# The ICRH System for the Stellarator Wendelstein 7-X

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**Abstract.** An important test for W7-X is to demonstrate confinement of fast trapped ions at volume averaged beta values up to 5%, corresponding to plasma densities above $10^{20}$ $m^{-3}$. Energetic ions in W7-X with energies $50 < E < 100$ keV mimic alphas in a reactor. To generate such a population is a challenging task in high-density plasmas but this can be efficiently realized with the H-($^3$He)-D three-ion heating ICRH scenario, foreseen for f ~ 25 MHz in W7-X. An ICRH system is prepared for W7-X, expected to deposit RF powers up to ~1.5 MW (depending on the coupling) at frequencies between 25-38 MHz in pulses up to 10s. A two-strap ICRH antenna for W7-X is under construction. Each strap of the antenna is on one side connected to a tuning capacitor and grounded to the antenna box at the other end. A prematching has been implemented by connecting the RF transmission lines at an intermediate position on each strap. The main dimensions of straps and antenna box have been optimized to maximise the power delivered to the plasma, using the reference plasma density profile in front of the antenna, provided by the W7-X team. A dedicated test stand is under construction to check the main functional tests of the full ICRH antenna system.

## INTRODUCTION

The superconducting stellarator Wendelstein 7-X at the Max-Planck-Institute in Greifswald started operations in 2015. It will allow in its final configuration plasma pulses of up to 30 minutes duration with ECRH as main heating system with up to 10 MW steady state at 140 GHz. Very interesting results have been obtained so far in the first campaigns OP1.1 [1] and OP1.2a [2]. An important aim of W7-X is to demonstrate confinement of trapped fast ions at volume averaged beta values up to 5% for which W7-X was optimised [3]. These high beta values correspond to plasma densities above $10^{20}m^{-3}$. Mimicking the behaviour of alpha particles in a future stellarator requires the presence of energetic ions with energies in the range ~100 keV in the core of W7-X high-density plasmas [3]. This is a challenging task, but Ion Cyclotron Resonance Heating (ICRH) is ideally suited for this task as it has no high density cut-off. RF power can thus be deposited unimpeded in the plasma centre using various heating schemes, including the newly demonstrated 3-ion heating scenario [4, 5].

## ICRH FOR WENDELSTEIN 7-X

### Main specifications of the ICRH antenna system in construction

A schematic overview of the ICRH system for W7-X, aiming at delivering RF power levels up to ~1.5 MW in the frequency range 25-38 MHz with pulse lengths up to 10 s [6], is shown in Figure 1. The antenna consists of two straps connected to a tuning capacitor on one side and grounded to the antenna box at the other end. An approximate equivalent electrical schema of each antenna strap (with length $l_{strap} < \lambda/4$, $\lambda$ being the length of the launched RF waves) together with the tuning capacitor consists of an inductance in parallel with a variable capacitor, as shown in Figure 2. For a given input voltage to the strap, the maximum voltage in the RF transmission lines is determined by the pre-matching, done by positioning the connection of the transmission lines ('tap') at a fraction $\alpha X_L$ from of the total strap inductance $X_L$ with $0 < \alpha < 1$. The voltage at the position of the tap is then $\alpha V$, with V the maximum allowable voltage on the antenna. All geometrical quantities of the antenna have been optimized to maximise the power delivered to the plasma with the commercially available 3D electromagnetic code CST Microwave Studio (MWS) [7] and TOPICA [8] using a reference plasma density profile in front of the antenna as provided by the W7-X team.

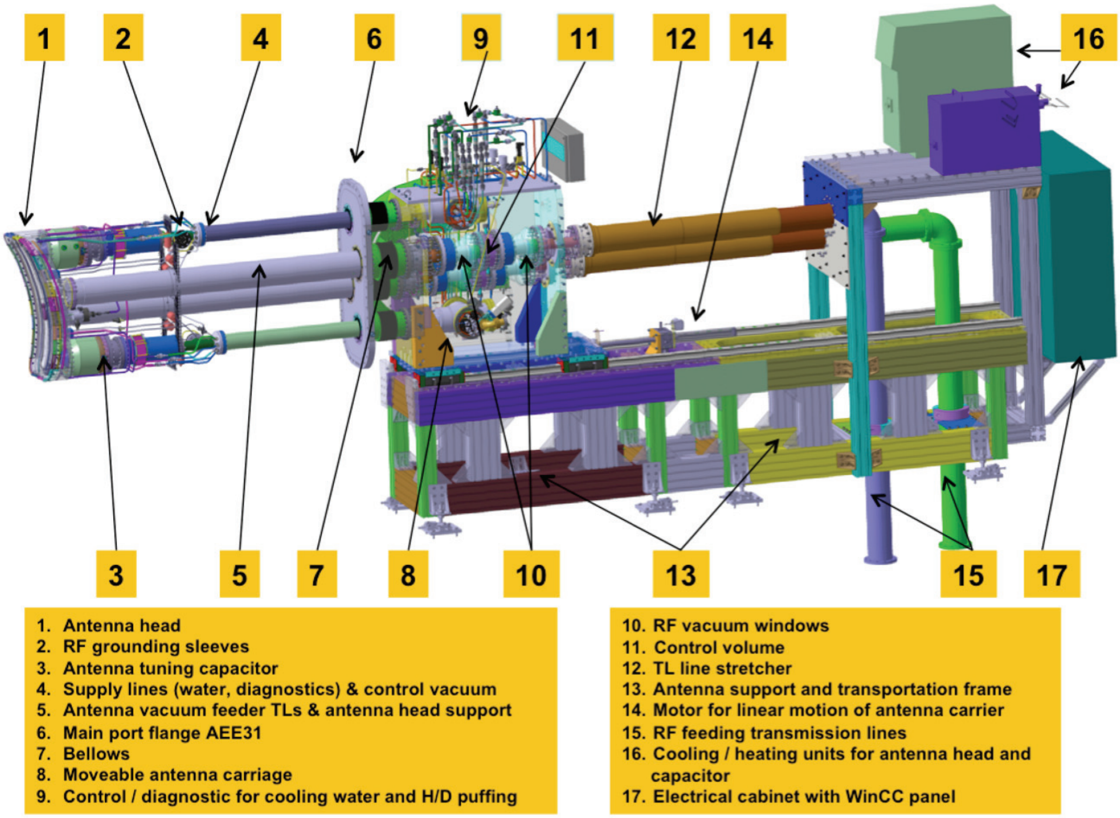

**FIGURE 1**: Overview of the ICRH antenna system for W7-X with main components highlighted.

To further optimize coupling (i) 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 [9], (ii) the antenna can be moved radially over max. 35 cm (with a speed ≤ 3 mm/s), (iii) gas puffing is foreseen in the region between the scrape-off layer (SOL) and the LCMS to locally improve the coupling. The ICRH system in its final form will consist of 2 RF generators (25MHz<f<38MHz) connected via the matching system and transmission lines to the antenna, allowing for simultaneous operation of the two generators and thus full flexibility in strap phasings, e.g. $(0, \pi/2)$, maximising power deposition. The construction of the system is in full swing, in view of first ICRH pulses in W7- X in OP2 [10].

## ICRH scenarios for fast ion generation in W7-X

ICRH scenarios applicable at W7-X at 2.5T are: (i) minority heating of H in D or $^4$He, at $f$=38 MHz, (ii) second harmonic heating of D (or $^4$He), at $f$=38 MHz and (iii) three-ion heating scheme D-($^3$He)-H (or $^4$He-($^3$He)-H) at $f$=25 MHz. Note the degeneracy between 2nd harmonic D heating and fundamental H heating at low H concentrations; they operate at the same frequency and the dominant heating scheme depends on the H concentration in the plasma. Using the TOMCAT [11] code we find (Figure 3) 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). Figure 4 gives the conditions for optimal RF power absorption by the $^3$He ions using the 3-ion scheme, showing that nearly total RF power absorption occurs for $X[^3He] = n_{3He}/n_e \sim 0.1\%$ in a plasma with X[H] ~ 70% and X[D] ~ 30%.

Fast H particles can 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%), as discussed above. 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 species. This results in energetic $^3$He particles with perpendicular energies over ~100 keV in the plasma centre, even at $n_e > 2\times10^{20}$ m$^{-3}$. The expected $^3$He ion energies due to acceleration by RF heating can be estimated using the Stix formula [12] for the minority ion distribution function heated at the fundamental cyclotron frequency.

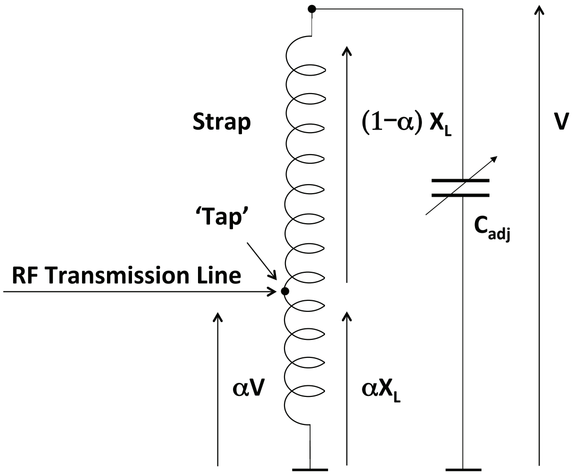

**FIGURE 2**: Pre-matching using a tuned resonator with feeding at a 'tap' along the strap. The maximal voltage V in the system is located at the capacitor and the maximum feeding line voltage is reduced to $\alpha V < V$. $X_L$ is the total strap inductive reactance and the tap is placed at a position such that the reactance between tap and grounding is $\alpha X_L$.

Applied to the D-($^3$He)-H 3-ion scheme [13] we find ~90-120 keV for the energy of the minority ions at the optimal concentration of X[$^3$He] ~ 0.1% (see Figure 3). The efficiency of the 3-ion heating scheme has also been estimated with the Fokker-Planck code SSFPQL [14] for (i) the 3-ion scenario and (ii) (H)-D minority heating with X[H]=3%, at $T_e$=3keV, $n_e=2\times10^{20}$ m$^{-3}$ and assuming $\langle P_{RF}\rangle$=0.5MW/m$^3$. Comparing the number of fast ions that reach an energy above 50keV in the steady-state ICRH generated fast ion distribution, we find $4\times10^{16}$ $^3$He ions/m$^3$ for the 3-ion scenario D-($^3$He)-H and $1.3\times10^{15}$ fast H ions/m$^3$ for the (H)-D minority heating scenario. The 3-ion scenario is thus about 30 times more effective in generating fast ions with energies above 50keV under conditions as expected at high beta in W7-X. A similar ratio was found in [5], using a more detailed ICRH modeling. Let us also note that ICRH heating will cause fast particles with a dominant $v_\perp$ velocity component, resulting mostly in trapped fast particles. These particles need to be confined in the central zone of the plasma and this represents an important test for the optimized configuration of W7-X.

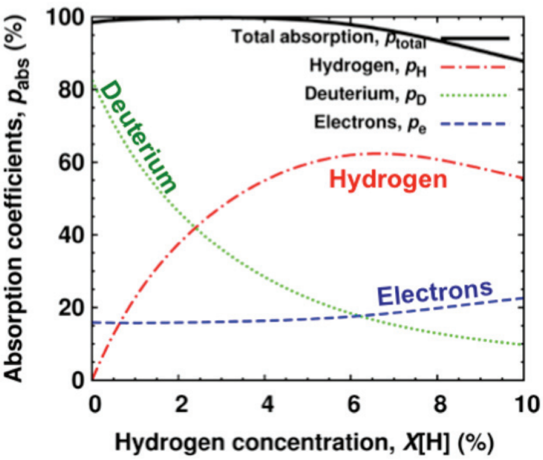

**FIGURE 3** Illustration of the competition between fundamental H and second harmonic D ICRH heating at 38MHz in (H,D) or (H, $^4$He) plasmas in W7-X for 2.5. RF Power is dominantly deposited to D or H ions depending on the hydrogen concentration in the plasma.

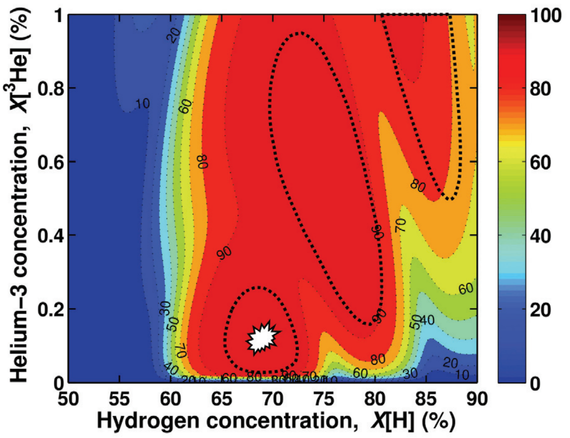

**FIGURE 4**: Contour plot of the fraction (in %) of the RF power absorbed by the $^3$He ions as a function of the H and $^3$He concentration for the D-($^3$He)-H heating scheme at 25MHz in W7-X.

## Power Capability of the Antenna System

The amount of power that can be deposited by the ICRH system depends not only on the antenna, but also on limitations in all components of the ICRH system. Each of these components has its specific limitations in voltage and current maximum. 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. ~ 2MW could be delivered for (0,0) phasing and up to ~ 1MW for $(0,\pi)$ phasing, confirming earlier calculations [15].

## Test stand for the ICRH system

A test stand is being assembled to check the main properties of the ICRH antenna. It consists of (i) a large vacuum vessel with a built-in W7-X duct mock-up (including heating elements and thermo sensors), (ii) a moveable antenna carriage together with the matching system and one RF generator. This should allow to check (i) the vacuum compatibility; (ii) voltage standoff of the antenna; (iii) the cooling properties and functioning of the thermo-sensors; (iv) the radial movement of the full system; (v) the functioning of the control cubicles (vi) the use of the matching system. The scattering matrices of the antenna head have been determined [16] and first tests of the full system are foreseen in the coming months.

## CONCLUSIONS

An ICRH system for W7-X is under construction in a collaborative effort between IEK-4, Forschungszentrum Jülich and LPP/ERM-KMS, Brussels, and IPP Greifswald for implementation in W7-X starting after the installation of an actively cooled divertor (OP2), with first experiments planned in 2021. It is designed to couple 1-1.5MW of ICRH power for frequencies in the range 25-38MHz. Fast particles can be generated using the H-($^3$He)-D three-ion heating scheme. Using the Stix formula [11] we find that we should be able to generate fast $^3$He particles with energies up to ~100 keV even at the highest plasma densities. The efficiency of the D-($^3$He)-H 3-ion 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). Construction and implementation of the ICRH system for W7-X is ongoing, aiming at delivering ICRH power to W7-X in OP2.

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## ACKNOWLEDGEMENTS

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.