Impurity Transport Studies using TESPEL in W7-X stellarator

N. Tamura[1, 2], R. Bussiahn[3], K.J. McCarthy[4], B. Buttenschön[3], M. Kubkowska[5],
N. Pablant[6], A. Langenberg[3], D. Zhang[3], Th. Wegner[3], R. Burhenn[3] and the W7-X team*

[1]*National Institute for Fusion Science, NINS, Toki, Japan*
[2] *SOKENDAI (The Graduate University for Advanced Studies), Toki, Japan*
[3]*Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*
[4]*Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain*
[5]*Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland*
[6]*Princeton Plasma Physics Laboratory, Princeton, USA*
Author list in T. Klinger et al., Nucl. Fusion* ***59* *(2019) 112004.*

Introduction The tracer-encapsulated solid pellet (TESPEL) [1], which can be considered as an impurity-embedded hollow pellet, was developed at NIFS, Japan, to promote detailed impurity transport studies in magnetically-confined high-temperature plasmas. Recently, a TESPEL injection system has been commissioned on the Wendelstein 7-X (W7-X) stellarator at IPP-Greifswald, Germany, in the frame of a collaboration between NIFS, IPP and Ciemat [2]. This has been prompted by the need to identify W7-X operation scenarios that avoid the impurity accumulation predicted for high-density steady-state discharges of this optimized stellarator [3]. In W7-X, a laser blow-off (LBO) system is also installed [4]. Therefore, the impact of impurity source location (at the core by TESPEL and at the edge by LBO) on impurity transport can be uniquely investigated in W7-X. In this paper, initial assessments of results from the TESPEL injection experiments in the recent experimental campaign (OP1.2b) of W7-X are reported.

Experimental setup Since the plasma volume (~ 30 m^3) of W7-X is almost the same as that of the Large Helical Device (LHD), similar sized TESPELs were used for W7-X: the outer diameter is about 700 or 900 μm. The outer shell of TESPEL is made of polystyrene (-$CH(C_6H_5)CH_2$-). The impurities injected into the W7-X plasma during OP1.2b of W7-X are Al, Si, Ti, V, Mn, Fe, Ni, Cu, Mo and W. Sometimes multi-impurities (e.g., V, Mn and Ni) are embedded simultaneously inside the TESPEL shell. One advantage of TESPEL is that it produces a 3-dimensionally isolated extrinsic impurity source inside the magnetically confined plasma. Such a local deposition of the tracer impurity embedded in the TESPEL has been confirmed in W7-X plasmas by signals from filtered photo-multipliers (PMTs), which view the light emissions from the ablation cloud from its injection port. The temporal evolution of various emission lines from the highly-ionized tracer impurities was observed by spectroscopic diagnostics (e.g., HEXOS, PHA, XICS, HR-XIS) installed at W7-X [5].

Experimental results and discussions A unique feature of the impurities injected by the TESPEL was observed with the high-time resolved XUV spectrometer, HEXOS at W7-X. Figure 1 shows temporal evolutions of the line emissions [(a) Fe XXII, XXIII, XXV, (b) Fe XIX, Fe XXI, (c) Fe XV, Fe XVI] from the Fe impurity ions measured with the HR-XIS and HEXOS spectrometers in the W7-X discharge, 20180906.038. Around the time of TESPEL injection, the line-integrated electron density is about 4 x 10^{19} m^{-2} and the ECRH power is about 2 MW. As can be seen, the line emissions (Fe XXII and Fe XXIII) from the highly-ionized Fe impurity appear just after the TESPEL injection. The decay time of Fe XXV, which is considered as an impurity transport time, is estimated as 143.14 ± 3.45 ms. As shown in Fig. 1(c), the HEXOS clearly observed a local maximum (2nd peak in Fig.1(c)) in the temporal behaviour of more edge localized line emissions (Fe XV and Fe XVI) from lower charge-state ions originated from the Fe impurity injected by the TESPEL. This is primarily attributed to the processes of outward transport and recombination of the impurity ions that come from inside the plasma where the Fe tracer impurity is deposited. Thus, this experimental result clearly emphasizes the usefulness of the TESPEL for precise (local) studies of impurity transport.

In OP1.2b of W7-X, a clear difference between LBO and TESPEL was also observed in W7-X. Figure 2 shows temporal evolutions of the line emissions from the highly-ionized Fe impurity injected by (a) the LBO and (b) TESPEL in the W7-X plasma heated by low ECRH power (~ 0.7 MW). The line emissions shown in each frame are normalized by the maximum

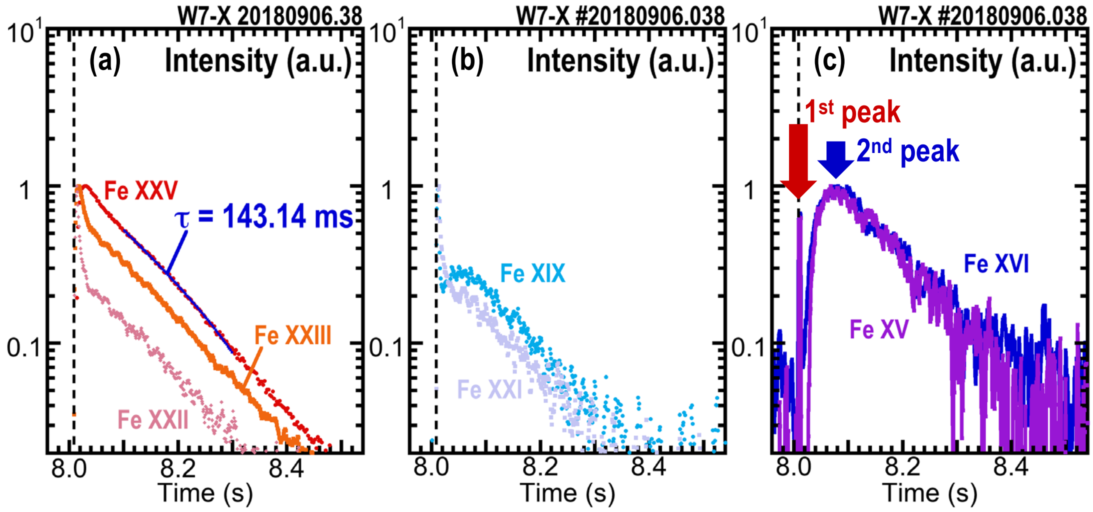

Fig.1. Temporal evolutions of the line emissions [(a) Fe XXII, Fe XXIII, Fe XXV, (b) Fe XIX, Fe XXI, (c) Fe XV, Fe XVI] from the Fe impurtiy ions measured with the HR-XIS and HEXOS spectrometers in the W7-X discharge, 20180906.038. The line-integrated electron density around the time of TESPEL injection is about 4 x 10^{19} m^{-2}. In each frame, the vertical dashed line represents the time of TESPEL injection.

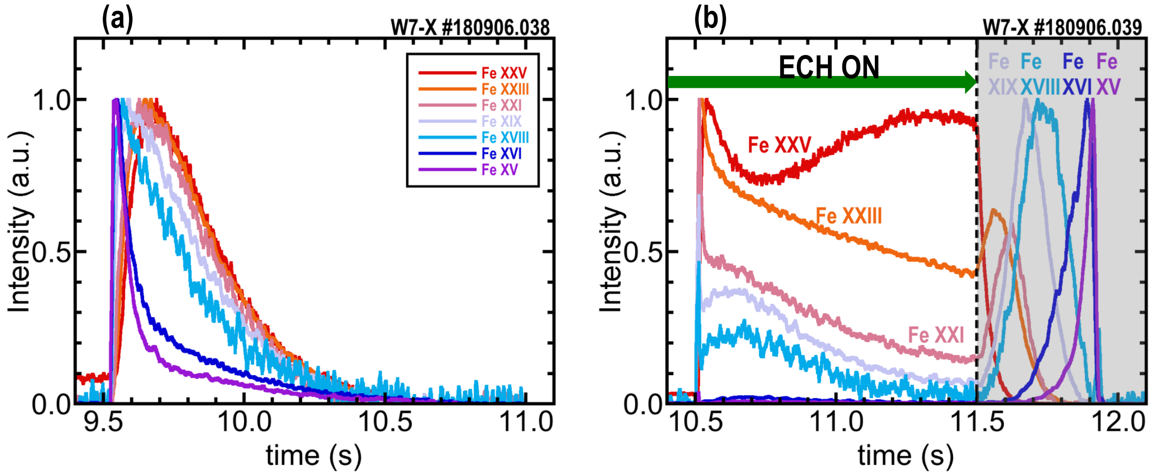

Fig.2. Temporal evolutions of line emissions from the highly-ionized Fe impurity ions injected by the LBO (a) and the TESPEL (b). In (a), the ECRH was applied completely during the time shown in the frame. In (b), the ECRH was stopped at the time of 11.5 s. In each frame, all the line emissions are normalized by the maximum druing the time period shown.

in the time period shown in each frame. A line-integrated electron density around the LBO is ~ 4 x 10^{19} m^{-2} and that around the TESPEL injection is ~ 3 x 10^{19} m^{-2}. In the LBO case, as can be recognized easily, all the line emissions from the Fe impurity ions are clearly decayed and completely disappeared around 1 s after the LBO. On the other hand, in the TESPEL case, just after the TESPEL injection, the line emissions (Fe XXI, Fe XXIII, Fe XXV) from the highly-ionized Fe impurity are also decayed, but the He-like Fe line (Fe XXV) is suddenly increased from the time of 10.7 s until the time of 11.2 s, while other line emissions are still decaying (bumps in Fe XIX and F XVIII around t = 10.6 s are attributed to the processes of outward transport as described above). This result suggests that the charge-state of Fe ions is concentrating in the He-like state after the time of 10.7 s. Such a concentration in very high charge-states of the impurity ions may be an indication of impurity accumulation in the core plasma. Thus this experimental result clearly shows the importance of the impurity source location on the impurity behaviour in the magnetically-confined plasma.

The TESPEL method can exclude the influence of the SOL on the impurity transport study in the confined plasma owing to its unique feature. Therefore, the TESPEL allows us to investigate more clearly the impurity transport in the core plasma of W7-X in different configurations. In OP1.2b of W7-X, the Fe-TESPEL injection experiments have been performed in standard (EJM), high-mirror (KJM), high-iota (FTM), and low-iota (DBM) configurations with almost the same plasma conditions, with the line-integrated electron density of about 7 x 10^{19} m^{-2} and ECRH power of about 3.5 MW. As a result, the W7-X plasma in the standard configuration (EJM) shows longer decay time (131.63 ± 2.50 ms for EJM, while 80.77 ± 1.18 ms for KJM and 80.79 ± 2.39 ms for FTM) of Fe XXV measured with HR-XIS, although no HR-XIS data is available in the low-iota (DBM) configuration. Thus the results from this experiment set suggest that the W7-X plasma with the standard configuration seems to have a longer impurity confinement than the W7-X plasma with the high mirror and high iota configurations.

Summary The TESPEL injection system has been successfully commissioned on the W7-X stellarator. The local deposition of the tracer impurities of the TESPEL has been confirmed at the various W7-X plasmas. Depositing the impurities in the core plasma of W7-X by means of the TESPEL offers a unique opportunity to study the impurity transport in the core plasma. The comparison between LBO (impurity source at the edge) and TESPEL (impurity source in the core) allows us to obtain an enhanced view on profiles of impurity transport coefficients, diffusivity and convection velocity. Taking advantage of the unique feature of the TESPEL, the impurity transport in the core plasma of W7-X in different configurations has been studied with the TESPEL. The experimental results suggest that the W7-X plasma with the standard configuration seems to have a longer impurity confinement than that with the high mirror and high iota configurations. In order to draw an accurate conclusion, a one-dimensional modelling with the STRAHL code for estimating impurity transport coefficients is highly important and it will be a next step.

Acknowledgments NT acknowledges financial supports from the JSPS KAKENHI 17KK0121, the NIFS/NINS Program for Enhancing Research Collaboration (UFEX105), the NIFS/NINS Young Researchers Supporting Program (UFEX106), the NIFS/NINS under Strategic International Research Exchange Promotion Program (UFEX402), and the NINS program of Promoting Research by Networking among Institutions (Grant No.01411702). KJM acknowledges financial support from the Spanish MINECO (Grant FIS2017-89326-R). This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] S. Sudo, J. Plasma Fusion Res. 69, 1349 (1993).
[2] R. Bussiahn et al., Rev. Sci. Instrum. 89 10K112 (2018).
[3] R. Burhenn et al, Nucl. Fusion 49 (2009) 065005.
[4] Th. Wegner et al., Rev. Sci. Instrum. 89, 073505 (2018).
[5] H. Thomsen et al., JINST 10 P10015 (2015).