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Development of the Guide Tube for Magnetic High Field Side Pellet Injection

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Abstract

For attaining a higher fueling efficiency in JT-60U centrifugal pellet injection experiments, guide tubes for a magnetic high-field side (HFS) injection were developed. The guide tube for HFS (top) injection is about 15 m in length, 5 mm in inner diameter and 600 mm in the smallest curvature radius, and has been connected to the upper port of the vacuum vessel. The speed exceeding 220 m/s led to pellet destruction in the guide tube, while the injected pellet mass estimated from the increase of plasma density reached about 80 % of that from low-field side (LFS) injection. A simple impact model was applied to explain the above result. The perpendicular pellet velocity limit on the wall inside the tube was estimated to be 20 m/s indicating that less than 100 m/s pellets can pass through the guide tube even with a minimum curvature of 200 mm. Based on this estimation, a new guide tube for HFS (mid) injection was designed and installed in March, 2001. Pellets with 100 m/s were successfully injected to the plasma through the HFS(mid) guide tube.

Keywords:

high field side pellet injection, guide tube, JT-60U, deuterium pellet, pellet velocity limit

1. Introduction

In JT-60U, in order to attain higher density and higher confinement plasmas by successive refueling to the plasma core, development of a centrifugal pellet injector started in 1994. The centrifugal pellet injector which can eject trains of up to 40 cubic (2.1 mm)^3 pellets at a frequency of 1~10 Hz and speeds of 100~1000 m/s was developed and installed in 1998 [1,2].

On ASDEX-U pellet injection experiments from a magnetic high field side (HFS) in 1996 [3] showed higher fueling efficiency than magnetic low field side (LFS) injection under the high power heating plasma. In 1999, a guide tube for HFS (top) injection was adopted in JT-60U. The recent report of Takenaga *et al.* [4] shows that the HFS (top) pellet can be deposited deeper in the plasma than that of LFS (mid) and 70 % of Greenwald density with H_{89P} of 1.94 was attained. Therefore, to attain more effective fueling, another guide tube for HFS (mid) injection, in which pellets were injected from the inboard midplane, was installed and started operation in March 2001.

In this report, the design of guide tubes for HFS (top) and HFS (mid) injection, and operational results are described.

2. Design of guide tubes

The configuration of two types of guide tube, HFS (top) and HFS (mid), and the vacuum vessel is shown in

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Fig. 1. Pellets ejected from centrifugal pellet injector pass through the line selector which selects the tube for HFS (top) or HFS (mid) injection as also shown in Fig. 1. The line selector has a movable funnel connected to the guide tubes for HFS (top) or HFS (mid) injection through a gate valve.

The target point of HFS (top) injection is the bottom area of the inner divertor baffle plate. The tube (5 mm in inner diameter, 7 mm in outer diameter and ~15 m in length) has four curves. The curvature radius of the first curve is limited to R = 600 mm because of obstructive devices around the tube. According to the reports [5,6], the inner diameter (D) of the guide tube should be less than twice of the pellet size (d), $D/d < 2$. In JT-60, the inner diameter (5 mm) approximately two times the diagonal line of a pellet was adopted.

The guide tube has a double-tubed structure. The outer secondary tube is pumped out to lower the influence on unexpected air leakages. The guide tube consists of several sections of tubes. Each tube was connected by a flange structure. To prevent the destruction of the pellet, inlet sides of the tubes have tapered structures.

Two microwave cavities were installed for measuring the number and mass of passing pellets. One was installed between the injector and the line selector. The other was installed in the outlet side of the HFS (top) guide tube (Fig. 1, point A). The average pellet speed through the HFS (top) guide tube can also be investigated by the time of flight method.

The guide tube for HFS (mid) is 5 mm in inner diameter, 7 mm in outer diameter and about 5 m in length. Pellets are injected from the inboard side of the vacuum vessel at 45° to the plasma midplane. The guide tube was set up between the inner vacuum vessel skin and the first wall tiles. The outlet of the guide tube is 5 mm lower than the first wall surface to protect from the plasma exposure. For this modification, LFS (mid) injection was canceled. Based on the estimation from HFS (top) injection results, the inlet and outlet curvature of the guide tube are designed to be 200 mm and 100 mm, respectively.

3. Operational Results

HFS (top) pellet injection experiments were performed from January to November 2000. Pellet injection speed into the plasma is important for the central fueling. Average pellet speed was measured by two microwave cavities. Figure 2 shows the relationship between the ejected pellet speed calculated by the rotational frequency of an acceleration motor and the measured average pellet speed. For these measurements, different fuel gases H_2, D_2 and Ne were used. The measured pellet speeds were about 79 % of the calculated speed and a difference in the pellet gas species was not clear.

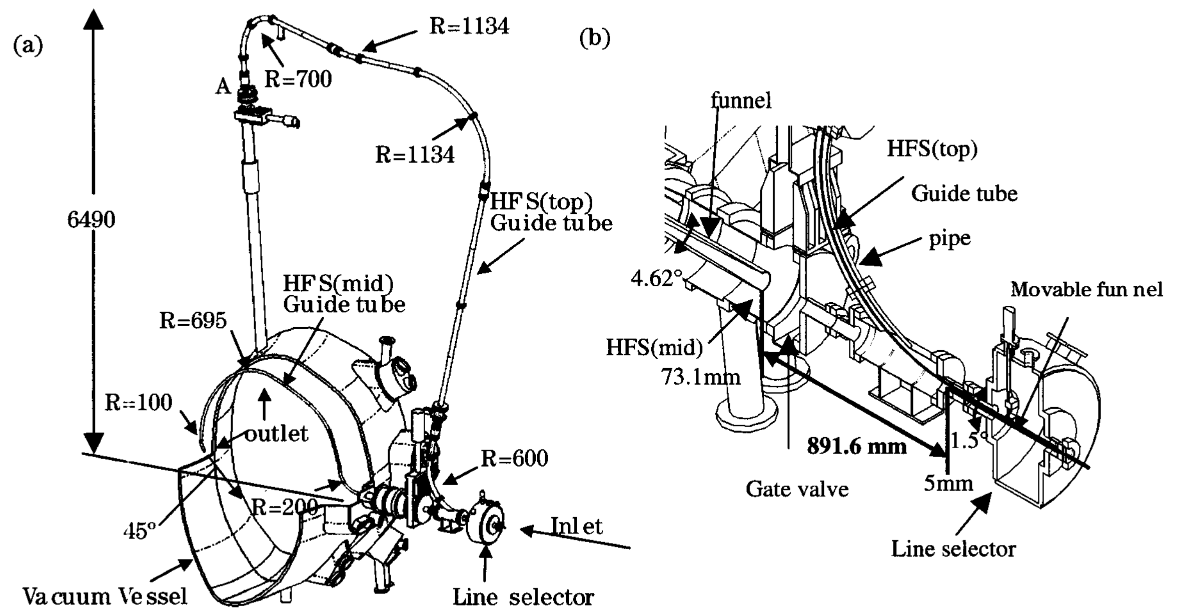

Fig. 1 Schematic drawing of guide tubes for JT-60U (a) and the line selector (b).

Pellet masses injected from the HFS were also investigated. Figure 3 shows the pellet speed dependence of the increase of the electron number in plasma (ΔN_e). It was supposed that ΔN_e is nearly equal to the injected pellet mass because of OH plasma. Pellets were injected into OH plasma with pellet speed from 100 m/s to 400 m/s. Here, pellet speeds are calculated ones. Open circles are the results of HFS (top) injection. The solid line shows the maximum value of HFS (top) injection. It is clear that pellet masses from HFS (top) increase as the pellet speed decreases. This indicates that the most of ejected pellets are destroyed through the guide tube even at 300 m/s. Destruction of pellets was also observed by the microwave cavity located at point A. Pellets with 220 m/s successfully show the pellet signal. On the other hand, in the range of 320 to 400 m/s, pellet size reduction and pellet breaking was observed.

A simple impact model was applied to the experimental data. The collision of a pellet on the guide tube inner wall was supposed to be like Fig. 4. A pellet whose speed is V impacts on the guide tube inner wall which curvature radius is R. When perpendicular velocity (V_{perp}) of the pellet to the wall is larger than a limit value, the pellet will be broken. The relationship between V and V_{perp} is written as,

$$V_{perp} = V \sin \theta \qquad (1)$$

$$\cos \theta = 1 - (D - d/2)/R \qquad (2)$$

where θ, D and d mean the pellet impact angle on the wall, inner radius of guide tube and pellet size, respectively. From eqs. (1) and (2), the maximum perpendicular pellet velocity without destruction by the impact is derived. From Fig. 3, we supposed that the maximum pellet speed to pass through the guide tube was 220 m/s.

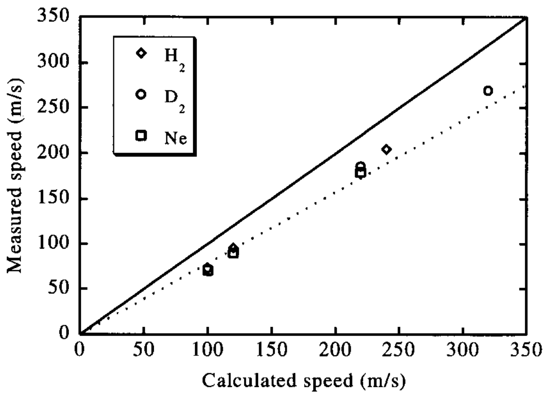

Fig. 2 Relationship between calculated pellet speed and observed pellet speed.

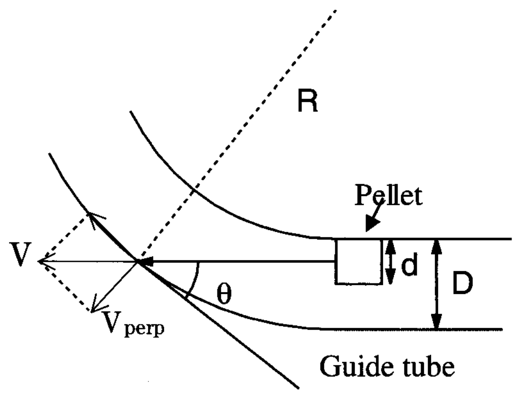

Fig. 4 Schematic diagram of simple impact model.

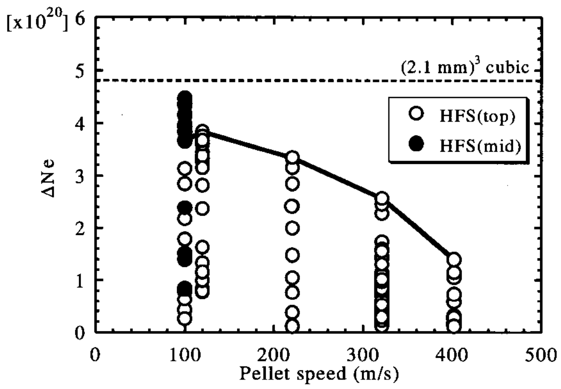

Fig. 3 Ejected pellet speed dependence of increment in electron number.

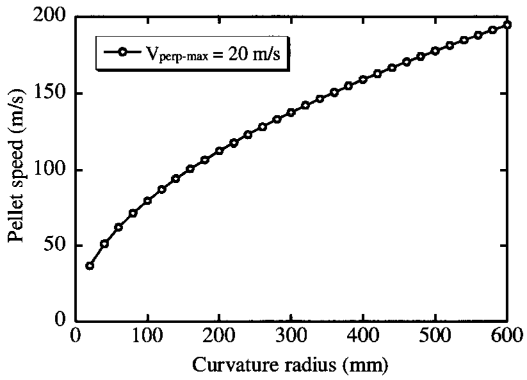

Fig. 5 Relationship between curvature radius and survival pellet speed derived from adopted model.

The pellet speed passing through the HFS (top) guide tube became around 80 % of calculated speed. Therefore, the limit velocity which can pass through the curve of 600 mm in curvature radius supposed to be 200 m/s, indicating that the V_{perp} is from about 20 m/s. A theoretical calculation by Artaud *et al.* [6] shows that the maximum V_{perp} ($V_{perp\text{-}max}$) below 15 K is 20 m/s and that $V_{perp\text{-}max}$ gradually becomes smaller with increasing temperature. This means that the $V_{perp\text{-}max}$ derived from the simple impact model agrees with the literature value.

The guide tube for HFS (mid) injection was designed based on the estimation with the above simple impact model. Figure 5 shows the calculated result of survival pellet speed versus curvature radius. The simple impact model shows that the pellet with the velocity up to 100 m/s can go through the first curve of R = 200 mm. Unfortunately, because the space between the vacuum vessel skin and the first wall was insufficient, the curvature radius at the outlet was limited to 100 mm and pellet speed below 80 m/s was available for this guide tube. After the first R = 200 mm curve, a pellet shifts its position to the outside of the tube wall being forced outward by an acceleration up to the end of the guide tube. Therefore, the centrifugal model [7] may be adoptable in the outlet of HFS (mid) rather than the simple impact model. Considering the centrifugal model, a pellet speed of 280 m/s is allowed even with the minimal curve of R = 100 mm.

Pellet injection experiments from HFS (mid) begun in March 2001. The results of the increase of electron number by HFS (mid) injection were also indicated in Fig. 3. Pellets injection with 100 m/s from HFS (mid) increases the number of electron in plasma much larger than HFS (top) injection. This demonstrates that the centrifugal model is applicable to HFS (mid) injection results.

4. Summary

For attaining a higher fueling efficiency, guide tubes were developed for JT-60U HFS (top) pellet injection experiments with the centrifugal pellet injector.

Pellet (H_2, D_2 and Ne) speeds were measured by time of flight technique using two microwave cavities. The measured pellet speeds were about 79 % of calculated speed.

The speed exceeding 220 m/s led to pellet destruction in the HFS (top) guide tube, while the injected pellet mass estimated from the increase of plasma density reached about 80 % of that from low-field side (LFS) injection. The increase of plasma density after injection depends on the pellet velocity. These results mean that the pellets wear away through the guide tube.

The simple impact model was applied to explain the HFS (top) results. Perpendicular pellet velocity limit on the wall inside the tube was estimated as 20 m/s indicating that pellets with a speed less than 100 m/s can pass through the guide tube even with a minimum curvature of 200 mm. Based on this estimation, a new guide tube for HFS (mid) injection was designed and installed in March, 2001. Pellets with 100 m/s in speed were successfully injected to the plasma.

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