Integration of the TESPEL injection system at W7-X

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Since impurities determine the plasma performance in magnetically-confined fusion plasmas, analyzing their behavior and controlling their confinement is significantly important for a stable and steady-state operation of fusion devices. A comparison of the impurity transport in the core region of large stellarators, such as Wendelstein 7-X and Large Helical Device (LHD) is quite useful to gain a better understanding of the impurity transport in reactor-relevant stellarator plasmas. Therefore, a Tracer-Encapsulated Solid Pellet (TESPEL) injection system has been newly installed for the operational phase OP1.2b of W7-X. The injector was designed and manufactured by NIFS to achieve a similar TESPEL deposition location as in LHD. Technical guidelines and functional specifications, addressing the specific conditions at W7-X had been implemented in close collaboration between NIFS and IPP. This resulted in a compact 3-stage differential pumping system considering spatial restrictions due to existing and future diagnostics, material requirements and limitations due to the magnetic stray field in the vicinity of the turbo pumps. This contribution reports on the design and the integration of the new TESPEL injection system to W7-X and first achievements during the commissioning of the system.

Keywords: TESPEL, Pellet, Injection system, Integration, Design, Assembly, Test

1. Introduction

For the development and design of future fusion reactors, the understanding of impurity transport in such a reactor is of crucial importance. Because impurities can inhibit the fusion process and in the worst case damage a fusion reactor itself, it is the aim of impurity transport studies to determine how to remove impurities in a controlled way from the plasma and deposit them at well-defined spots. Large fusion experimental machines like LHD or Wendelstein 7-X (W7-X), as potential precursors of a fusion reactor prototype, are ideal for such studies.

Impurities of interest (Ti, V, Fe, Mo, W, Cu, Ni, Mn, etc.) can be introduced into the plasma via various methods. The laser blow-off system (LBO) uses a laser to vaporize small amounts of tracer material coated on a glass plate that is located near the plasma edge. Hence, the ablated material is ionized as it enters the plasma, so this impurity source is considered external thereby complicating impurity transport studies to some extent.

The utilization of a TESPEL injection system compensates this drawback. The TESPEL (Tracer-Encapsulated Solid Pellet) is a polystyrene shell (C_8H_8) filled with tracer particles (Figure 1), which will be shot into the plasma. The deposition of the tracer material is on a well-defined location in the core plasma, because the shell dimension and speed of the TESPEL can influence the penetration depth of the plasma. The amount of injected impurity material is precisely controlled during the TESPEL fabrication. The analysis of the impurity transport can be done by diagnostics like XUV-spectrometers, X-ray or bolometer cameras and various other systems.

The TESPEL injection system was developed by NIFS [1][2] and has already been installed on different machines [3]. The aim of this work was to integrate a TESPEL injector to the W7-X stellarator during the commissioning phase 1.2b. This article shows only the engineering perspective of integration. All physic related topics and the first results of this system are shown in an additional presentation[4].

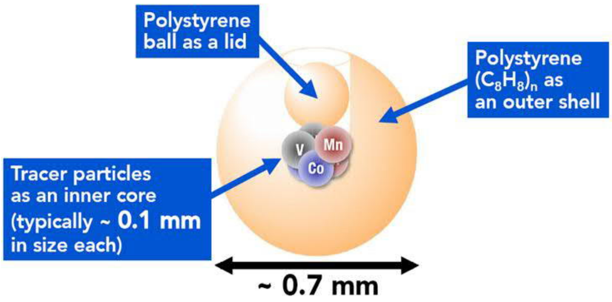

Fig. 1: Typical structure of a TESPEL

2. Concept of the TESPEL injection system

The TESPEL injection system uses the principle of the air rifle, in which a projectile is accelerated by the gun barrel in a defined direction by means of a pressure surge.

In the case of the TESPEL injection system the pressure surge will be realized by helium gas at a pressure of typically 30 bar released into vacuum by a

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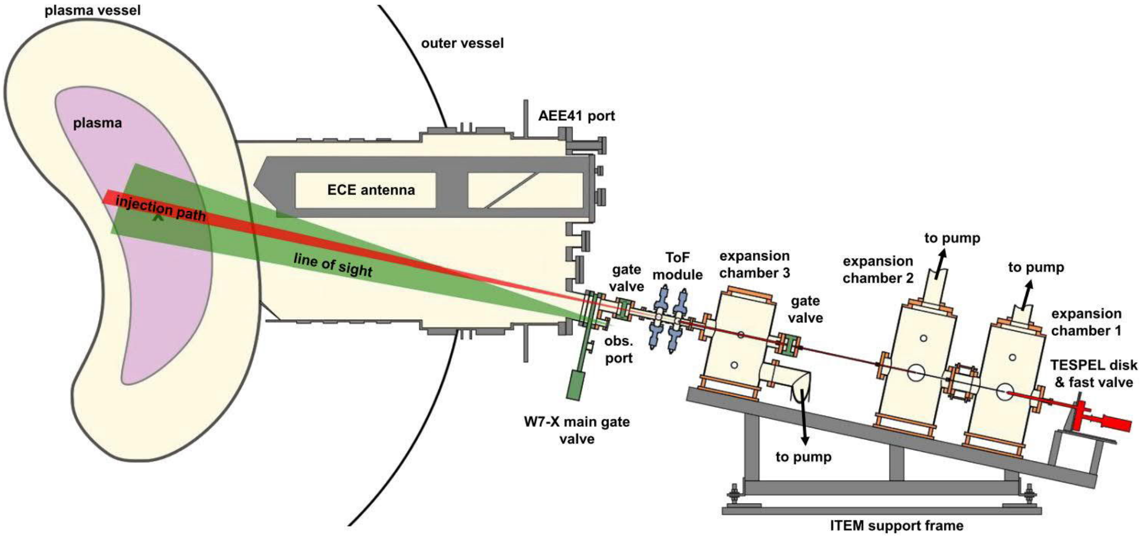

Fig. 2: Schematic representation of the TESPEL injector

fast valve. Within the first 2 ms of the shot the propellant gas accelerates only one TESPEL up to about 500 m/s. In order to influence the plasma vessel vacuum (10^{-5} mbar) as little as possible, the inflowing helium is removed by three differential pumping stages (Figure 2). Each pumping stage consists of an expansion chamber, which is evacuated by a turbo pump and a dry pump. The TESPEL passes from one expansion chamber to the next chamber via guiding tubes with increasing diameter. After the TESPEL passes the last expansion chamber, it is guided through a time of flight (ToF) module. This module provides the TESPEL speed measurement by two laser light barriers separated by a precise distance. Each barrier is connected to a HeNe laser (5 mW) and a photodetector by optical fibers, both situated outside the torus hall. The observation system that detects the light ablation radiation through an observation port window, whose axis is slightly tilted towards the injection axis (Figure 2) consist of a lens, an optical fiber and an detection system (filterscope / monochromator). Additionally, a fast frame camera system [6] can be utilized to image the spatial evolution of the ablation cloud and its detached drifting cloud along the magnetic field lines. An optical interlock circuit, also connected to the observation system is used to open the fast injection valve only when plasma radiation is detected.

3. Design tasks and solutions

3.1 Space allocation

The TESPEL injector was developed at NIFS and has a length of 2.3 m. The weight of the 3 expansion chambers with all additional components was estimated to be less than 300 kg. To support them, a stiff aluminum frame with a height of 80 mm was designed. The support frame has an upper part, which fixes the relative position of all the injector components to each other, and a lower part, which allows locating the injector in the right place by only adjusting the lower frame in advance. Bringing the whole system to a tightly packed machine like W7-X without affecting other components is a difficult undertaking, because in addition to the existing installations of W7-X, future projects have to be considered, too. For the TESPEL injector the AEE41 port of W7-X is employed [4], adjacent to the injector will be the systems for LBO and PCX (pellet charge exchange) diagnostic in OP2. Therefore, unlike other machines, the injector is mounted at an angle of 13 degrees to the port axis of AEE41 at W7-X. Furthermore, even before the development of the TESPEL injector, an ECE transmission line ran through the possible installation space of the injector. In order to consider all of these components, a very precise control and coordination was required during the design phase, since at the same time there could be design changes on these installations, too. This was done through a daily updated database image, which provides reduced amounts of data for an environment scan in CATIA [7]. This helped to identify interfaces to other components at an early conceptual stage, but also increased TESPEL visibility to other designers.

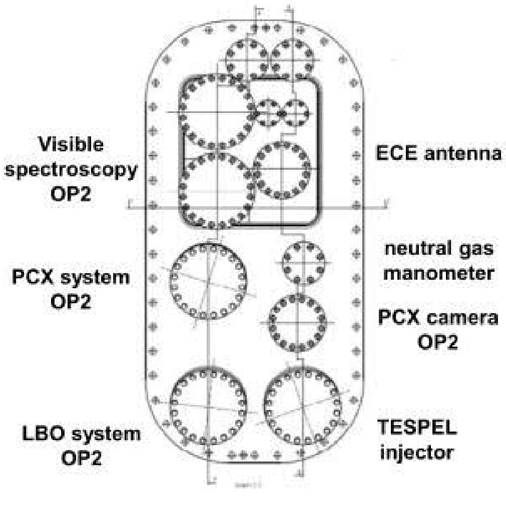

Fig. 3: Installations at AEE41 Port

3.2 Port displacements

When positioning the injector, consideration had to be given to the different load cases of W7-X. These can result in a movement of up to 5 mm between two load cases. This movement could already be detected by metrology in OP1.2a. During this survey a displacement of 14 mm against CAD of the port by inaccuracy during installation was detected [8]. In order to compensate this port displacement and to maintain the foreseen injection axis, a special flange adapter, based on the metrology data, was designed and fabricated. This Y adapter ensures that all other components remain at their CAD positions. Therefor no further as-built compensation is necessary.

3.3 Design of pump rack

A pump rack was designed to hold the turbo and dry pumps of the three differential pumping stages and their entire periphery. This rack has been designed to avoid obstructing access to the injector system and to the escape route. The frame consists of aluminum profiles and guarantees, even after construction, sufficient space for future expansion. In order to fix the turbo pumps as vibration-free as possible, all pipes are held with stainless steel pipe clamps and special flame retardant inlays. In addition, vibration dampers were installed underneath the dry pumps to further reduce vibrations. Due to its compact design, the rack has the dimensions 0.8 m x 0.3m x 1.8m and a weight of 250 kg.

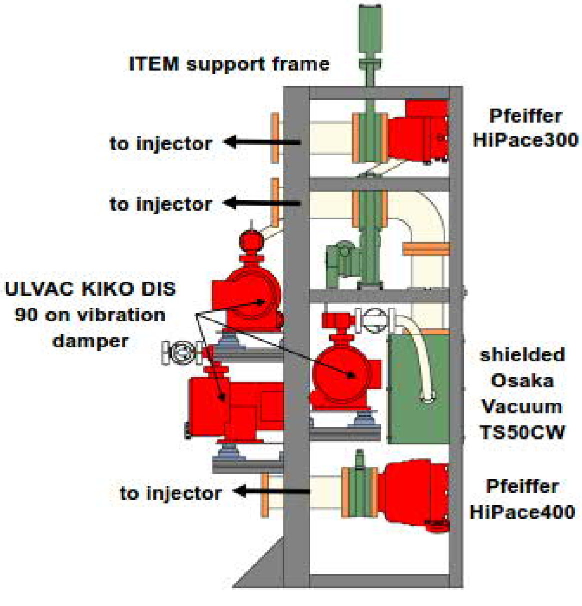

Fig. 4: Pump rack with installations

3.4 Restricted magnetic field resistivity

Within the installation space of the TESPEL injector, magnetic flux densities of up to 100 mT in the standard mode are expected. In order to ensure the correct operation of the turbo pumps, these were placed as far away as possible from the W7-X. Nevertheless, 5 mT [9] still prevails in this area, which is no problem for the Pfeiffer vacuum pumps. However, for the Osaka Vauum pump TS50CW an upper limit of 3.5 mT was assumed [10]. Thus, a magnetic shield was designed to decrease the maximum field strength in this area. The shield consists of four bolted 3 mm-thick pure iron plates (ARMCO by AK Steel).

Fig. 5: Pure iron shield

3.5 Assembly accuracy

Even the smallest deviations in the orientation of the injector components to each other can prevent the optimum functioning of the TESPEL injector. This was evident from the first laboratory tests. While only a few successful test injections were performed in a prealigned system, a 100% success rate was achieved after fine alignment [11]. In order not to interfere with this fine adjustment by subsequent installation operations, the system was fixed with additional stiffeners after alignment. Additionally, 13 reference points were attached to the support frames. These, the injection axis and the stud bolts, which connect the lower support frame with the upper support frame, were measured with a Leica Absolute Tracker AT901 (accuracy: ~ 0.5 mm). By defining the CAD position of the injection axis, the actual position of the reference points and the stud bolts in the torus hall are determined.

4. Installation and commissioning

The installation of the TESPEL injector was undertaken in 5 essential steps. First, as shown in Fig 6a, the lower support frame was positioned and fixed to the working platform according to the determined coordinates. This was done with a displacement of 2.1 mm. Afterwards the upper frame with the injector was positioned as shown in Fig 6b. A shift of less than 1 mm of the CAD position was measured. The installation of the pump rack is shown in Fig 6c. Then the connection of the injector and the pump rack was done with the three pumping lines (Fig 6d). Each line has bellows at each end to compensate inaccuracies during the assembly procedure. Finally, all peripheral connections were made. During this process, a large tolerance in the assembly caused a shift of the injector away from the W7-X, which was measured to be 4 mm by the final metrology.

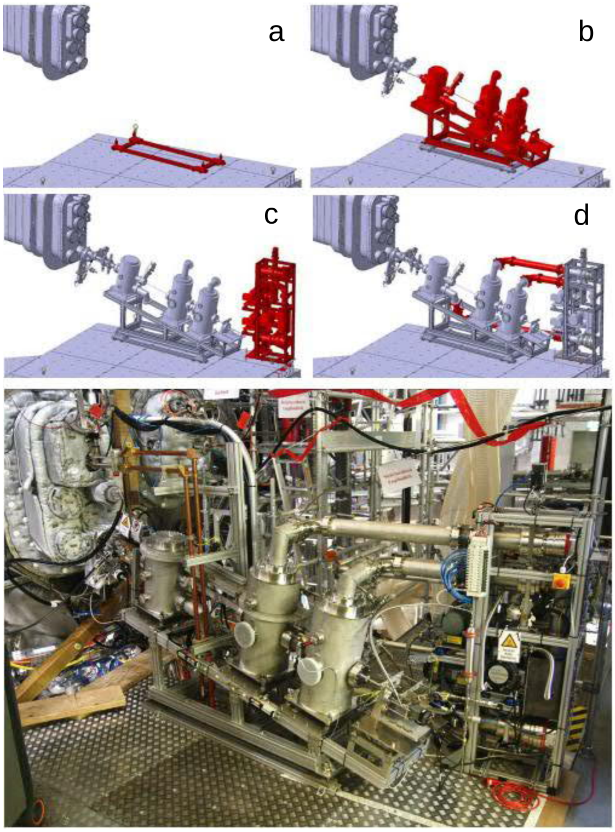

Fig. 6: Steps of TESPEL injector installation at W7-X

For the commissioning of the system, the material properties of all parts had been documented, the vacuum tightness of the system had been tested and all electronics had been checked. Additional three W7-X safety functions (local emergency stop, W7-X emergency stop and cancelation of permission) were implemented and tested for the central safety system.

5. Summary

On 31th of July 2018, two years after starting the integration, the first TESPEL was injected into a W7-X plasma. During these two years of work, the TESPEL injector design was successfully adapted to the special requirements of W7-X, the transport of the main injector parts from LHD to W7-X has been performed and the injector was successfully assembled and test in the laboratory. The alignment and the function of the system was proven by sufficient tests and the whole system was installed to W7-X. Finally, the commissioning of all necessary functions was completed and the first successful shots during OP1.2b had been detected by various diagnostics, including XMCTS, HEXOS, PHA, bolometer cameras.

Acknowledgments

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