tubes to route the pellets from the acceleration devices to the inside wall launch or vertical launch locations; thus, the speed must be limited to ensure pellet survivability.

To more thoroughly understand and document the capability of curved guide tubes for the alternative injection schemes, experimental studies have been carried out for several years at the Oak Ridge National Laboratory (ORNL) [6–9], including mock-up tests of guide tube installations for DIII-D, Joint European Torus (JET), Large Helical Device (LHD), and FIRE. The range of pellets sizes for those mock-ups ranged from 2.7 to 4.0 mm, and the overall tube lengths varied from ≈3 to 20 m. The D_2 data from those mock-up tests are summarized in Table I and Fig. 1 in which the speed transition range (both intact and broken pellets observed) and minimum bend radius are identified for each mock-up. In Fig. 1, the boundaries of the data bands are connected, and the shaded area shows the trend. To ensure the reliable delivery of intact pellets, the speed should not exceed the lower speed limit (the start of the transition range) or the left boundary in Fig. 1. Thus, the pellet speeds should be limited to a few hundreds of meters per second. For the actual installations on the active fusion experiments (DIII-D, JET, and LHD), the pellet speed limits

observed in the fueling experiments have been in good agreement with the results from the ORNL mock-up tests. Recently, an experimental mock-up of the proposed ITER guide tube installation for inside pellet launch was set up in the lab and tested with 5.3-mm D_2 pellets. When accounting for mass loss in the acceleration device and guide tube, this pellet size (117 mm^3 for L/D = 1) is a close match to the largest size specified in the present ITER design (92 mm^3 ± 20% delivered to the plasma). The length of the frozen pellet can be varied to accommodate the incremental size range. In the next sections, the experimental set-up for the ITER mock-up is described briefly, and the data are presented and discussed. The ITER mock-up data are also included in Table I and Fig. 1.

2. Experimental set-up

A simple schematic of the experimental set-up for the ITER mock-up tests is shown in Fig. 2. A single D_2 pellet is frozen (≈10 K) in situ in the gun barrel, using a technique commonly referred to as the pipe gun. The pipe gun is equipped with a breech-side mechanical punch and propellant valve that provide the means for pellet acceleration in the gun barrel. Thorough descriptions of the components and operating procedures can be found in previous publications [6–9]. The key parameters in this study were the pellet speed and mass. Four diagnostics provided timing marks for accurate speed measurements, and the two microwave cavity mass detectors [10] provided mass measurements upstream and downstream of the test tube. In addition, in-flight pellet photos could be captured at the muzzle (triggered by the light gate) and at the upstream and downstream microwave cavity mass detectors. The average pellet speeds through the curved guide tube are reported here as determined by the time of flight between the upstream and downstream microwave cavities (separated by 10.5 m). Inlet and outlet pellet speeds were also obtained from the diagnostics, and those speeds usually agreed within a few percent of the average speed. Thus, no discernible slowing down of the pellets was observed in the curved guide tube. In all of the previous ORNL studies referenced here, pellet photography at the guide tube exit was the best technique available to determine pellet integrity and thus the speed limit. In this study, the two microwave cavities provided a

better technique to determine pellet integrity and accurately measure the pellet mass loss as a function of pellet speed. Before installing the ITER guide tube mock-up in the lab, calibration tests were carried out with the two microwave cavities placed in close proximity of the gun muzzle. Pellets of varying lengths were fired through the cavities, and individual and cross calibrations of the cavities were obtained for different pellet sizes. With this information, the percentage of pellet mass delivered to the downstream end of the guide tube could be evaluated for every intact pellet in the mock-up tests. From the signal signature of the downstream microwave cavity, it was straightforward to identify broken pellets. Only pellets with ≥80% of the mass delivered downstream were considered to be intact (this mass is relative to that measured in the first cavity). From pellet muzzle photos, it is estimated that ≈15% of the frozen pellet mass is lost during acceleration in the relatively warm (room temperature) gun barrel.

3. ITER mock-up and test results

The proposed curved guide tube layout for inside launch on ITER is shown in Fig. 3, including a table describing the five bends and lengths of the tube segments. This actual ITER mock-up requires a 3-D description; however, the simple 2-D illustration is sufficient to show the crucial bends. The initial long straight section (≈10 m) that couples directly to the ITER pellet injector is not shown. The tightest bend radius is 800 mm and is located at the downstream end of the tube. The ORNL mock-up included all of the bends, and some of the straight sections were extended to facilitate the lab installation. A stainless steel tube with an inside diameter (ID) of 10 mm was used for the mock-up with a total length of 10.5 m. Previous test results suggest that the lengths of straight sections and tube bore variations should have only minimal effect on the pellet speed limit and mass loss. Figure 4 includes some typical pellet photographs at the gun muzzle. Data from the mock-up tests are summarized in Fig. 5. The abscissa is the pellet speed, and the speed transition range in which intact and broken pellets were observed is identified (≈300 to 480 m/s). This data along with the tightest bend radius (800 mm) are included in Table I and Fig. 1. In the bottom section of the Fig. 5, the fraction of intact pellets for each speed bracket is illustrated with columns. Results

from the mock-up tests indicate that any pellets with speeds <300 m/s should be delivered intact. On the top section of the plot, the percentage of the mass delivered downstream is shown as a function of pellet speed for intact pellets. As expected, the mass loss increases with pellet speed, and very low mass losses (only a few percent) are observed at 100 m/s. At the 300-m/s speed limit, about 10% of the pellet mass is lost in the curved guide tube; the mass loss approaches 20% for the fastest intact pellets.

4. Summary

Based on the experimental data from the ORNL mock-up of inside pellet launch on ITER, the pellet speed limit will most likely need to be limited to ≈300 m/s for reliable delivery of intact pellets to ITER plasmas. At that speed, the experimental data suggest that about 90% of the pellet mass should be delivered to the plasma. Presently, a reference value of 300 m/s for pellet speed is being used in the ITER design and planning activities, and this study supports that value. As shown in Fig. 1, the data from the ITER mock-up falls in line with that from other fusion experiment mock-ups. In Fig. 6, the data boundaries from the mock-ups in Fig. 1 are compared with test data of tubes with a single 90º bend. In some cases, the speed limit for the mock-ups approach that of a single bend of the tightest radius, and it is clear that the tightest bend radius of the guide tube is the key parameter in limiting pellet speed. While researchers have used techniques to improve the speed limit for specific curved guide tube installations [11], significant improvements are not likely without a considerable increase in pellet mass loss. In previous fusion fueling experiments with H_2 and D_2 pellets, the mass loss has not been an issue. However, it will be an important issue for ITER because deuterium-tritium pellets will be part of standard operations.

Acknowledgement

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Figure captions

Fig. 1. Test data from ORNL mock-ups of curved guide tube installations; the speed transition range in which intact and broken pellets are observed is shown for each data set

Fig. 2. Experimental set-up showing pellet injector, diagnostics, and test tube

Fig. 3. D_2 pellet photos from ITER mock-up tests (gun barrel is identified; OD = 6.35 mm)

Fig. 4. Guide tube 2-D layout for inside launch on ITER (actual installation is 3-D, and ≈10 m of initial straight tube is not shown)

Fig. 5. Pellet survival results and mass measurement data from ITER mock-up tests (5.3-mm D_2 pellets).

Fig. 6. Comparison of data from mock-ups of curved guide tube installations and tubes with a single 90º bend

Table I. Summary of test results from ORNL mock-ups of curve guide tube installations for fusion experiments

Mock-up	Injection scheme	Tightest bend radius (mm)	Speed transition range (m/s)
DIII-D	Inside launch I	63	230–290
	Inside launch II	231	260–300
	Vertical launch	920	350–450
JET	Inside launch	220	160–250
	Vertical launch I	1500	340–500
	Vertical launch II [a]	1725	600–750
	Vertical launch III [a]	545	270–310
LHD [b]	Inside launch	300	270–370
FIRE [c]	Inside launch	165	130–175
ITER [c]	Inside launch	800	300–480

[a] Tube was tested with single bend, which would correspond to an injector mounted and operating vertically.
[b] H_2 pellets were used on LHD; however, data from tests with D_2 pellets are shown for this comparison.
[c] Tube layouts from the present designs of these proposed experiments were tested.

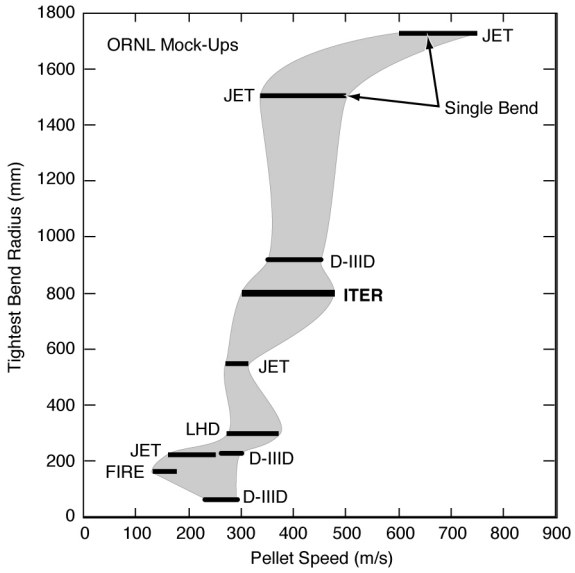

FIG. 1.
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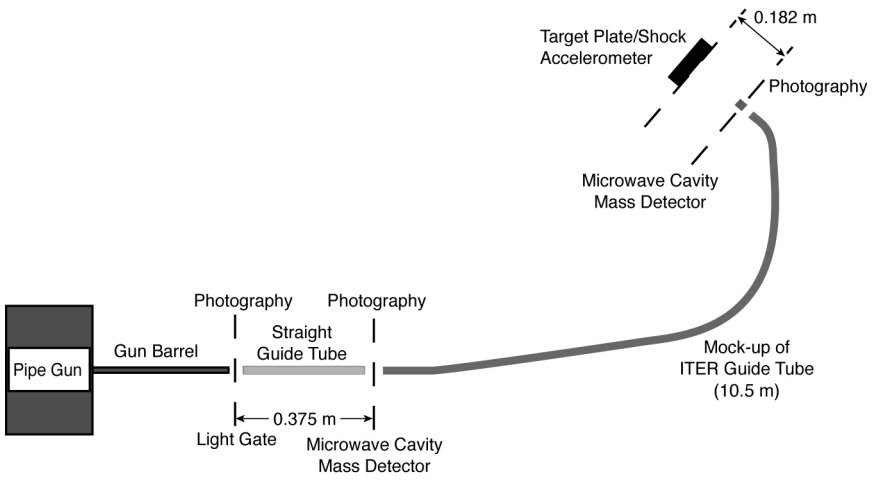

FIG. 2.
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Segment	Bend Radius (mm)	Included Angle (deg)	Length (mm)
AB	5000	8.17	714.2
BC	0	–	3026.5
CD	1525	34.9	930.0
DE	1700	64.9	1342.0
EF	0	–	470.2
FG	1525	10.0	265.3
GH	0	–	195.1
HI	800	52.6	734.7
Total			7678.0

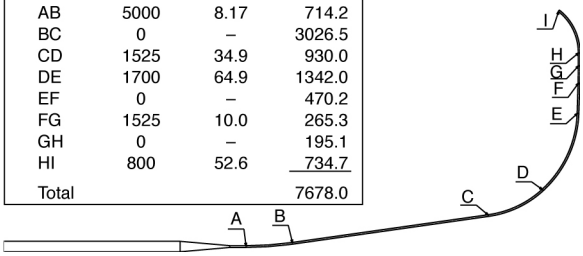

FIG. 3.
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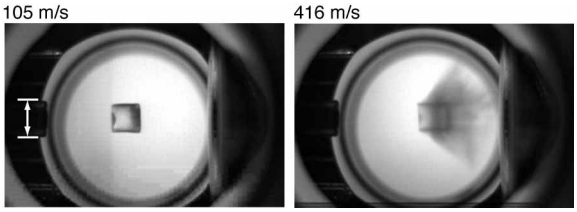

FIG. 4.
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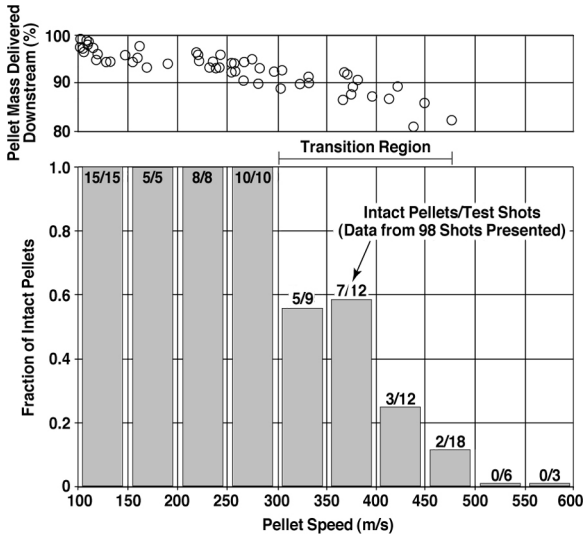

FIG. 5.
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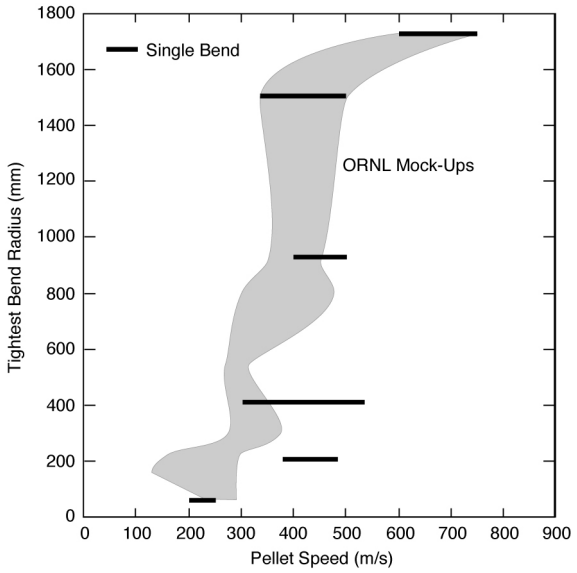

FIG. 6.
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