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Vacuum leak search on Wendelstein W7-X using a numerical regression analysis

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ABSTRACT

The stellarator Wendelstein W7-X, a fusion plasma experiment, is almost ready to be set into plasma operation. Seventy superconducting coils produce the magnetic field that is required to confine the plasma. The coils are arranged in a cryostat vacuum vessel in shape of a torus. The superconductors are cooled by supercritical helium down to the nominal operating temperature between 3 K and 4 K. Before operation, vacuum leak search was performed on the machine, both the cryostat and the plasma vessel. Most of the leaks could be fixed; however not all. But the residual helium leak rate is too small to hamper the successful coil operation. A refined leak search is pending for the future, in order to localize and fix all the remaining leaks. This paper describes a numerical regression analysis, performed to localize these remaining leaks. The regression analysis could gain information on the size and position of the leak, and, at least in principle, on the hydraulic helium flow behavior inside the leak channel. It could be a helpful complement to the standard leak search techniques that had been used before.

1. Introduction and motivation

In this chapter we describe briefly the set-up of the Wendelstein W7-X cryostat, and the results of the standard leak search performed so far. A motivation is given for the refined leak search using the numerical regression analysis.

All superconducting coils for the stellarator W7-X [1–3] are situated inside a cryostat vacuum vessel [4]. Fifty of them are non-planar, twenty are planar coils. The set-up of the cryostat vessel, the arrangement of the plasma vessel, the vacuum systems and the standard leak search on them are described in detail in Ref. [5]. The technical commissioning of W7-X is described in Ref. [6]. In order to perform the standard vacuum leak search on the cryostat vessel, helium leak detectors were connected to the five vacuum pumping stations. That leak search was performed for leaks against air, the water cooling/heating pipes inside the cryostat, the helium supply pipes and all superconducting components. Helium gas puff was performed from the air side to localize leaks on the ports towards the experimental hall. The helium pressure inside the pipes was varied in time to record the time response of the leak detectors. Neon was applied in pressure steps to the water cooling pipes. Then mass spectrometers were used to measure leaking neon into the cryostat vacuum. The leak search was interrupted, after the remaining leak rate was considered as small enough to allow for the safe operation of the magnet system.

However, all pipes of the helium cooling system are connected to each other. No closing valves exist within the cryostat which can be used to separate the branches from each other. This is a consequence of the extremely narrow space situation inside the cryostat, and the requirement for a minimum number of feed-throughs for the valve actuators on the surface of the cryostat skin. In addition, each valve will increase the risk of leaks, the risk of a failure and it will increase the complexity of the system even more. For future machines it might be advisable to foresee, despite of these risks, some valves at strategic locations, for instance such that individual coils or groups of coils can be separated from each other. Grouping of the valves at positions close to the vessel wall is recommendable, if possible with a service flange close to them.

It is difficult to localize leaks within this distributed network. Nevertheless, helium pressure variations at the inlet pipes can show up to several seconds of delay time until they are measurable at more distant pipes, and sharp pressure transients at the inlet appear as temporarily smeared out response at the outlet. This hydraulic time response behavior of the entire pipe network is the

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key to the regression analysis. Fig. 1 shows a strongly simplified sketch of the coil arrangement inside the cryostat, together with the five existing helium supply lines.

Not shown in Fig. 1 are the vacuum pumps, the vessel ports, the electric cable feedthroughs, the water cooling pipes, the current bus-bars, the superconductor current joint system. One has to keep in mind that the cryostat vessel is large (volume about 420 m^3) and contains the superconducting coil with a weight of about 5 tons each, houses a very complex superconducting bus-bar system, many kilometers of different types of helium and water supply lines with thousands of welding seams, many kilometers of sensor cables and hundreds of electric cable feedthroughs.

Pressure and temperature gauges measure the helium pressure p and temperature T at the two inlet pipes, labeled by “M” and “K”, and the outlet pipes labeled by “L2N2”, “L1” and “N1”. Each coil is equipped with up to eight additional temperature gauges. No further pressure gauges or flow meters are available inside the cryostat. The helium leak detectors provide the helium leak rate q, measured for the leaks between the helium pipes, the cryostat air side and the cryostat inner vessel volume. Due to the absolute calibration of the leak detectors, the leak rates are available as a pV-flux, i.e. in units of mbar l/s. The major part of the leaks had been detected and fixed during the standard leak search campaign in the year 2014. The remaining leaks exist between the helium pipes and the cryostat vacuum. Their integral size is in the order of $q \approx 3\cdot10^{-5}$ mbar l/s at 4 bar helium pressure. In addition, leaks remain between cryostat and air with an integral leak rate of $\approx 4.6–9.6\cdot10^{-4}$ mbar l/s. Just as the leaks between helium pipes and cryostat, they turned out as too small to interfere with the coil operation. Due to the huge cryogenic pumping power of the cold surfaces, the air is immediately adsorbed on the cold surfaces and does not disturb the machine operation. Finally, the helium pipes have leaks towards the air, their leak size is unknown.

The photographs in the Figs. 2 and 3 show a part of the interior of the cryostat. Besides all installations visible, some of the mechanical supports are still missing, as well as the super-insulating multi-foil layers. Those were of particular concern, because they provide a large surface area inside the vessel, which can adsorb water and gases. In addition, they reduce the guidance values inside the cryostat vessel for the gas flow during pumping down, and for the leaking helium from the leaks on its way to the pumping stations.

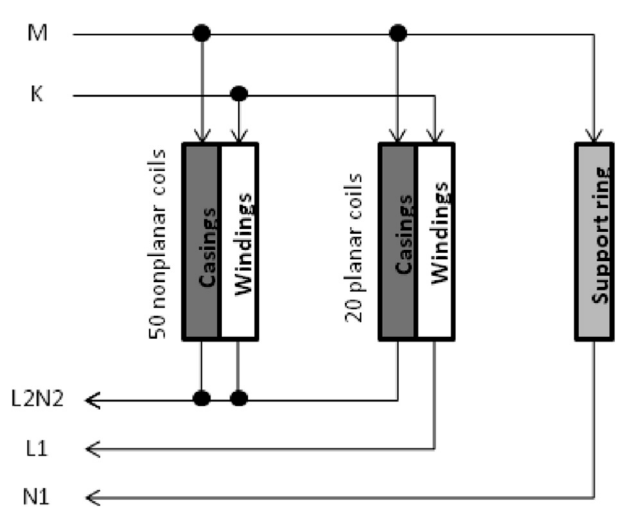

Fig. 1. Strongly simplified sketch of the superconducting coil arrangement inside the W7-X cryostat vessel. Shown are the helium supply/exhaust pipes labeled by “M”, “K”, “L2N2”, “L1”, “N1”, the sets of non-planar and planar coils including their windings and casings, and the coil support structure.

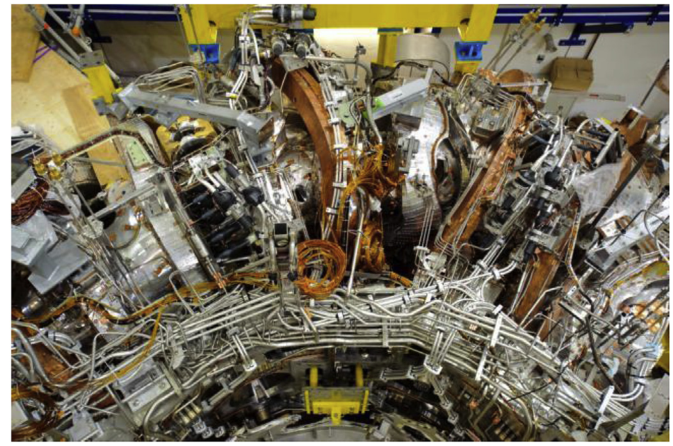

Fig. 2. Photograph of the installations inside the W7 cryostat. One can see a small part of the vacuum vessel, the nonplanar and planar superconducting coils, the conductor bus-bars and the helium tubes, the water tubes and the bundles of the sensor cables.

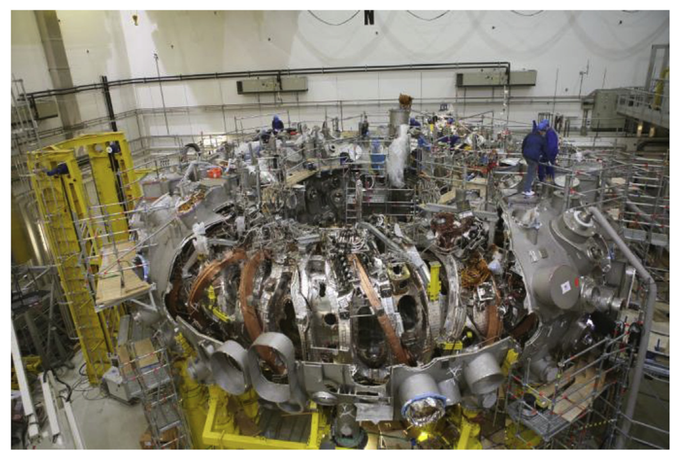

Fig. 3. Photograph of the entire torus, just a few days before the cryostat vessel was closed. One fifth of the cryostat skin remains to be closed at this stage. One can see the entire torus with the port openings, reaching through into the cryostat and plasma vessel and the nonplanar and planar superconducting coils. Still missing are some of the port tubes, some mechanical supports and the multi-foil super-insulation. The technicians give an impression on the size of the experiment.

To minimize the risk of leaks, all tube connections are welded.

Within the measurement time interval 14.02.2015 and 8.03.2015, the W7-X cryostat was cooled down from room temperature of about 290 K to the working temperature of about 4 K. For our numerical investigations, the slightly longer time interval between 4.02.2015 and 26.03.2015 is considered. This provides a few days of constant starting (room) temperature at the beginning, and at cryogenic conditions at the end of the measurement time interval. In the following, emphasis is on the measurement of the time traces $p(t)$, $T(t)$ at the five pipes “M”, “K”, “L2N2”, “L1” and “N1”. The leak detector signal $q(t)$ was taken on one single pumping station with one and the same leak detector, measured continuously throughout the entire time interval. However, the measurements were not completely undisturbed, because several technical working teams were busy on W7-X doing technical tests, system commissioning, last welding activities, water temperature excursions on the cooling water pipes etc. Further helium leak search activities in vicinity of the torus caused, from time to time, a temporal increase of the measured helium flux $q(t)$ through the remnant leaks towards the air. Therefore the measured helium