First results with the ICRH antenna system for W7-X

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The superconducting stellarator Wendelstein 7-X (W7-X) at the Max-Planck-Institute in Greifswald began operation in 2015. ICRH has been installed on W7-X in a collaboration between the Laboratory for Plasma Physics of the Royal Military Academy (LPP-ERM/KMS) in Brussels, the Institute for Energy and Climate Research / Plasmaphysics (IEK-4) of the Forschungszentrum Jülich and the Max-Planck Institute of Plasma Physics in Greifswald. The ICRH antenna for W7-X consists of two poloidal straps. Each strap is terminated by a pre-matching capacitor at one end and short-circuited at the other, with RF power fed at an intermediate position along the straps. The antenna's shape is tailored to match the 3D shape of the Last Closed Magnetic Surface (LCMS) in the standard magnetic field configuration of W7-X, resulting in variable curvature in both toroidal and poloidal directions over the plasma-facing surface [1]. The antenna can also be moved radially up to 35 cm, and a gas puffing system is incorporated to inject gas in the region between the scrape-off layer (SOL) and the LCMS to locally improve coupling. The antenna is made of low Co content stainless steel with μ_r=1 which is the material used for the metallic parts and the vessel of W7-X. The antenna straps are coated with a thin Cu layer, and the head of the antenna box is protected by Carbon tiles. Antenna head and straps are cooled to limit the maximum temperature of the antenna material by the heat flux from the plasma and the heat generated by the RF currents in the straps The antenna was commissioned on W7-X in ^{4}He plasmas with a few percent of H as minority in February and March of 2023. Only one strap was energized, because of a faulty pre-matching capacitor (and vacuum feedthrough), leading to operation with $k_{\|} \sim 0$. Two main goals were reached: (i) operation at power levels up to 700kW at the antenna at the nominal magnetic field of 2.5T on W7-X, with clear increase of the plasma stored energy and (ii) plasma breakdown using ICRH only. After removal of the antenna from the W7-X plasma vessel only a slight discoloration of the antenna straps and box was observed, confirming the absence of major breakdowns during these first commissioning experiments.

The antenna system and RF Generators have been upgraded in recent months for operation with both straps simultaneously. Zero and pi-phasing of the antenna straps will now be possible, both at 25 and 38 MHz. The upgraded system will be commissioned in the upcoming experimental campaigns on W7-X, with start foreseen for September 2024.

Commissioning the ICRH antenna in W7-X for power deposition and plasma startup.

During ICRH operations on plasma in W7-X, the antenna was positioned between 100 and 30 mm from the Last Closed Flux Surface (LCFS). At the end of each ICRH pulse, the antenna was retracted to minimize the power load from the plasma on the antenna. During RF power tests of the ICRH system on plasma, the RF power was increased stepwise up to 500 kW for pulses with a duration of up to 3 seconds. For longer pulses, the duration was increased to 10 seconds at lower ICRH power levels (< 360 kW). A slight but definite increase in the stored plasma energy was observed in those discharges (panel 2, Fig. 3). Only a few breakdowns were observed during these experiments, primarily when the antenna was at its closest to the LCFS (~ 30 mm). These breakdowns were attributed to an increase in desorbed gas particles from the antenna surface due to the higher heat load from the plasma on the antenna structures. The limited experimental time available did not allow for sufficient repetition of pulses at constant RF power to maximize outgassing and achieve a stable power on the antenna for the full duration of the RF pulse.

Beta values of about 2% are necessary for the optimized magnetic field configuration in W7-X, which will be achieved by lowering the magnetic field to 1.7 T. However, at this lower magnetic field, ECRH at 140 GHz is not resonant, preventing its use for plasma start-up. To demonstrate the feasibility of ICRH for plasma start-up under these conditions, a series of dedicated experiments was conducted on the last day of the experimental campaign OP2.1. Stable plasma startup was observed at an ICRH power of about 300 kW (Fig. 1) for the full duration of the RF pulse. The line-integrated plasma density reached 10^{18} m^{-2}, but the density distribution in SOL and core was asymmetric. This is expected to be improved in the coming experimental campaign operating with dipole phasing at the antenna; possibilities for NBI takeover for various magnetic field configurations will then also be explored.

Impurity behaviour during ICRH operation on W7-X

The ICRH antenna is not equipped with a Faraday Screen, based on extensive experience from TEXTOR [2]. As in addition only one strap was powered during the experiments, the dominant k// of the antenna is close to zero, characteristic for monopole operation, and an expected increased interaction with the first wall. Important questions are the stability of ICRH operation, the location of the deposited power and the impurity release from the antenna structures and the first wall in W7-X. The time evolution of the impurities was monitored with VUV spectrometers and the soft X-ray diagnostic. At low RF powers (≤ 100kW), no substantial increase of impurities could be observed (Fig. 2a). At higher powers an increase is observed of Cu impurities (Fig. 2b). However the levels are rather small, and do not affect Z_{eff}. The radiated power is originated from the outboard side [3] (panel 3, Fig .3) and mainly stems from ^{4}He plasma ions in the island in front of the ICRH antenna (Fig. 4), again pointing to edge power ICRH deposition. Similarly, during startup experiments, camera and bolometer observations together with divertor spectroscopy [4] also show that the plasma is formed mainly in the island in front of the antenna, consistent with edge deposition with monopole operation ($k_{||}$ ~ 0) because of the use of only one strap of the ICRH antenna.

Two strap dipole operation should increase central power deposition and (strongly) reduce the previously observed edge effects. Comparisons between ICRH monopole and dipole operation for power deposition, impurity production and the volume of the plasma during startup using ICRH alone will be an important part of the experimental studies in the upcoming experimental campaigns on W7-X.

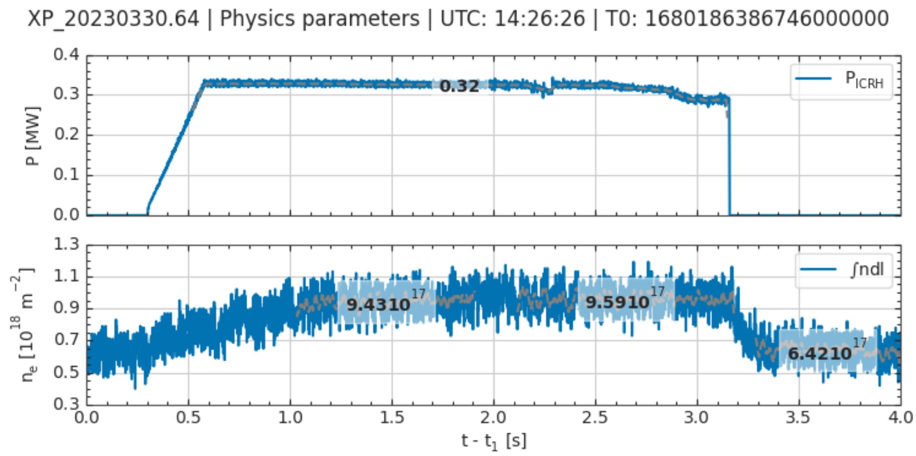

Fig.1: Illustration of ICRH plasma startup at 1.7T reached with ~ 300kW of RF power. An asymmetric plasma with a line-averaged density of ~ 10^{18} m^{-2} is present for the full ~3s duration of the ICRH power at the antenna.