PREPARING THE ICRH SYSTEM FOR THE WENDELSTEIN 7-X STELLARATOR

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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 \(10^{20} \text{ m}^{-3}\). 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 \(50 < E < 100\) 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. However, fast particles can be very efficiently using the H-("He)-D three-ion heating ICRH scenario, foreseen for \(f \sim 25\) 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 Alfven Waves in plasmas. A two-strap ICRH antenna is under construction for W7-X. Each strap is on one side connected to a tuning capacitor (15-200 pF) 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 in IEK-4 / FZJ to perform main functional tests on the antenna.

1. INTRODUCTION

The superconducting stellarator Wendelstein 7-X at the Max-Planck-Institut 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]. A wealth of interesting results can be expected in future campaigns with
increased heating power and a growing set of diagnostics. An important aim of W7-X is to demonstrate fast ion confinement at volume averaged beta values up to 5% for which W7-X was optimised [3]. These high beta values correspond to plasma densities above $10^{20} \text{ m}^{-3}$.

Mimicking the behaviour of alpha particles in a future stellarator requires the presence of energetic ions with energies in the range $\sim 100 \text{ keV}$ 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].

2. ICRH FOR WENDELSTEIN 7-X

2.1. Overview of the ICRH Antenna system

The ICRH system under construction for W7-X aims at delivering RF power levels up to $\sim 1.5 \text{ MW}$ in the frequency range 25-38 MHz with pulse lengths up to 10 s [6]. The antenna consists of two straps connected to a tuning capacitor on one side and grounded to the antenna box at the other end. A pre-matching has been implemented by connecting the RF transmission lines at an intermediate position on each strap. 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) [7] and the TOPICA [8] code using a reference plasma density profile in front of the antenna as provided by the W7-X team.

![Fig. 1: Overview of the ICRH antenna system for W7-X, with its main components.](image-url)
To further optimize coupling 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], resulting in a variable curvature in toroidal and poloidal direction over the surface of the antenna. 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 $\leq 3$ mm/s), where the antenna position is feedback controlled with the temperature of the (carbon) protection tiles as actuator. In its final specifications a gas puffing system is foreseen to puff gas in the region between the scrape-off layer (SOL) and the LCMS to locally improve the coupling, and a reflectometer system to measure the density profile in front of the antenna. The antenna system in its final form will consist of 2 RF generators, thus allowing for full flexibility in strap phasings, e.g. $(0, \pi/2)$, maximising power deposition. An overview of the system is presented in Fig.1. The construction of the system is in full swing, in view of first ICRH pulses in W7- X in OP2 [10].

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 $^3$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.

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 (Fig. 2a) that optimal H heating occurs for $\sim 6\%$H in D (or $^4$He) and optimal D heating at $\sim 1\%$H in D (or $^3$He). Fig. 2b 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 $X[^3\text{He}] = n_{^3\text{He}}/n_e \sim 0.1\%$ in a plasma with $X[H] \sim 70\%$ and $X[D] \sim 30\%$.

Fig.2a: Illustration of the competition between fundamental H and second harmonic D ICRH heating at $\sim 38$MHz 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.

Fig.2b: 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 $\sim 25$MHz in W7-X.
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-(³He)-H combines a low concentration of ³He (<1%) with a near 100% power transfer to this resonant ion. This results in energetic ³He particles with perpendicular energies over 100 keV or more in the plasma centre, even at nₑ > 2×10⁻²⁰ m⁻³, as shown below.

Fast H particles can also be obtained with the (H)-D or (H)-⁴He minority heating scheme at H concentrations below 1%. For sufficiently hot plasmas, fast D (or ⁴He) ions can be generated using 2⁰th harmonic heating if the concentration of residual hydrogen ions is sufficiently low (< 2–3%), as discussed above.

3. GENERATION OF FAST ION POPULATIONS IN W7-X USING ICRH

Mimicking fast ⁴He fusion ions in a future Helias type reactor corresponds to creating a fast ion population between 50 and 100keV in W7-X [11]. A good estimate of what can be reached using ICRH can be obtained using the formula derived by Stix [12] for the minority ion distribution function heated at the fundamental cyclotron frequency, applied here to the D-(³He)-H 3-ion scheme [13]. The energy of the accelerated minority ions is given by:

\[
E_{\text{mino}} = k_0 T_e \xi Stix_{\text{mino}} \quad \text{where} \quad \xi Stix_{\text{mino}} = \frac{0.18 \sqrt{T_e} \langle P_{RF} \rangle}{n_e X[³He]} \]

with k₀ of the order unity, nₑ the electron density (10⁻²⁰ m⁻³), X[³He] the concentration of ³He as defined above, <P_{RF}> the volume averaged RF power density (MW/m³) seen by the resonant ions (in the plasma centre), and Tₑ the electron temperature in keV. Applying this formula for Tₑ = 3 keV, central volume averaged <P_{RF}> ~ 0.3-0.5MWm⁻³ (estimated using 1-1.5MW of ICRH coupled into the central part of the plasma), and nₑ = 2 10⁻²⁰ m⁻³ one finds:

\[
\xi Stix_{\text{mino}} \approx 0.04 \frac{X[³He]}{X[⁴He]} \]

For the optimal concentration of X[³He] ~ 0.1% (see Fig. 2b) under those conditions, we find that \(\xi Stix_{\text{mino}}\) ~ 30 – 40, or in other words, ~90-120 keV for the energy of the minority ions, which is the energy range needed.

To illustrate the efficiency of the 3-ion heating scheme, we compare the number of fast ³He ions that reach an energy above 50keV in steady-state phase in the ICRH generated fast ion distribution. The estimates have been done using the Fokker-Planck code SSFPQL [14] for the 3-ion scenario and H minority heating in a D majority plasma with X[H]=3%, again at Tₑ = 3 keV, nₑ = 2×10²⁰ m⁻³ and assuming <P_{RF}>=0.5MW/m³. We thus find 4×10¹⁶ ptcls/m³ for the fast ³He ions when using the D-(³He)-H 3-ion scenario and 1.3×10¹⁵ ptcls/m³ for the fast H ions using 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 modeling of the ICRH heating and comparing the D-(³He)-H 3-ion scenario with the (³He)-H minority heating scheme. The final number of fast particles generated and escaping the W7-X plasma to be detected will evidently further depend on the confinement and turbulence properties of the W7-X plasmas.
4. THE ICRH TEST STAND

A purposely-built test stand in the Institute for Energy and Climate Research/ Plasma Physics (IEK-4, Forschungszentrum Jülich, Germany) is being assembled to check the main properties of the ICRH antenna. It consists (see Fig. 3) of (i) a large vacuum vessel with a built-in W7-X duct mock-up (including heating elements and thermo sensors) (ii) the moveable antenna carriage (item 8, Fig. 1), the matching system and RF generator.

The main purpose of the test stand is to check: (i) the vacuum compatibility and (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.

5. MATCHING AND DECOUPLER NETWORK

The mutual coupling between closely spaced straps in the small antenna could lead to a large difference in the radiated power per strap and power being transferred from one generator to the other. This can be avoided by inserting a decoupler [15] between the two lines connecting the generators to the straps. The power transfer between straps is proportional to \( \sin(\Delta \phi) \), where \( \Delta \phi \) is the difference in the phase of the RF currents in the straps. A power transfer is thus present for all phasings, (except for the ideal perfect case of \( \Delta \phi = 0 \) or \( \pi \)), with a maximum transfer present for \( (0, \pi/2) \) phasing. A decoupler consists of two sections of \( \sim \lambda/4 \) lines connected to an adjustable reactance. 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 \( Y \).
6. 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 (item 5, Fig. 1), vacuum window (item 10, Fig. 1), the TL line stretchers (item 12, Fig. 1) and the 6” and 9” transmission lines. A detailed layout of the matching/decoupler network is shown in Figs. 4a and 4b: 6” lines are in green, 9” lines are in red, 9” to 6” transitions in blue. These components are at air pressure. Each of these components has its specific limitations in voltage and current: maximum 35kV/700A for the 9” lines, 23kV/462A for the 6” lines and TL line stretchers, 53kV/1060A for the antenna vacuum feeding lines, and 40kV/800A 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. ~ 2MW could be delivered for (0,0) phasing and up to ~ 1MW for (0,π) phasing, confirming earlier calculations [16].

7. CONCLUSIONS

ICRH is an ideal tool 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. 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.
Various ICRH heating schemes for plasma heating and the creation of fast particle populations have been identified. 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 3-ion 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 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) as they require minority ion concentrations of a few % to guarantee good core absorption of RF waves. Construction and implementation of the ICRH system for W7-X is in full swing, with the aim to deliver ICRH power in OP2, the next operational campaign of W7-X.

REFERENCES


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