DEVELOPMENT, CONSTRUCTION AND FIRST EXPERIMENTAL RESULTS OF THE ICRH SYSTEM FOR WENDELSTEIN 7-X

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Abstract

An important aim of W7-X is to demonstrate fast ion confinement at volume averaged beta values up to 5 %, corresponding to plasma densities above 10^{20} m^{-3}. To this end, an ICRH system is prepared for W7-X, with RF power up to ~1.5 MW (depending on the coupling) at frequencies between 25-38 MHz in pulses up to 10 s. Energetic ions in W7-X with energies between 50 and 100 keV mimic alphas in a reactor. To generate such a population is challenging in high-density plasmas with traditional ICRH heating scenarios and different auxiliary heating methods. Fast particles can be very efficiently generated using the H-(^{3}He)-D three-ion heating ICRH scenario, foreseen for f ~ 25 MHz in W7-X. ICRH is an ideal heating method to deposit power in the plasma center at such high density as it is not hampered by a high-density cut-off, a fundamental property of the propagation of Fast Alfvén Waves in plasmas. A two-strap ICRH has been constructed in IEK-4 and ZEA-1 of the Research Centre in Jülich, Germany and was installed in W7-X in 2021-2022. First succesful experiments took place in the first months of 2023. A total of 700 kW of RF power was launched in the plasma and in addition, ICRF assisted plasma breakdown at reduced magnetic field of 1.7 T was succesfully demonstrated. First effects of ion heating are observed with negligible increase in the impurity signals.

1. INTRODUCTION

The superconducting stellarator Wendelstein 7-X (W7-X) located at the Max-Planck-Institute in Greifswald started operations in 2015. 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}. The stellarator Wendelstein 7-X will allow in its final configuration plasma pulses with a duration of up to 30 minutes using ECRH as main heating system. It is currently equipped with nominal 10 MW ECRH for up to 30min at 140 GHz and with a 7 MW Neutral Beam Injection system in hydrogen with acceleration voltages up to 55 kV and pulse lengths up to 5 s. The nominal magnetic field is 2.5 T. Very interesting results have been obtained so far in the first experimental campaigns OP1.1 [1], OP1.2a [2] and OP2.1 [3].

To mimic the behaviour of alpha particles in a future stellarator reactor a population of fast ions with energies up to 80-100 keV is required in the core of W7-X high density plasmas [4]. This is a challenging task, but such a population can be generated with Ion Cyclotron Resonance Heating (ICRH) using 37.5 MHz for fundamental heating of H or 2nd harmonic heating of D or using the D-(^{3}He)-H or equivalently ^{4}He-(^{3}He)-H three ion heating scheme [5] at 25 MHz. ICRH is ideally suited for this task as it has no high density cut-off and RF power can thus be deposited unimpeded in the plasma centre even at the highest plasma densities envisaged on W7-X.

To reach plasmas with sufficiently high beta, needed to realize the optimized magnetic configuration on W7-X, experiments will also be carried out at magnetic fields of 1.7 T. This is lower than the nominal 2.5 T of W7-X. We demonstrated that at this lower field, ICRH can also contribute substantially to the experimental programme of W7-X by assisting the plasma breakdown.

2. ICRH FOR WENDELSTEIN 7-X

2.1. Overview of the ICRH Antenna system

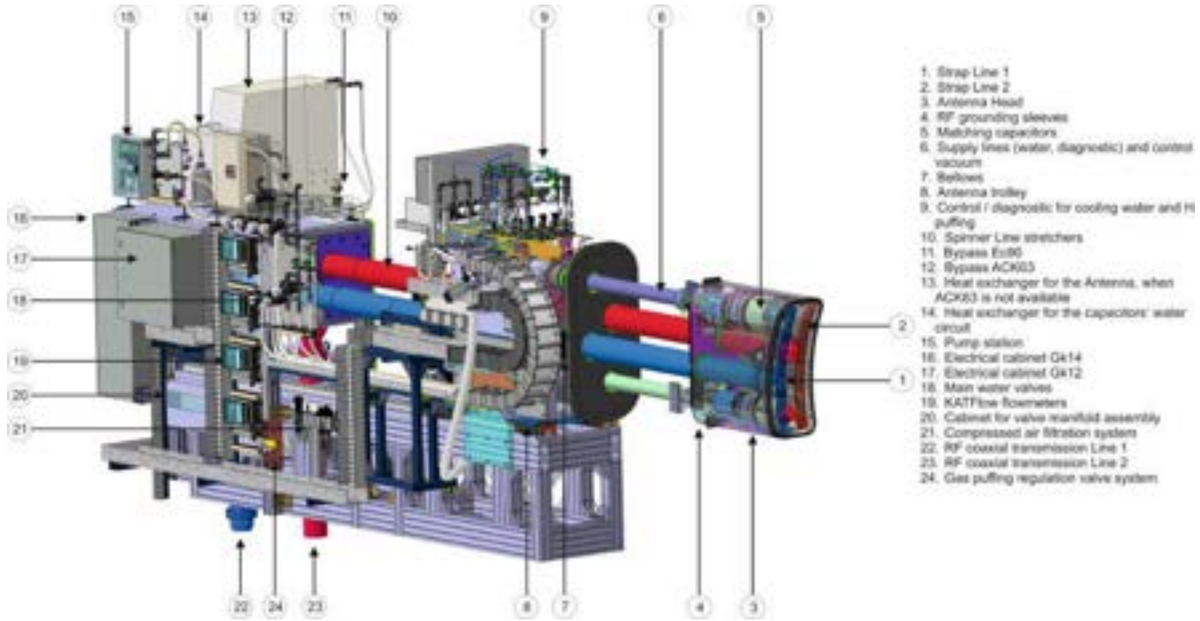

Fig. 1: Overview of the ICRH antenna system for W7-X with its main components.

The ICRH system for W7-X has been designed and constructed in the past years in an intense collaboration between the Laboratory for Plasma Physics of the Royal Military Academy (LPP-ERM/KMS), the Institute for Energy and Climate Research/Plasma Physics (IEK-4) and the Central Institute for Engineering, Electronics and Analytics (ZEA-1) of the Research Centre in Jülich, Germany under the Trilateral Euregio Cluster (TEC) umbrella together with the Max Planck Institute for Plasma Physics in Greifswald, Germany [6, 7]. The final ICRH system is designed to deliver up to about 1.5 MW of RF power (depending on the density profile in front of the antenna) with pulse lengths up to 10 s [8] in the frequency range 25-38 MHz. The system was commissioned on W7-X plasmas in operational campaign OP2.1, using only one RF generator and one powered antenna strap. We demonstrated succesfully the two main milestones: launching over 500 kW of RF power and ICRH only assisted plasma breakdown. This will be further discussed in Section 6. The system is currently undergoing an upgrade to allow the use of two RF generators and full flexibility in the relative RF current phasing of the straps for use in Operational Campaign OP2.2.

The complete ICRH system consists of the antenna head mounted on a moveable trolley in the torus hall (Fig. 1), the two RF generators outside the torus hall, and the 96 m long transmission lines together with the matching system that connects the RF generators to the equipment in the torus hall. The antenna consists of two poloidal current straps, each connected to a tuning capacitor on one side, grounded to the antenna box at the other end, and fed near the centre. In this way prematching of the antenna impedance can be achieved. Strap width and length and the antenna box depth have been optimized to maximise the power delivered to the plasma with the commercially available 3D electromagnetic code CST Microwave Studio (MWS) [9] and the TOPICA [10] code using a reference plasma density profile in front of the antenna as provided by the W7-X team.

To further optimize power coupling to the plasma the shape of the antenna is carefully matched to the 3D shape of the Last Closed Magnetic Surface (LCMS) of the standard magnetic field configuration on W7-X [11], resulting in a variable curvature in toroidal and poloidal direction over the surface of the antenna. The antenna can be moved radially over max. 35 cm (with a speed ≤ 3 mm/s), to be able to position it as close as possible to various possible magnetic configurations in W7-X, where the antenna position is feedback controlled with the temperature of the (carbon) protection tiles as actuator. In addition, to optimize coupling over the strap surface to magnetic scenarios where the LCMS has a different shape than that of the standard configuration, gas can be puffed at the outer ends of the antenna or in the equatorial region, between the scrape-off layer (SOL) and the LCMS, via gas supply lines mounted in the antenna limiter. A reflectometer system with two horn antennas is included in the antenna head to measure the density profile in front of the antenna. The final antenna system in its final form will consist of 2 RF generators, thus allowing for full flexibility in strap phasings, e.g. (0, π/2). This should maximise the power deposition according to simulations and will be tested experimentally in future campaigns.

2.2 ICRH heating scenarios for W7-X to generate fast ions

The following ICRH scenarios can be used at the standard magnetic field of 2.5T:

(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 the lower field of 1.7 T minority heating of H or second harmonic heating of D at $f \approx 25$ MHz can be used. Note that there is degeneracy between 2nd harmonic D heating and fundamental H heating at low H concentrations, as they operate at the same frequency and the dominant heating scheme depends on the H concentration in the plasma. Using the TOMCAT code we find that optimal H heating occurs for ~6 % H in D (or ^{4}He) and optimal D heating at ~1 % H in D (or ^{4}He). Optimal RF power absorption by the ^{3}He ions using the 3-ion scheme occurs for concentrations X[^{3}He] = n_{3He}/n_e ~ 0.1 % in a plasma with X[H] ~ 70 % and X[D] ~ 30 %.

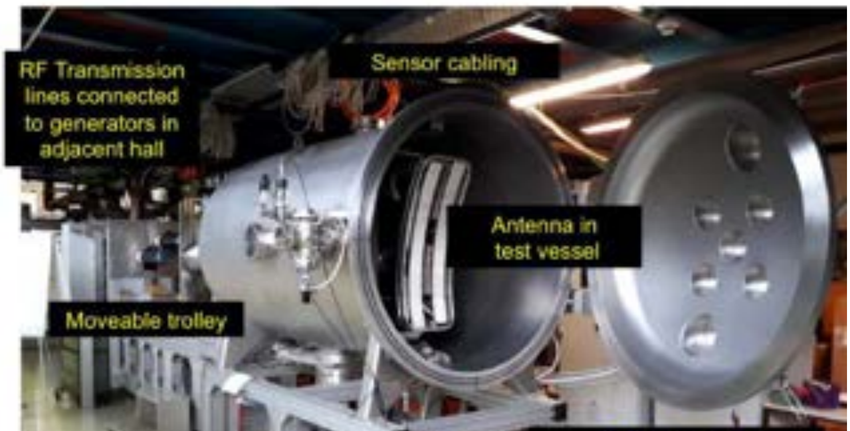

Fig. 2 : The purposely built test stand in IEK-4, Research Centre Jülich, with the antenna inside the vacuum vessel.

The big advantage of ICRH over other heating methods is the absence of a high density cut-off. This is a direct consequence of the application of Maxwell's laws for the propagation of the fast Alfvén wave in plasmas. Thus RF power can flow unimpeded to the plasma centre even at the highest densities. In addition, the three-ion scheme D-(^{3}He)-H combines a low concentration of ^{3}He (<1%) with a near 100% power transfer to this resonant ion. This results in energetic ^{3}He particles with perpendicular energies over 100 keV or more in the plasma centre, even at $n_e > 2\times10^{20}$ m^{-3}.

Fast H particles can also be obtained with the (H)-D or (H)-^{4}He minority heating scheme at H concentrations below 1 %. For sufficiently hot plasmas, fast D (or ^{4}He) ions can be generated using 2nd harmonic heating if the concentration of residual hydrogen ions is sufficiently low (< 2−3 %).

3. TESTING THE ANTENNA AND INTEGRATION INTO W7-X

After the assembly the antenna was subjected to a thorough set of tests using a purposely-built stainless steel vacuum test stand in the Institute for Energy and Climate Research/ Plasma Physics (IEK-4, Forschungszentrum Jülich, Germany). It consists (see Fig. 2) of:
(i) a large vacuum vessel with a built-in W7-X duct mock-up. To mimick the conditions expected during operations in W7-X this duct contains heating elements to heat it to 150° C and sensors to verify the temperature reached
(ii) the moveable antenna carriage (item 8, Fig. 1), the matching system and RF generator.

The complete antenna on the trolley was installed into the test stand in IEK-4 (see Fig. 2). One strap at a time was connected via transmission lines and a matching system to an RF generator. Simultaneously also all required PCS7 control equipment was tested. Tests were performed on the voltage stand-off, the radial movement of the antenna together with the vacuum feed throughs and the transmission line stretchers to adapt the radial position of the antenna. This also allowed to simultaneously check the performance of the matching system. Tests of all ancillary systems needed to control the radial positioning of the antenna, and the fine tuning of the pre-matching capacitors were also successfully concluded, in addition to vacuum tests, leak tests, high voltage stand-off tests, electromagnetic tests and temperature tests. In addition, also all PCS7 control equipment needed was tested.

Fig. 3: The ICRH antenna at three radial positions inside the vacuum vessel of W7-X. Left: inside the plasma vessel, during ICRH operations; middle: as part of the first wall of W7-X during plasma operations without ICRH; right:inside the ICRH port.

Low power measurements to determine the electromagnetic characteristics of the full system were carried out: the scattering matrices of (i) the antenna with the capacitors mounted, (ii) with vacuum bellows and transmission lines up to the matching unit and (iii) including the matching unit. All results obtained showed good agreement with the calculated scattering matrices. Short RF pulses up to ~60 kW in the vacuum test tank powering one strap (with the other port terminated by an open line) were sufficient to reach ~40 kV on the corresponding capacitor. This is the maximum rated voltage for the capacitors, and it should be less during operations on plasma. Detailed calculations will be undertaken in the future using a fully curved 3-D antenna model considering the plasma composition and density profiles from experiments as soon as they become available.

The ICRH antenna system was installed in W7-X in August 2021 (Fig. 3) and commissioning of the full system, including safety tests, were successfully finished in time for operation on W7-X plasmas in OP2.1. First experiments were carried out in February and March 2023. In these experiments only one of the two straps of the antenna could be powered due to a fault in one of the pre-matching capacitors that developed during the transport of the system between FZ-Jülich and IPP-Greifswald.

4. MATCHING AND DECOUPLER NETWORK

With the two RF generators operational in coming campaigns, arbitrary RF current phasings will become possible between the two antenna straps. The close spacing of the straps in this small antenna leads to a substantial mutual coupling and to RF power transfer between the straps, proportional to sin(Δφ), with Δφ the phase difference of the RF currents between the straps. This will then result in RF power being transferred between the generators, maximised for $\Delta\varphi = \pi/2$. To overcome this, we have included a decoupler [12] between the two lines connecting the generators to the straps, consisting of two sections of ~$\lambda/4$ lines connected to an adjustable reactance. The reactance of the decoupler, put in parallel to the two-port network with admittance matrix Y, can be adjusted to cancel the reactive parts of the coupling terms of the matrix Y.

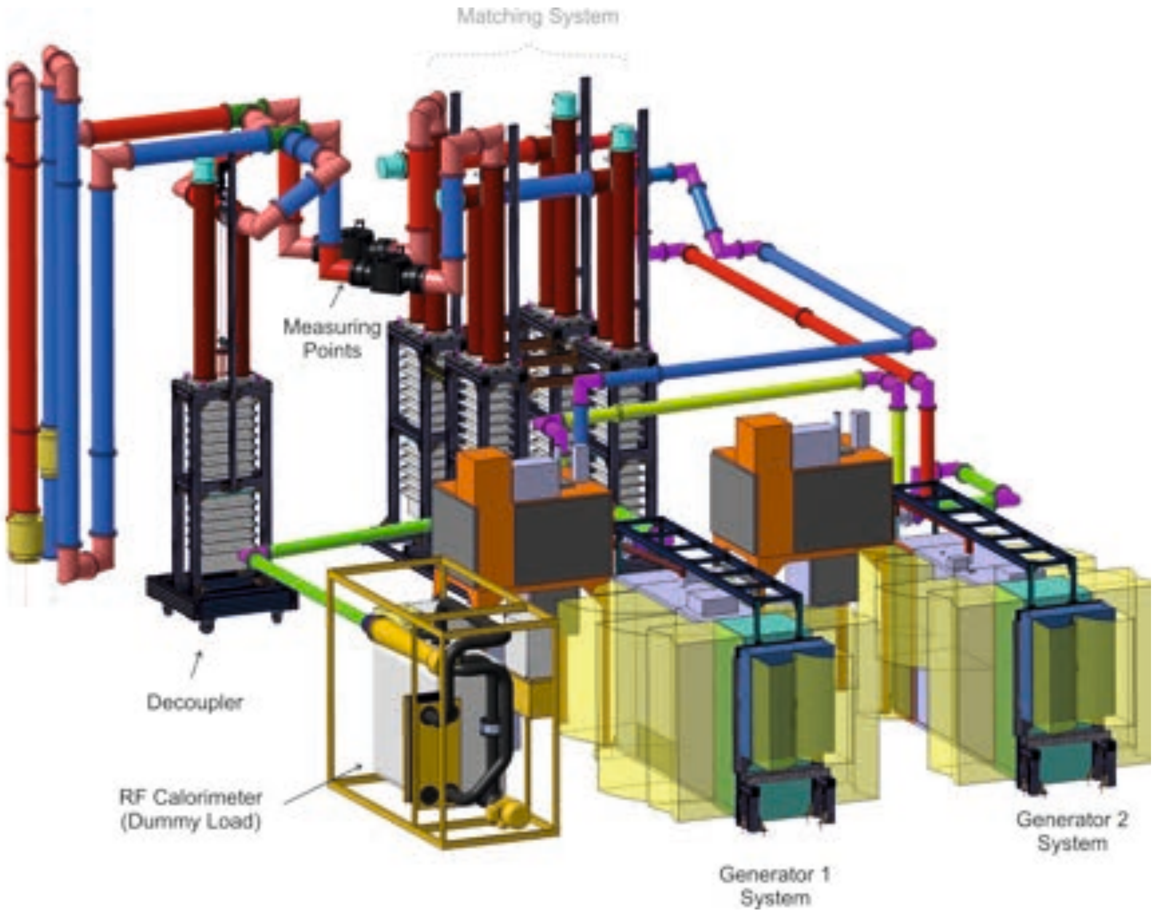

Fig. 4: 3D view of the RF system outside the torus hall in W7-X including the matching/decoupler network

5. POWER CAPABILITY OF THE ANTENNA SYSTEM

The power capability of the ICRH system depends not only on the antenna, but also on limitations in the other components, i.e. the RF voltage and current limitations in the tuning capacitors (item 3, Fig. 1), the antenna vacuum feeder lines, vacuum window, the transmission line (TL) line stretchers (item 10, Fig. 1) and the 6" and 9" transmission lines. A detailed layout of the complex matching/decoupler network, including the decoupler, is shown in Fig. 4. The transmission lines are filled with air at atmospheric pressure. Each of these components has its specific limitations in voltage and current: maximum 35 kV/700 A for the 9" lines, 23 kV/462 A for the 6" lines and TL line stretchers, 53 kV/1060 A for the antenna vacuum feeding lines, and 40 kV/800 A on the tuning capacitor in the antenna. The maximum power that can be coupled to the plasma at each frequency and phasing has been calculated taking into account the operational limits of these components, starting from the scattering matrix calculated by TOPICA for the W7-X antenna facing a reference electron density profile. These calculations show that RF powers of max. ~2 MW could be delivered for (0,0) phasing and up to ~1 MW for (0,π) phasing, confirming earlier calculations [13].

6. COMMISSIONING THE ANTENNA ON W7-X PLASMAS AND FIRST EXPERIMENTAL RESULTS

The complete ICRH system was commissioned on W7-X plasmas in February and March 2023. In total four sessions were attributed for operation with the ICRH antenna on W7-X plasmas. In the first two sessions, the antenna was used as a piggy-back experiment in other leading experimental programs and were dedicated to test the radial movement and positioning of the antenna head in the torus, in addition to verifying the communication protocols and trigger sequences between the central W7-X control system and the ICRH system. A pre-trigger, set at 60 s before the main trigger at t_0, started the radial movement of the antenna and during the ICRH phase of these piggy-back experiments, the nearest position with respect to the LCMS was 30 mm, corresponding to 140 mm from the W7-X first wall. At the end of the ICRH pulse the antenna was retracted to minimise power load from the plasma.

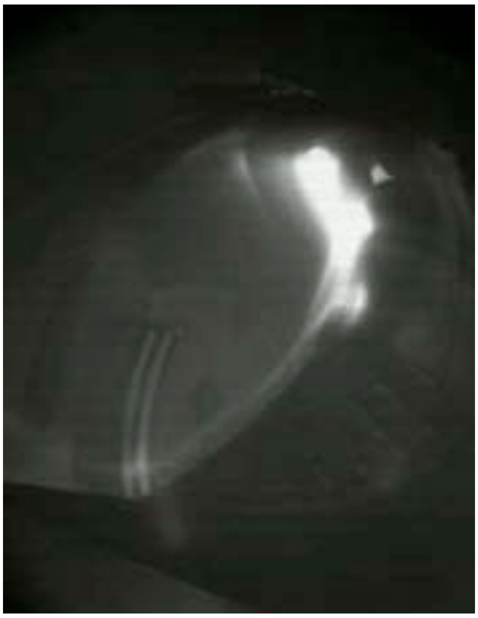

Fig. 5: The ICRH antenna, visible in the reflection of H_α light during high power experiments on W7-X plasmas. Limited breakdown activity and minimal first-wall interaction was observed. Note that this has no Faraday Screen.

The next two sessions were committed for dedicated ICRH operation on W7-X plasmas. In these experiments only one of the two straps of the antenna was powered, because of the broken pre-matching capacitor, leading to operation with $k_{||} \sim 0$. At session three on 23 February 2023 the launched ICRH power was increased in steps to 500 kW for durations of about 3 s. The longest ICRH pulse duration was about 10 s at 360 kW. A limited number of breakdowns were observed, mainly when the antenna was positioned closer to the LCFS.
There was not sufficient time to condition the outer surfaces of the antenna box and the strap surfaces using RF-power, and a higher power load from the plasma at those close positions might have caused an increase of desorbed gas particles from the antenna surface, explaining the small increase in breakdowns.

On 30 March 2023, a fourth full day was reserved for ICRH operations on plasma. In a first series of experiments at 2.5 T the launched RF power was further increased to 700kW. Although there were no technical limitations to launch even more power, time constraints forced us to switch to testing ICRH assisted plasma breakdown. This was done in a first series of experiments at a magnetic field of 2.5 T and in a second series at 1.7 T. Plasma breakdown was successfully demonstrated at 1.7 T with 300 kW of ICRH power. The line averaged electron density reached $\sim 1\times10^{18}$ m^{-3}, which is sufficiently dense to maintain the plasma using NBI when ICRH is stopped. This demonstrates that the planned high-β program in future experimental campaigns at 1.7 T could be run using ICRH only assisted plasma breakdown.

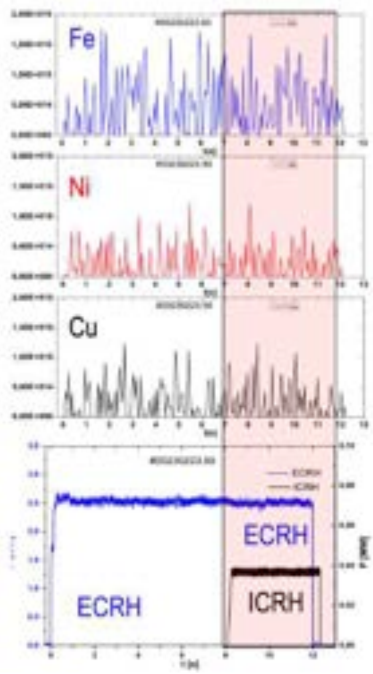

Fig.6: No difference seen in impurity signals between ECRH only and combined ICRH and ECRH heated phases in W7-X pulses.

Despite the unfavourable heating conditions ($k_{||} \sim 0$), a clear increase of the plasma stored energy was seen at constant electron density, pointing to an increase in the ion temperature. The Faraday Screen has been left out in this antenna, based on extensive successful experience using antennae without Faraday Screen on TEXTOR [14]. No edge interaction could be observed (an example is shown in Fig. 5), and the impurity signals remained low when ICRH was added on top of ECRH (see Fig. 6).

After removal of the antenna from the W7-X plasma vessel, no damage from arcs etc. could be observed on the antenna straps or the antenna box, except for a slight discoloration of the antenna box (see Fig. 7)

6. CONCLUSIONS

ICRH is an ideal heating system to deposit power in the plasma centre, even at the highest densities, as it is not hampered by a high-density cut-off, a fundamental property of the propagation of the Fast Alfvén Wave in plasmas. The antenna was installed in W7-X in August 2021 and succesfully commissioned in the first months of 2023, with the demonstration of the two main milestones: launching high power to the plasma (up to 700 kW) and ICRF assisted plasma breakdown at a magnetic field of 1.7 T.

In future campaigns the antenna will be used for plasma heating, generation of fast particles, plasma breakdown and wall coniditioning. Various ICRH heating schemes for plasma heating and the creation of fast particle populations can be used. The three-ion heating scheme uses a low concentration (<1 %) of a minority ion (e.g. ^{3}He for W7-X) in a plasma consisting of two majority ions (e.g. H and D for W7-X). This allows to substantially increase the amount of absorbed RF power per resonant ^{3}He ion. Using the D-(^{3}He)-H scheme on W7-X the ^{3}He minority ions should acquire energies up to 100 keV or higher, even at the highest plasma densities. The efficiency of the D-(^{3}He)-H scheme for generating fast ^{3}He ions in W7-X is also ~30 times higher than traditional minority heating scenarios (H minority or second harmonic D in hot plasmas) as they require minority ion concentrations of a few % to guarantee good core absorption of RF waves.

Fig. 7: The ICRH antenna after the first high power commissioning on W7-X plasma's. Only a slight discoloration could be seen in the antenna box.

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