The ICRH system for the stellarator Wendelstein 7-X Status and Prospects

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Abstract. The ICRH antenna for the stellarator Wendelstein 7-X (W7-X) foreseen for heating, fast particle production, plasma start-up and wall conditioning in W7-X, is designed to operate at powers up to ~1.5 MW in pulses of maximum 10s, in the frequency range 25-38 MHz. Construction and testing was performed in the institute IEK-4 of the Research Centre Jülich, in an intense collaboration with the Laboratory for Plasma Physics of the Royal Military Academy in Brussels (LPP-ERM/KMS). The antenna is installed in W7-X and is now in its commissioning phase. The paper will review the design, the construction and installation in W7-X including an overview of the commissioning plans for the ICRH system in the coming months**.**

ICRH FOR THE STELLARATOR WENDELSTEIN 7-X (W7-X)

One of the important aims of W7-X is to demonstrate fast ion confinement at volume averaged beta values up to 5% for which W7-X was optimised [1], corresponding to plasma densities above 10^{20} m^{-3}. Mimicking the behaviour of alpha particles in a future stellarator reactor requires a population of fast ions with energies up to 80-100 keV in the core of W7-X high density plasmas. This is a non-trivial task, but it can be accomplished using Ion Cyclotron Resonance Heating (ICRH). As there is no high density cut-off, RF power can be deposited in the plasma centre using various heating schemes, including the succesful 3-ion heating scenario [2, 3].

There is an additional important task for IRCH in W7-X, as experiments are also planned at magnetic fields of 1.7 T, lower than the nominal 2.5T of W7-X. At this lower field, plasma breakdown is not possible with the 140GHz ECRH system, but ICRH can contribute substantially by assisting the plasma breakdown.

SPECIFICATIONS AND OPERATIONAL SCENARIOS FOR THE ICRH SYSTEM AT W7-X

The final ICRH system aims to deliver RF power levels up to ~1.5 MW (depending on the density profile in front of the antenna) with pulse lengths up to 10 s [4]. The antenna will be fed by the 2 former TEXTOR RF generators, fully refurbished to be conform with current safety requirements. They operate in the frequency range 25-38 MHz. The full ICRH system consists of the antenna head and the moveable trolley in the torus hall, the 2 RF generators outside the torus hall, and the 96m long transmission lines together with the matching system that connects the RF generators to the equipment in the torus hall. An overview is given in Figure 1.

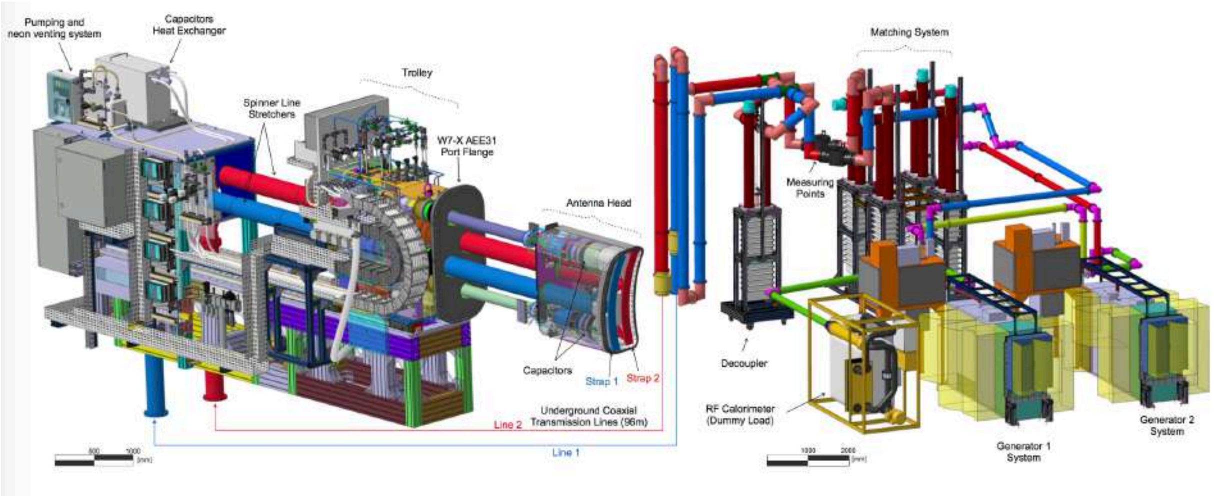

FIGURE 1. Overview of the ICRH system for W7-X. Left: the ICRH antenna trolley and antenna head in the torus hall. Right: the matching system in the ICRH hall of W7-X.The two parts are connected by 96m long transmission lines.

The main purposes of the ICRH system at W7-X are (i) plasma heating (ii) studying the confinement of fast particles (iii) assisting the plasma start-up, especially at reduced magnetic fields, and (iv) exploring ion cyclotron resonance wall conditioning (ICWC).

ICRH scenarios that can be used at the standard magnetic field of 2.5T are:

(i) minority heating of H in D or ^{4}He, at $f \approx 38$ MHz
(ii) second harmonic heating of D (or ^{4}He), at $f \approx 38$ MHz
(iii) three-ion heating scheme D-(^{3}He)-H (or ^{4}He-(^{3}He)-H) at $f \approx 25$ MHz.

At a magnetic field of 1.7T, Hydrogen minority heating in ^{4}He or D plasmas can be performed at 25 MHz.

Second harmonic D heating and fundamental H heating at low H concentrations require both the same frequency. The dominant heating scheme depends on the H concentration in the plasma. With the TOMCAT code we find that an optimal H heating occurs for ~6% H in D (or ^{4}He) and an optimal D heating at ~1% H in D (or ^{4}He). Using the 3-ion scheme, concentrations $X[^3\mathrm{He}] = n_{3He}/n_e \sim 0.1\%$ in a plasma with concentrations for H, $X[H] \sim 70\%$ and for D, $X[D] \sim 30\%$, create optimal conditions for RF power absorption by the ^{3}He ions. This should allow to create energetic ^{3}He particles with perpendicular energies of 100 keV or more in the plasma centre, even at $n_e > 2\times10^{20}$ m^{-3}. It should also be possible to create fast H particles using the (H)-D or (H)-^{4}He minority heating scheme with H concentrations less than 1%. If the plasmas are sufficiently hot, fast D (or ^{4}He) ions could also be generated using 2nd harmonic heating if the concentration of residual hydrogen ions is sufficiently low (< 2−3%), as indicated above.

The antenna consists of two straps connected to a tuning capacitor on one side and grounded to the antenna box at the other end. Pre-matching has been implemented by connecting the RF transmission lines at an intermediate position on each strap. First operations will be done with π and 0 phasing of the straps. In later operational campaigns, other phasing will be possible, and the matching system (see Figure 2) is designed to allow large variations in the relative phasing of the straps. As the mutual coupling between the closely spaced straps in the small antenna box could lead to power being transferred from one generator to the other, a decoupler has been inserted between the two lines connecting the generators to the straps [5]. Without this decoupler, a power transfer between the two straps is present for all phasings, (except for the ideal perfect case of $\Delta\varphi = 0$ or π), with a maximum transfer present for $\pi/2$ phasing as the power transfer between straps is proportional to $\sin(\Delta\varphi)$, with $\Delta\varphi$ is the difference in the phase of the RF currents in the straps. The reactance of the decoupler, put in parallel to a two-port network with admittance matrix Y, can be adjusted to cancel the reactive parts of the coupling terms of the matrix Y, and thus should be able to eliminate power transfer between the two straps at any phasing.

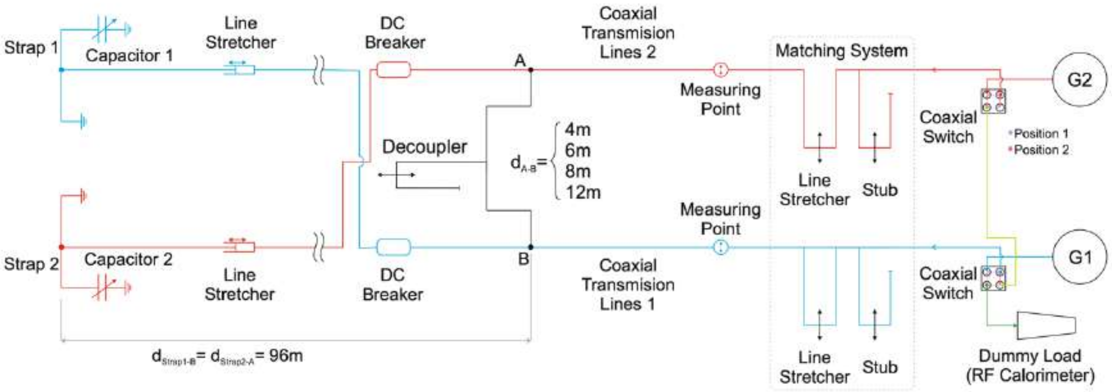

FIGURE 2. Layout of the matching system for the ICRH antenna in W7-X.

OPTIMISING COUPLING FOR THE VARIOUS MAGNETIC SCENARIOS IN W7-X: RADIAL MOVEMENT OF THE ANTENNA HEAD AND LOCAL GAS PUFF

The shape of the antenna straps is carefully matched to the 3D shape of the Last Closed Magnetic Surface (LCMS) of the standard magnetic field configuration on W7-X [6]. To optimize coupling to other magnetic scenarios that are less well matched to the shape of the antenna, the antenna can be moved radially over max. 35 cm (with a speed ≤ 3 mm/s). The antenna position is feedback controlled with as actuator the temperature of the (carbon) protection tiles. The gas injection system will provide gas in the region between the scrape-off layer (SOL) and the LCMS to locally improve the coupling along the length of the antenna strap. The gas flow (^{4}He or H) is regulated by pulse width control of the piezo valves with an operational frequency of 10 Hz. Gas is injected via rows of small holes in the graphite tiles on both sides of the antenna. On one side 6 holes are located on the top and the bottom, on the other side 6 holes are located in the middle.

DETERMINING THE DENSITY PROFILE IN FRONT OF THE ANTENNA

A fast sweep heterodyne reflectometer system operating in X-Mode [7] is installed to measure densities up to 6×10^{19}m^3 in front of the ICRH antenna at a magnetic field of 2.5T. The measurement is performed by two sectorial horn antennas which are mounted at two poloidal different positions in the back plane of the ICRH antenna. The horn antennas are made of steel 1.4429 with dimensions 40 × 3.6 × 30 mm and are located a few millimetres behind the ICRH straps to avoid difficulties with e.g., arcing in between the straps. The width of the antenna mouth is carefully selected to avoid reflections from the straps. The reflection of the side lobs of the antenna depends on the probing frequency of the reflectometer and is in the worst case −20 dB. The reflectometer utilizes two frequency bands the E-band (60 GHz to 90 GHz) and the W-band (75 GHz to 110 GHz). The cut-off density range is 0.15 ∼ $6\times10^{19}\mathrm{m}^{-3}$ which fits the expected density range in front of the antenna.

INSTALLATION OF THE ICRH SYSTEM AT WENDELSTEIN 7-X

The integration of the antenna unit and the mechanical adjustment of the antenna inside the duct of port AEE31 took place in 2021. A heavy-duty crane lifted the whole antenna system (with a weight of about 3.5 tonnes) to port AEE31 on W7-X. Eight electrically insulated adjustable feet (with a resistance of several MΩ) connect the antenna support system with the basic platform. While constantly monitoring possible electrical contacts between antenna head and duct and adjusting the antenna position to eliminate all possible contacts, the antenna head was moved into the AEE31 port. Figure 3 shows the antenna head in three positions in the plasma vessel. The assembly team at W7-X fixed the flange to the cryostat and verified the vacuum tightness. After alignment, the position of the antenna basic structure was found to be conform, within tolerances, with the CATIA design drawings. The He-leakage rate was below 1·10-9 mbar·ℓ/s at a pressure of 10^{-5} mbar. Both RF generators are installed in the ICRH hall of W7-X. The separately transported high power end tubes (Thomson, TH525) were inserted, and all electrical cabling was checked.

FIGURE 3. The radially moveable ICRH antenna in three different positions inside W7-X.

COMMISSIONING PLANS AND OUTLOOK FOR EXPERIMENTS ON W7-X

The basic functionality of the matching system and the RF generators has been confirmed in the first half of 2022. The commissioning of the antenna will start in the last quarter of 2022. In a first phase it will be performed in vacuum. In a second phase, antenna commissioning will be performed on W7-X plasmas in several steps. As soon as the basic RF functionality of the antenna head is confirmed, careful tests will be performed to determine the optimal radial position of the antenna: a compromise has to be found between good coupling and sufficiently low heating of the antenna components from particles leaving the plasma and ECRH stray radiation. Once this is determined, additional gas puffing at the antenna will an optimized, and a compromise will have to be found between the needs for coupling optimization and sufficiently low perturbations of the density control of W7-X. When the gas puff and the positioning commissioning is concluded, the ICRH power will be slowly increased, again monitoring carefully the heating of the antenna components.

It is planned that ICRH will assist plasma start-up in OP2.1, more in particular at low magnetic fields. From OP2.2 onwards, heating, fast particle generation and wall conditioning with ICRH will be explored.

CONCLUSIONS

The ICRH system for W7-X has been designed and constructed in an intense collaboration between the partners of the Trilateral Euregio Cluster (LPP/ERM-KMS, Brussels and IEK-4/Plasma Physics of the Research Centre Jülich) together with the colleagues of the Zentralinstitut für Engineering, Elektronik und Analytik (ZEA-1) and of the Max-Planck Institut for Plasma Physics in Greifswald over the past years. The antenna has been installed at the stellarator Wendelstein 7-X in the second half of 2021, together with the former RF generators of TEXTOR. The matching system is also installed and foreseen to allow a flexible phasing of the antenna straps in future experimental campaigns. Commissioning of the full system is currently ongoing, to be ready for the first experiments with ICRH, starting with plasma start-up in OP2.1, and heating, fast particle generation and ICWC in OP2.2.

ACKNOWLEDGMENTS

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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