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Plasma-wall interaction, exhaust and wall conditioning studies in the stellarator Wendelstein 7-X with actively cooled high heat flux divertor and experiments with tungsten PFCs

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Wendelstein 7-X (W7-X) is an optimized stellarator with 3-dimensional twisted geometry. It is in operation since 2015 and four operational phases (OP) labeled OP1.1, 1.2a, 1.2b and 2.1 have been completed successfully. The next operational phases, i.e., OP2.2 and 2.3 are planned to begin in the fourth quarter of 2024. As for the plasma-facing components (PFCs), OP1.1 operated with five inboard graphite limiters, OP1.2a/b with ten inertially cooled island divertors called test divertor units (TDUs) and graphite baffles and heat shields. Since OP2.1 the TDUs have been replaced with the high heat flux CFC divertor and active water-cooling is introduced in all the PFCs. Long discharges up to 500 s with a total injected energy of 1.3 GJ were achieved in the recent operation phase OP2.1 [1].

Plasma-wall interactions (PWI) have been studied extensively with different magnetic configurations. Involved techniques were: installation of 18 targets in the TDU with marker layers (C layers with Mo interlayer), introduction of $^{13}CH_4$ at the end of OP1.2b, long term deposition/erosion samples at the panels, exposing samples using multi-purpose manipulator, in-situ thickness measurements with colorimetry, arc-traces analysis etc.. Post-mortem analysis was carried out on a number of retrieved components after each operation phase, i.e., targets, first wall tiles, glow discharge anodes, dust and other components. The main results are [2-4]:

(1) Net erosion occurred mainly at the divertor strike lines, net deposition took place in the vicinity of the strike line on the divertor, baffles and the first wall tiles and panels. This is somewhat different from tokamaks in which besides the strike line erosion is also seen at the first wall and deposition mainly in the divertor region.

(2) The erosion/deposition was found to be asymmetric toroidally i.e. along the ten half-modules and poloidally i.e. top and bottom sides within a module.

(3) Net erosion rate was decreased by a factor or 5-6, i.e., from 5.8-8.4 nm/s in OP1.2a to 1.1-2.5 nm/s in OP1.2b by introducing boronization which strongly reduced O and C impurities.

(4) Until the end of OP2.1, close to 400 arc-traces have been observed on the PFCs, however, the total erosion occurred from these arc-traces is found to be negligible.

(5) About 100 samples of dust and loosely bound particles/flakes were collected over two operational periods. The analysis showed a number of samples with pure C flakes or C+O co-deposited with W, Fe, Si, Cu, Cl impurities.

(6) The erosion/deposition pattern and the migration of materials are reasonably well simulated by the ERO2.0 and WallDYN-3D codes.

Experiments were conducted by introducing tungsten (area ≥ 2 m^2) as PFCs, i.e., W-coated TDU tiles (OP1.2b), bulk tungsten and tungsten-alloy ($W_{95}Ni_{3.5}Cu_{1.5}$) tiles at the baffles and W-coated graphite tiles at the heat shield [5]. At the TDU, a tungsten erosion rate of 0.13 nm/s was measured, at remaining locations no measurable tungsten erosion was found.

To improve the exhaust, ten divertor cryo-vacuum pumps were installed for OP2.1, these were tested successfully with a combined pumping speed of 70±1 m^3/s for all the 10 pumps. Pressures of the order of 10^{-4} mbar were measured in the sub-divertor region [6]. Baking, H/He glow discharge cleaning, boronization and electron-cyclotron cleanings were successfully employed for the wall conditioning before and during the plasma operations. Boronization was characterized by exposing the material probes with the estimated rate of boron layer deposition of 5 nm/h. For the next operation phase OP2.2, the tungsten area on the PFCs is increased by ca. 0.7 m^2, the first results including the experiments for the tungsten erosion will be presented.

References

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