Improvements in a Tracer-Encapsulated Solid Pellet and Its Injector for More Advanced Plasma Diagnostics

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Abstract. A Tracer-Encapsulated Solid Pellet (TESPEL) has been developed for promoting a precise study of the impurity transport in a magnetically-confined high-temperature plasma. This paper gives a brief report of the recent improvements in the TESPEL and its injector for more advanced plasma diagnostics. The TESPEL can be considered as a double-layered impurity pellet. This structure enables us to produce a both poloidally and toroidally localized "tracer" impurity source in the plasma, and to specify the total amount of the tracer impurity deposited in the plasma precisely. Recent experiments on the Large Helical Device by using the TESPEL suggest that the importance of the impurity source location in the impurity transport study. Thus we have developed new-type TESPELs, which are greatly improved in regard to the above-mentioned unique features. In addition, we also developed a new TESPEL injector, which enables us to inject the TESPEL obliquely into the plasma. This injector can also contribute to a further shallower penetration of the TESPEL into the plasma.

1. Introduction

Although we are approaching the age of the International Thermonuclear Experiment Reactor, many physics issues related to the confinement of magnetically-confined toroidal plasma still remain to be clarified. For example, under some conditions, impurities inside the magnetically-confined toroidal plasma tend to accumulate in the core region of the plasma [1, 2]. This will cause a dilution of fusion fuel. Moreover, radiation loss from the core plasma will be enhanced due to the impurity accumulation, and then the temperature in the core region will be decreased dramatically. Consequently, fusion plasma performance will be degraded below the acceptable level. In order to develop strategy for obviating and suppressing impurity accumulation, it is important to gain a full understanding of impurity transport in the magnetically-confined toroidal plasma.

In the study of impurity transport in the magnetically-confined toroidal plasmas, a spatio-temporal behavior of the impurity injected into the plasma whether intentionally or accidentally has been utilized [3, 4]. The most common method for the external injection of impurities is a bare impurity pellet injection method [5]. The impurities injected by this conventional method will be deposited inevitably even in the edge ergodic region (outside the last closed flux surface). This would become a
problem in estimating the total amount of the externally-injected impurity deposited in the confined plasma. In order to overcome this disadvantage, a Tracer-Encapsulated Solid Pellet (TESPEL) [6, 7, 8] has been developed at the National Institute for Fusion Science (NIFS) in Japan. This paper reports recent improvements in the TESPEL and its injector for more advanced plasma diagnostics.

2. Improvements in the Tracer-Encapsulated Solid Pellet (TESPEL)

The TESPEL can be considered as a double-layered impurity pellet. The TESPEL basically consists of a hydrocarbon polymer as an outer shell and a tracer impurity as an inner core. This configuration enables the following unique features: a) the TESPEL injected into the magnetically-confined toroidal plasma can produce both a toroidally and a poloidally localized tracer impurity source in the core region of the plasma; b) the total amount of the tracer impurity deposited in the core plasma can be identified clearly; since the size of the inner core of TESPEL can be measured during the TESPEL production process; c) various elements can be selected as the tracer impurity; and d) variable penetration depth of the tracer impurity can be obtained owing to the flexible TESPEL size. When the TESPEL enters into the magnetically-confined toroidal plasma, the outer shell of the TESPEL is first ablated, and then is followed by the ablation of the tracer impurity in the core of the TESPEL. Therefore, the control of the penetration depth of the TESPEL corresponds to that of the deposition location of the tracer impurity by the TESPEL. The detailed production procedure of the TESPEL is summarized in ref. [8].

The first version of the TESPEL is a thick-shell, single-tracer type, as shown in Fig. 1(a). The typical outer diameter and shell thickness of this thick-shell, single-tracer type TESPEL is ~ 700 μm and ~ 240 μm, respectively. The outer diameter can range widely from 400 to 900 μm. Consequently, the feature of this type of TESPEL is a wide range of the total amount of the tracer impurity. The second version of the TESPEL is a thick-shell, multi-tracer type, as shown in Fig. 1(b). This type of TESPEL has been developed for the purpose of estimating precisely the difference of the behavior between the intrinsic (chromium (Cr), iron (Fe) and nickel (Ni)) and the tracer impurities (vanadium

![Diagram of TESPEL types](image)
(V), manganese (Mn) and cobalt (Co)) [9]. In the case of the above-mentioned types of the TESPEL, the penetration depth of the TESPEL is mostly affected by the outer diameter of the TESPEL. That is, the region where the tracer was deposited can be controlled almost by the size of the TESPEL. Recent TESPEL experiments on the Large Helical Device (LHD) suggest the importance of the impurity source location in the impurity transport study [10]. Thus when the region of interest is the outer region of the plasma (e.g., that near the last closed flux surface), the required TESPEL size becomes inevitably smaller, and correspondingly the amount of the tracer impurity also becomes smaller. This becomes a problem that confronts the impurity diagnostics such as a spectrometer. In order to solve this problem, we developed a thin-shell type TESPEL, which is based on the fabrication technology of a polystyrene polymer shell [11]. The typical outer diameter and shell thickness of this thin-shell type TESPEL is ~ 700 μm and ~ 75 μm, respectively. Thus the shell thickness of this thin-shell type TESPEL is 70% thinner than that of the thick-shell type TESPEL. Another advantage of the thin-shell type TESPEL is that the amount of the tracer impurity can be increased more than that of the thick-shell, single-tracer type TESPEL. For obtaining a further shallower penetration than even with the thin-shell type TESPEL, we developed a thin-shell, tracer-doped type TESPEL [12]. For this type of TESPEL, the shell is made of poly-2,6-dichlorostyrene (C₈H₆Cl₂)n. Thus the chlorine (Cl) in the shell behaves as a tracer impurity. The typical outer diameter and shell thickness of this thin-shell, tracer-doped type TESPEL is ~ 600 μm and ~ 75 μm, respectively. As can be seen from Fig. 1(d), the thin-shell, tracer-doped type TESPEL can also contain the tracer impurities in the core.

The deflection effect of the TESPEL flight path due to the fast ions originated from the neutral beam injection for the plasma heating could affect the deposition location of the tracer impurity by the TESPEL. However, the deflection effect of the TESPEL flight path has no appreciable effect on the impurity transport study, because the impurity transport study generally does not need the deep deposition location of tracer impurity in the confined plasma, in contrast to the solid hydrogen isotope ice pellet injection for the plasma fueling. And in the case for the shallow penetration with the thin-shell type TESPEL, the deflection effect due to the fast ions could occur further inner side of the target region with the thin-shell type TESPEL [13], and thus the deflection effect of the TESPEL flight path has little impact on the study of interest.

3. New TESPEL Injector

As described above, the recent LHD experiments using the TESPEL suggest that the importance of the impurity source location in the study of impurity transport. Therefore, it is very important to put more control into the placement of the tracer impurity deposition for further promoting the impurity transport study. One solution is the development of the new-type TESPELs described above. Another solution is the development of an injector, which can control more precisely the location of the tracer impurity deposition. In the development of such an injector, we decided to build a new TESPEL injector capable of making an oblique injection of the TESPEL into the LHD plasma, because the existing TESPEL injector has no room for the addition of such a function.

The basic design of the new TESPEL injector is almost the same as the current injector, which consists of the TESPEL injection system and the differential pumping system. In the TESPEL injection system, the TESPEL will be accelerated through the gun barrel (with the inner diameter of 1 mm and its length of ~ 410 mm) by a helium gas with a typical pressure of several MPa. The differential pumping scheme works for preventing the high-pressure helium gas for the TESPEL acceleration from penetrating into the LHD vacuum vessel. Here, a three-stage differential pumping system is installed. The volume of the expansion chambers is 0.05 m³ (first, furthest from LHD), 0.06 m³ (second) and 0.06 m³ (third, nearest to LHD), respectively. The first expansion chamber is evacuated by a helical groove pump (0.27 m³/s for He) and the second and third expansion chambers are evacuated by turbo-molecular pumps (0.16 m³/s for He and 0.32 m³/s for He, respectively). The first expansion chamber is connected with the second expansion chamber through an ultrafast shutter valve (closing time, less than 10 milliseconds), and then the second expansion chamber is connected with the third expansion chamber through a gate valve (closing time, ~ 1 second). After the ejection of
the TESPEL, these valves will be closed immediately. In order to realize effectively the oblique
injection of the TESPEL, the final guide tube (i.e., nearest to the LHD plasma) for the TESPEL is
installed in the vacuum vessel of LHD. Figure 2 shows a cross-sectional view of the LHD with the
plane of the TESPEL injection by the new injector. In figure 2, the magnetic surfaces with the
magnetic axis $R_{ax} = 3.75$ m are also depicted for reference. The remote-controlled mechanism can
move the slightly-bended final guide tube of the new injector upward and downward. Consequently,
the expected location of the tracer deposition with the new injector ranges from the location at $r/a \sim 0.6$ to that inside the ergodic region (outside the last closed flux surface).

**Figure 2.** Cross-sectional view of the LHD with the plane of the TESPEL injection by the new injector. The remote-controlled mechanism can move the final guide tube of the new injector upward and downward. Consequently, the expected location of the tracer deposition with the new injector is ranged from the location at $r/a \sim 0.6$ to that inside the ergodic region (outside the last closed flux surface).

4. Conclusion
Important improvements in the TESPEL and its injector have been recently performed for more advanced and precise study of the impurity transport. Concerning the TESPEL, two new types of the TESPEL, the thin-shell type and the tracer-doped-thin-shell type, have been recently developed. The thin-shell structure enables us to achieve the shallower penetration of the TESPEL. And the tracer-doped-thin-shell structure allows us to deposit the tracer impurity around the last closed flux surface. As a consequence, the possible location for the tracer impurity deposition by using the TESPEL technique becomes more flexible. Concerning the TESPEL injector, the new TESPEL injector has been recently installed on the LHD for realizing the oblique injection of the TESPEL. The new TESPEL injector empowers us to achieve the even shallower penetration of the TESPEL, in particular to deposit the tracer impurity only in the ergodic region outside the last closed flux surface.
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