Experimental Study of Pellet Delivery to the ITER Inner Wall through a Curved Guide Tube at Steady-State Pressure

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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 a curved guide tube to route the pellets from the acceleration device, under the divertor, and to the inside wall launch location. In an initial series of pellet tests in support of ITER, single 5.3-mm-diam cylindrical D\textsubscript{2} pellets were shot through a mock-up of the planned ITER curved guide tube. Those data showed that the pellet speed had to be limited to \( \approx 300 \text{ m/s} \) for reliable delivery of intact pellets. Also, microwave cavity mass detectors located upstream and downstream of the test tube indicated that \( \approx 10\% \) of the pellet mass was lost in the guide tube at 300 m/s. The tube base pressure for that test series was \( \approx 10^{-4} \text{ torr} \). However, for steady-state pellet fueling on ITER, the guide tube will operate at an elevated pressure due to the pellet erosion in the tube. Assuming the present design values for ITER pellet fueling rates/vacuum pumping and a 10\% pellet mass loss during flight in the tube, calculations suggest a steady-state operating pressure in the range of 10–20 torr. Thus, experiments to ascertain the pellet integrity and mass loss under these conditions have been carried out. Also, some limited test data were collected at a tube pressure of \( \approx 100 \text{ torr} \). No significant detrimental effects have been observed at the higher tube pressures. The new test results are presented and compared to the baseline data previously reported.

Keywords—pellet injection; inner wall; curved guide tube; plasma; ITER

I. 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 International Thermonuclear Experimental Reactor (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. Pellet injection from the inner wall (magnetic high-field side) has been shown on present day tokamaks to provide more efficient fueling (for instance, on ASDEX-Upgrade [3] and DIII-D [4]) and is planned to be used on ITER (Fig. 1). This injection scheme will require the use of curved guide tubes to route the pellets from the acceleration devices to the inside wall.

To more thoroughly understand and document the capability of curved guide tubes for alternative injection schemes, experimental studies have been carried out for several years at the Oak Ridge National Laboratory (ORNL) [5–9], including mock-up tests of guide tube installations on two of the world’s largest experimental tokamaks [DIII-D and the Joint European Torus (JET)]. The pellet sizes for those mock-ups ranged from 2.7 to 4.0 mm, and the overall tube lengths varied from \( 5 \) to \( 20 \) m. In general, the pellet speeds had to be limited to a few hundreds of meters per second to ensure that intact pellets were delivered through curved guide tubes. Recently, an experimental mock-up of the proposed ITER guide tube installation for inner wall launch was set up in the lab and tested with 5.3-mm D\textsubscript{2} pellets. This pellet size corresponds to the largest size specified in the present ITER design [10].

Figure 1. Pellet injection via the inner wall on ITER.
Initial results with an evacuated tube (≈10⁻⁴ torr) have been previously reported [9] and indicated a speed limitation of ≈300 m/s and a mass loss of ≈10%. However, for steady-state pellet fueling on ITER, the guide tube will operate at an elevated pressure due to the pellet erosion in the tube. Using the present ITER pellet fueling design rate of 100 Pa·m⁻³/s or 750 torr-L/s, 10% of that or roughly 75 torr-L/s should be deposited in the guide tube. Even though the conductance of the guide tube and vacuum pumping rates are not fully defined at this time, some simple calculations suggest steady-state pressures in the guide tube of ≈10 to 20 torr. In the next sections, the experimental set-up for the ITER pellet injection mock-up is described briefly; the initial data are reviewed; and new data at 10 and 100 torr are presented and compared to baseline data previously reported.

II. EXPERIMENTAL TEST TUBE AND SET-UP

The proposed curved guide tube layout for inside launch on ITER is shown in Fig. 2, including a table describing the five bends and lengths of the tube segments. This actual ITER mock-up requires a three-dimensional (3-D) description; however, the simple two-dimensional (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. Previous test results suggest that the lengths of straight sections should have only minimal effect on the pellet speed limit and mass loss. A stainless steel tube with an inside diameter (I.D.) of 10 mm was used for the mock-up with a total length of 10.5 m.

![Figure 2. Guide tube 2-D layout for inner wall launch on ITER.](image)

A simple schematic of the experimental set-up in the laboratory is shown in Fig. 3. A single D₂ 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 provides the means for pellet acceleration in the gun barrel. Thorough descriptions of the components and operating procedures can be found in previous publications [5–9]. For the initial data previously reported [9], the test tube was always evacuated (base pressure of ≈10⁻⁴ torr) by a mechanical vacuum pump prior to a pellet shot and actively pumped during the shot. For the new data reported here, an isolation valve was closed to remove active pumping, and H₂ gas was introduced into the test tube through a manual valve until the desired base pressure was obtained (≈10 or 100 torr). The D₂ pellet was then shot through the pressurized tube. After the shot, the tube was evacuated to remove the D₂/H₂ gas mixture, and the process repeated for the next pellet shot.

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 [11] provided mass measurements upstream and downstream of the test tube. In addition, in-flight pellet photos (Fig. 4) 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 usually 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. The two microwave cavities provided a good technique to determine pellet integrity and accurately measure the pellet mass loss as a function of pellet speed. While the absolute pellet mass was not determined from the microwave cavity signals, the relative mass change is estimated to be accurate within 5% or better in most cases. 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 because cross calibrations were made with the cavities in close proximity in a special test series).

III. TEST RESULTS

A. Tube Base Pressure ≈10⁻⁴ torr

Data from the initial 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). In the bottom section of 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.

B. Tube Base Pressure $\approx 10$ torr

New data taken at 10 torr are summarized in Fig. 6. The speed transition region ($\approx 280$ to $440$ m/s) and speed limit ($280$ m/s) are very similar to those reported for the fully evacuated tube. Also, the measured mass losses fell in the same range as for the original data. However, for some unexplained reason, more experimental scatter in the mass measurements is observed at 10 torr. Overall, no appreciable differences were observed between test data at $10^{-4}$ and 10 torr.

C. Tube Base Pressure $\approx 100$ torr

Only limited data were collected at 100 torr. There were not enough pellet shots to produce a useful column plot as for the other two data sets. In general, the speed transition region appeared to be similar to those reported for the lower two pressures. In the range of 300 to 350 m/s, five out of seven pellets were observed to be intact, and this percentage is similar to those recorded for the two lower pressures. In Fig. 7, the mass loss measurements at 100 torr are shown along with the data for the two lower pressures, and the mass loss measurements fall in the same range as for the two lower pressures. The scatter is similar to that recorded for the fully evacuation.
evacuated tube. One notable difference at 100 torr was that a significant slowing down effect on the pellets was observed (Fig. 8). No discernible slowing down was observed at the two lower test pressures.

IV. CONCLUSIONS

Based on the experimental data from the ORNL mock-up of inner wall pellet injection on ITER, operations at elevated pressures in the guide tube do not appear to be a significant issue for the present ITER pellet fueling design parameters. In comparing pellet survivability and mass loss measurement data for tube base pressures of ≈10⁻⁴, 10, and 100 torr, no appreciable differences were found, except for a slowing down effect (≈10–20%) on the pellets at 100 torr. Thus, for the proposed ITER pellet-fueling scenario, the pellet speeds will most likely need to be limited to ≈300 m/s for reliable delivery of intact pellets. 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.

REFERENCES