Overview of the ICRH system for Wendelstein 7-X

K. Crombé[1,2], J. Ongena[1], Ye. O. Kazakov[1], B. Schweer[1]
[1] *LPP-ERM-KMS, TEC partner, 1000 Brussels, Belgium*
[2] *Department of Applied Physics, Ghent University, 9000 Ghent, Belgium*

Context and motivation for ICRH on Wendelstein 7-X

In future fusion reactors an important part of the plasma heating will come from fusion-born alpha particles at energies of 3.5 MeV. Good confinement of these highly energetic alpha particles is crucial to optimise the reactor performance and obtain a sufficiently large net output power. The superconducting stellarator Wendelstein 7-X (W7-X) at the Max-Planck-Institute in Greifswald, Germany, started operations in 2015. One of the essentials aims is to demonstrate fast ion confinement at volume averaged β values up to 5%, for which W7-X was optimised and which corresponds to plasma densities above 10^{20} m^{-3} [1]. To mimic the behaviour of alpha particles in a future stellarator reactor a population of fast ions with energies in the range of 30 – 80 keV is required in the core of W7-X high density plasmas. It is imperative to generate an appropriate population with both trapped and passing fast ions. This challenging task can be realised with Ion Cyclotron Resonance Heating (ICRH).

Design and challenges of an ICRH system on Wendelstein 7-X

The ICRH system for W7-X is designed by the Trilateral Euregio Cluster (TEC) team and IPP-Greifswald. It aims to deliver RF power levels up to ~1.5MW with pulse lengths up to 10s [2, 3]. The antenna is a two-strap design. Each strap is terminated by a pre-matching capacitor at one end and is short-circuited at the other end. The RF power is fed at an intermediate position. The strap width and length and the depth of the antenna box are optimised to maximise the power delivered to the plasma. For that purpose, the commercially available code CST Microwave Studio and the TOPICA code were used. A reference plasma density profile in front of the antenna was assumed. The system can operate at two frequencies: 37.5MHz, for fundamental heating of hydrogen (*H*) or second harmonic heating of deuterium (*D*) or helium-4 (^4He), or 25MHz, for the three-ion scenario using D-(^3He)-H or the equivalent ^4He-(^3He)-H [2, 3]. The surface of the antenna head is fully 3D, with a curvature in both toroidal and poloidal direction. It is matched to the 3D shape of the Last Closed Magnetic Surface (LCMS) of the standard magnetic field configuration on W7-X. In addition, the antenna can be moved radially over maximal 35 cm (with a speed ≤ 6 mm/s), and a gas puffing system is incorporated to puff gas in the region between the scrape-off layer (SOL) and the LCMS to locally improve the coupling, in particular for operation with non-standard magnetic configurations. A schematic representation of the adjustment capabilities for operation is given in figure 1.

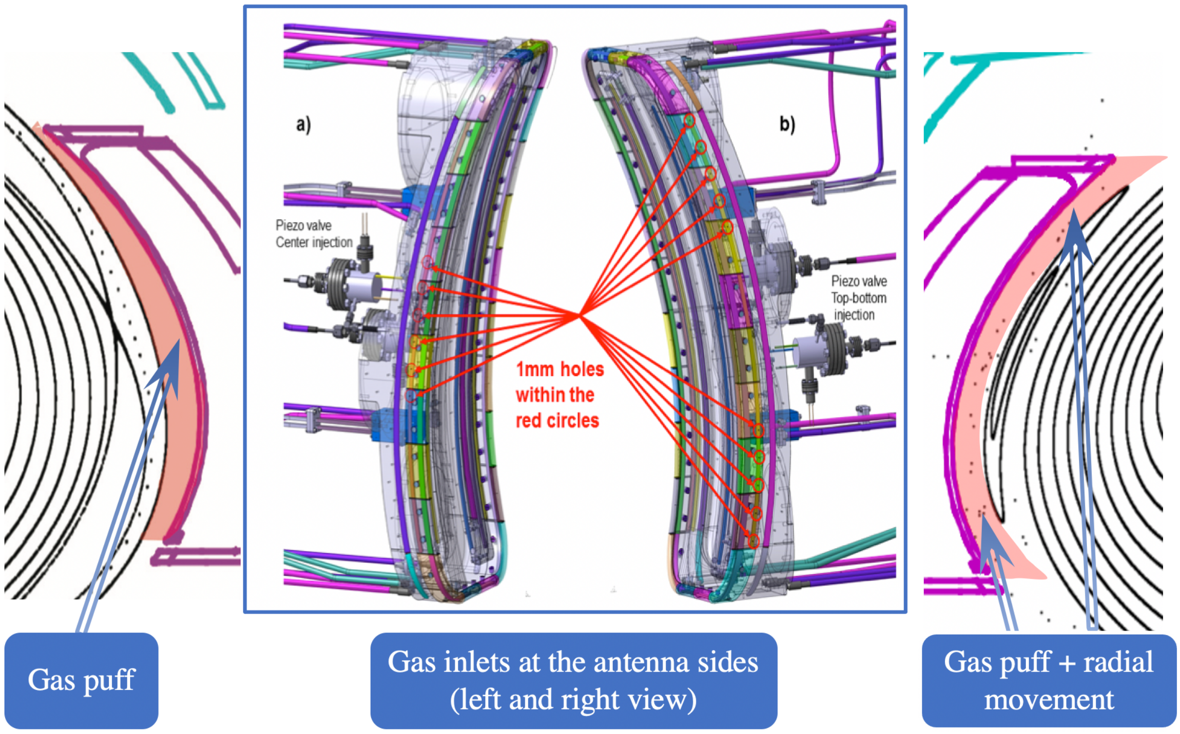

Figure1: Schematic view of the location of the gas puff system at the side walls of the antenna box (middle). The 3D shape of the antenna head is adapted to the standard magnetic configuration of W7-X (m/n =5/5). For other configurations two operational adjustments are foreseen: the antenna can move radially to bring the straps as close as possible to LCMS (heat load permitting), and the gas inlets can locally increase the density. Puffs can be made either in the middle of the poloidal cross-section of the antenna or at top and bottom (left and right).

The final antenna box and strap are made of stainless steel 1.4429, with a low μ_r (<1.01) and with a minimal cobalt content, to be compatible with W7-X operation. The 3D design and the limited space available in the port are challenging requirements from a constructional point of view. Therefore, the ICRH system has first been completely built using a prototype antenna head made of 1.4571 steel. The prototype head was needed to allow for an early detection of possible difficulties with the mechanical engineering procedures for the final design. Especially since the 1.4429 steel is more costly and much more difficult to machine.

Construction and tests

At present, the antenna is installed in a large vacuum vessel with a built-in W7-X duct mock-up, located at IEK-4 in Jülich, Germany [4] as depicted in figure 2. The test-facility is equipped with pre-matching capacitors and transmission lines, as well as all PCS7 control systems.

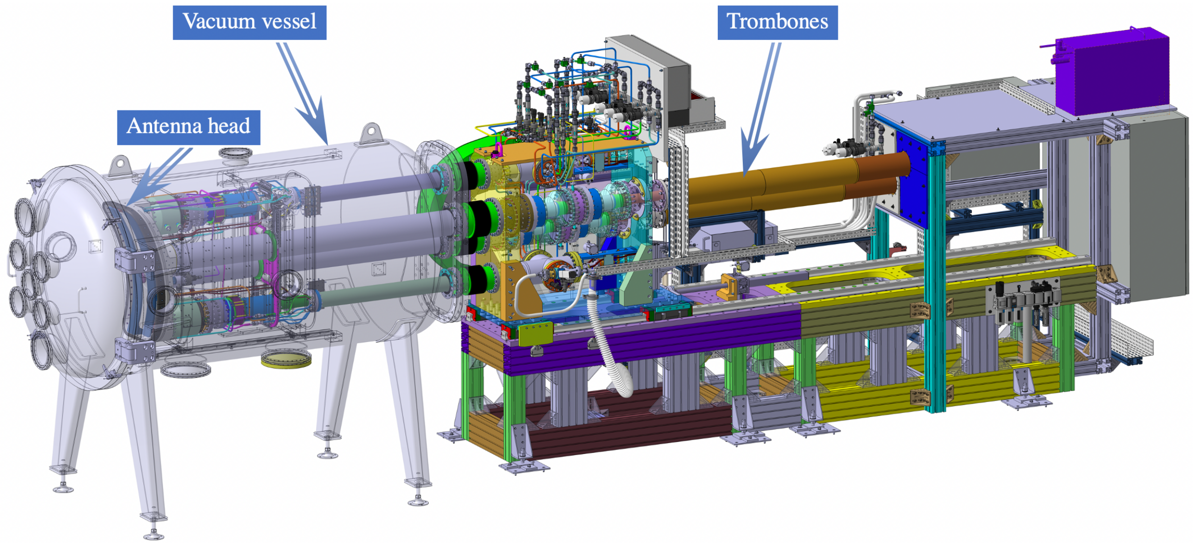

Figure 2: A schematic representation of the test facility in Jülich.

Checks of the systems for the radial positioning of the antenna have been performed successfully, including the integration of the stubs and line-stretchers in the matching unit, as well as the fine tuning of the pre-matching capacitors. Vacuum tests, leak tests, high voltage stand-off tests, electromagnetic tests and temperature tests have been finalised. In addition, low power measurements to determine the electromagnetic characteristics of the full system, have been carried out. The scattering matrices of the antenna have been measured in different configurations (i) with the capacitors mounted, (ii) with the vacuum bellows and transmission lines up to the matching unit and (iii) with the matching unit [5]. The obtained results show good agreement with the calculated scattering matrices. Short RF pulses up to ~60kW in the vacuum test tank powering one strap (with the other port terminated by an open line) have been found to be sufficient to reach ~40kV on the corresponding capacitor. The level of 40kV is the maximum rated voltage for the capacitors, the actual voltage should be less during plasma operations. Detailed calculations will be undertaken in the future using a fully curved 3-D antenna model and taking into account the plasma composition and the real density profiles from experiments, as soon as they become available. Next to these tests conducted at IEK-4 in Jülich, the construction of the transmission lines, the water-cooling system and other necessary auxiliaries is on-going at IPP-Greifswald and is progressing equally well. Figure 3 gives an overview of the actual antenna system as it is mounted at IEK-4 in Jülich. From right to left, the antenna head can be seen, followed by the antenna box, the trombones for the radial position and the W7-X flange (AEE31). On the photo the antenna is retracted from the vacuum vessel. Transport and grounding plates are indicated, as well as the cooling and gas puffing circuits and the special flow sensors, insensitive to magnetic fields, for the cooling water.

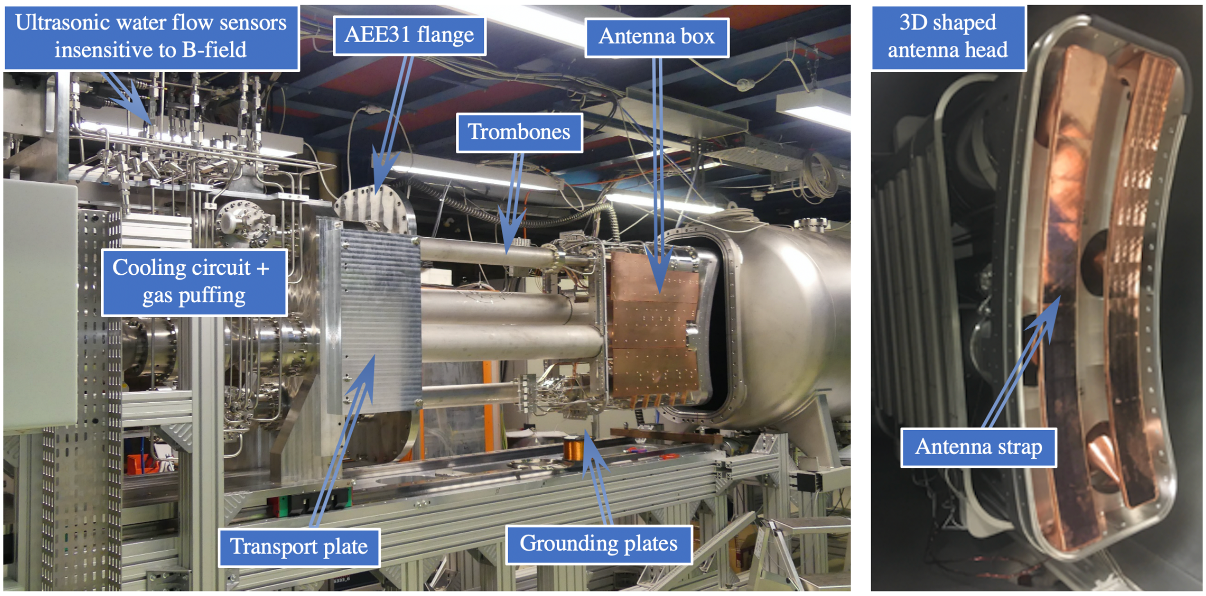

Figure 3: Present status of the antenna system at IEK-4 in Jülich, where all subcomponents are being checked before shipping to Greifswald.

Next steps

The antenna system will be delivered to IPP-Greifswald in the coming weeks. After an installation and commissioning phase, first physics operation is expected for end 2022. In the meantime, the ICRH scenario development is ongoing, as well as the exploration of the supporting measurements. In the initial operational phase, a H minority heating scenario will be applied in a ^{4}He majority plasmas. In a later stage the three-ion scenario will be added to optimise the heating efficiency and to generate a large fast ions population in the core at high densities.

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