Modelling of the Ion Cyclotron Resonance Heating Scenarios for W7-X Stellarator

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Abstract. The construction of the world largest superconducting stellarator Wendelstein 7-X (W7-X) has reached the final stage. One of the main scientific objectives of the W7-X project is to prove experimentally the predicted good confinement of high-energy ions. Ion cyclotron resonance heating (ICRH) system is considered to be installed in W7-X to serve as a localized source of high energy ions. ICRH heating scenarios relevant for hydrogen and deuterium phases of W7-X operation are summarized. The heating efficiency in (^{3}He)-H plasmas is qualitatively analyzed using a modified version of the 1D TOMCAT code able to account for stellarator geometry. The minority ion absorption is shown to be maximized at the helium-3 concentration ~2% for the typical plasma and ICRH parameters to be available during the initial phase of W7-X.

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INTRODUCTION

The Wendelstein 7-X (W7-X) stellarator is now under construction at Max-Planck Institute for Plasma Physics (Greifswald, Germany) and it will be the largest fusion device of this type in the world (average major and minor radius $R_0 = 5.5$ m and $a = 0.55$ m, respectively; average magnetic field on the plasma axis $B_0 = 2.5$ T). The base of the machine was completed in November 2011 with mounting the last section of the outer shell of the assembly, and the first plasma is foreseen in 2015. In order to overcome the deficiencies of previous stellarators, an optimized magnetic field configuration was proposed for W7-X such that the drift losses are minimized in this configuration. The optimization in W7-X is achieved by using a very complicated superconducting coil system, which consists of 50 modular and 20 planar non-circular coils combined in 5 magnetic periods [1]. Accordingly, the plasma cross-section has a complicated structure, and varies toroidally between a bean shape and a triangular shape. The quality of plasma confinement in W7-X is aimed to be on a par with that of a tokamak [2]. However, this question cannot be answered by theoretical means only, and clarifying it experimentally is one of the main objectives of the W7-X.

ICRH AS A TOOL FOR FAST ION GENERATION

In order to prove good confinement of fast particles experimentally in W7-X, a source of energetic ions with energies in the range of $\sim 50 - 100$ keV is needed. Such particles will mimic the behavior of alpha particles in a stellarator-reactor, which is foreseen to have a similar geometry, but to be four times larger in linear size. Therefore, W7-X results will be crucial for future developments of a fusion reactor based on the stellarator concept.

W7-X system is designed to confine high-energy ions, which are quite close to the center, if the plasma beta is high enough ($\beta \approx 4\%$). Ion cyclotron resonance heating (ICRH) system is planned to be installed in W7-X to produce such energetic ions. The ongoing W7-X ICRH system design [3] considers an option of using the TEXTOR generators, which should couple up to 4 MW of ICRH power to the plasma within the frequency range $f = 25 - 38$ MHz. In addition to fast particle generation, the applications of the dedicated ICRH system considered for W7-X include plasma heating, current drive and wall conditioning.

Preliminary modeling of ICRH efficiency in W7-X plasmas was done by using the 1D full-wave ICRH code TOMCAT [4]. The TOMCAT code was initially developed for tokamak geometry, which has a $1/R$ dependence of the magnetic field and the parallel wavenumber, $k_{\|}$. It was modified to include proper treatment of the stellarator magnetic field, so that both the variations of the magnetic field and of $k_{\|}$ are properly described.

The port reserved for the ICRH antenna in W7-X is located at the toroidal angle $\varphi = 7.4^{\circ}$. The corresponding plasma shape and relevant geometry are depicted in Fig. 1(a). Using the output from the equilibrium code, the variation of the magnetic field along the major radius is shown in Fig. 1(b) for two lines of the wave propagation,

$Z = 0.0$ m and $Z = 0.2$ m. To incorporate the stellarator-like magnetic field into TOMCAT, a simple yet sufficiently accurate representation of the B-field dependence was found

$$B(x) = B_0\left[\frac{k_1}{1+x/R^*} + (1-k_1)(1+x/R^*)\right], \qquad (1)$$

where $x = R - R_0$, k_1 and R^* are the numerical coefficients found by matching the fitting curve to the given data points. The first term in Eq. (1) represents the usual $1/R$ B-field dependence, whereas adding the second term to the model allows one to obtain an almost perfect fit to the data, as Fig. 1(b) clearly illustrates. Note that the tokamak magnetic field is the limiting case described by Eq. (1) if setting $k_1 = 1$ and $R^* = R_0$. The fitting parameters for the W7-X poloidal plane $\varphi = 7.4^\circ$, where the ICRH antenna is to be located, are: $B_0 = 2.511/2.501$ T, $R_0 = 5.946/5.887$ m, $k_1 = 0.762/0.782$, $R^* = 1.27/1.52$ m for $Z = 0.0$ m and $Z = 0.2$ m, respectively. The variation of the fast wave toroidal wavenumber is imposed by the toroidal geometry and is basically given by $k_\parallel = k_\parallel^{(0)}/(1+x/R_0)$. For stellarators R^* and R_0 are in general case different, hence distinguishing between the radial dependence of B and $k_\parallel$ in the wave equation had to be done to allow describing the wave evolution faithfully.

The W7-X experimental programme is divided into two operational phases. In the Operational Phase 1 (OP-1) W7-X will use an inertially cooled divertor and pulsed operation is foreseen. The maximum heating power to be available for this phase is 7.5 MW. It is the aim in OP-1 to explore and optimize operating scenarios for the realization of steady-state operation of high density, high beta plasmas avoiding activation to allow the later foreseen installation of the cooled divertor. Therefore only hydrogen (H) operation will be allowed in OP-1. In the second operational phase (OP-2) with an actively cooled divertor full exploitation of the device with pulses of up to 30 min at steady heat fluxes of 10 MW/m^2 at the divertor with deuterium (D) plasmas will become possible. One of the main research aims of W7-X project is to check the confinement of fast ions in the optimized stellarator configuration using ICRH as a source of fast ions. The TEXTOR generators operating within the frequency range 25 – 38 MHz will be transferred to Greifswald and will enable to couple up to 4 MW of ICRH power to the plasma.

The accessible frequency range imposes a constraint on the available ICRH scenarios for OP-1 and OP-2 phases. Using Eq. (1), one can show that the location of the ion cyclotron (IC) in the plasma is given by

$$x_{\mathrm{IC}} = R^*\left[\frac{1-\sqrt{1-4k_1(1-k_1)\alpha^2}}{2\alpha\,(1-k_1)} - 1\right], \qquad (2)$$

where $\alpha = (\omega_{\mathrm{ci}}/\omega_{\mathrm{cH}})\,(15.25\,B_0[\mathrm{T}]\,/\,f\,[\mathrm{MHz}])$, ω_{ci} and ω_{cH} are the cyclotron frequencies of the resonant ions heated with ICRH and hydrogen ions, respectively, f is the RF generator (antenna) frequency and B_0 is the magnetic field on plasma axis. Heating at the fundamental cyclotron resonance of majority ions is usually ineffective due to unfavorable wave polarization and vanishing E_+ component responsible for the ion heating. Therefore, $\omega = \omega_{\mathrm{cH}}$ and $\omega = \omega_{\mathrm{cD}}$ heating schemes are not feasible for OP-1 and OP-2 phases of W7-X operation, respectively. Efficient ICRH heating can be achieved either using a small fraction of resonant minority ions (e.g., ^{3}He, ^{4}He) or utilizing the second and higher harmonics heating. In tokamaks both of these schemes have shown to produce small populations of ions accelerated by ICRH to high energies.

Figure 2(a) shows a location of the resonance layers for different ion species versus the magnetic field strength B_0 for ICRH system operating at the lowest frequency to be available, $f = 25$ MHz. The possible heating scenarios for central ion heating include: $\omega = \omega_{\mathrm{c,3He}}$ at $B_0 \approx 2.46$ T, $\omega = \omega_{\mathrm{cH}} = 2\omega_{\mathrm{c,4He}}$ at $B_0 \approx 1.64$ T and $\omega = 2\omega_{\mathrm{c,3He}}$ at $B_0 \approx 1.23$T. The latter two require operation with the reduced magnetic field, and thus can not be considered as a baseline scenarios. For $f = 25$ MHz fundamental heating of helium-3 ions requires the magnetic field close to the nominal value, and therefore this heating scenario is promising in view of central ion heating and fast particle generation for both OP-1 and OP-2 phases. In Fig. 2(b) the location of the IC resonance layers is plotted for the highest frequency to be available with TEXTOR generators, $f = 38$MHz. For this frequency the possible heating scenarios include: $\omega = \omega_{\mathrm{cH}} = 2\omega_{\mathrm{c,4He}}$ at $B_0 \approx 2.49$ T, $\omega = 2\omega_{\mathrm{c,3He}}$ at $B_0 \approx 1.87$ T, $\omega = 3\omega_{\mathrm{c,4He}}$ at $B_0 \approx 1.66$ T, and $\omega = 2\omega_{\mathrm{cH}}$ at $B_0 \approx 1.25$ T. For the nominal magnetic field at W7-X the first scenario provides possible heating schemes $\omega = 2\omega_{\mathrm{c,4He}}$ for OP-1 (H plasmas) and $\omega = \omega_{\mathrm{cH}}$ for OP-2 (D plasmas) phases.

(^{3}He)-H HEATING SCENARIO FOR OP-1 PHASE

Heating of helium-3 minority ions at their fundamental resonance is the preferred scheme to produce fast ions in the OP-1 phase of W7-X operation with hydrogen as a majority gas. In tokamaks efficient ICRH minority ion heating of (^{3}He)-H plasmas requires helium-3 concentrations of a few percent only [5, 6]. Since virtually all the RF power is absorbed by a small population of resonant helium-3 ions, it allows their acceleration to high energies with ICRH. According to the classical work by Stix [7], the minority ions are accelerated to the energy

$$\varepsilon_{\mathrm{m}} \simeq k_0\, T_e\, \xi, \quad \xi = \frac{m_{\mathrm{m}} \mathrm{v}_{te} < P_{RF} >}{8\sqrt{\pi}\, X_m n_e^2 Z_m^2 e^4 \ln \Lambda}, \tag{3}$$

where n_e is the local plasma density, $<P_{RF}>$ denotes the local ICRH power density absorbed by minority ions, $v_{te} = (T_e/m_e)^{1/2}$ is electron thermal velocity, $X_m = n_m/n_e$ is the minority concentration, m_m and Z_m are the mass and charge number of minority ions, and ln Λ is the Coulomb logarithm. The numerical coefficient k_0, which appears in Eq. (3), is of order of 1 ($k_0 \simeq 1.0 - 1.5$). It should be noted here that while the plasma density in tokamaks is limited by the current (Greenwald limit), in stellarators such a constraint does not exist. Hence, in W7-X an increase of the plasma density by one order of magnitude compared to typical tokamak values is foreseen, such that $n_{e0} = 2 \times 10^{20}$ m^{-3} is considered as a baseline density. Whereas in tokamaks MeV-range ions have been observed, the energies for fast ions accelerated with ICRH will be substantially lower in stellarators due to the quadratic dependence of the heating parameter ξ on plasma density. However, W7-X requires ions with the energy $\varepsilon_m = 50-100$ keV, and this seems to be plausible if providing efficient minority heating (by identifying the optimal minority concentration, which raises $<P_{RF}> / X_m$ ratio) and lowering the operation density to $n_{e0} \sim 1 \times 10^{20}$ m^{-3}.

Figure 3(a) shows the single-pass absorption coefficients in (^{3}He)-H plasma calculated with the baseline and modified versions of the TOMCAT solver. While the former is based on the equivalent tokamak approach [8] (dashed and dash-dotted lines), the results presented with solid and dotted lines in Fig. 3(a) are calculated with the modified version of TOMCAT accounting for the stellarator *B*-field dependence given by Eq. (1). One could note good agreement between these two approaches for $X[^3\mathrm{He}] < 3.5\%$, while for higher minority concentrations the baseline version of the code underestimates the absorption. The considered parameters are the following: $B_0 = 2.5$ T, $f = 26.1$ MHz (antenna frequency is adjusted to provide ion heating centrally), $T_0 = 3.0$ keV, $n_{e0} = 2 \times 10^{20}$ m^{-3}, $k_z = 6.5$ m^{-1}. At very low minority concentrations the corresponding ion absorption is negligible and electron absorption via fast wave electron Landau damping dominates. With the gradual increase in $X[^3\mathrm{He}]$ minority absorption efficiency increases and balances electron absorption at $X[^3\mathrm{He}] \approx 0.5\%$. The ion (and total) heating coefficient is maximized at $X[^3\mathrm{He}] \approx 2.2\%$ and starts to degrade for higher minority concentrations. For this minority concentration the total single-pass absorption coefficient is $\sim 67\%$, minority absorption $p_i \approx 51\%$, electron absorption $p_e \approx 16\%$. The radial absorption profiles for $X[^3\mathrm{He}] = 2.2\%$ are depicted in Fig. 3(b): the ion absorption maximizes at the plasma center, and thus such a scenario is a promising candidate for generating fast ions with ICRH in W7-X OP-1 phase. Note that the TOMCAT simulations shown in the paper exclude edge power losses, which for (^{3}He)-H inverted scenario were calculated to be ~15% [9].

CONCLUSIONS

The superconducting Wendelstein 7-X (W7-X) stellarator approaches the end of the construction stage, and the first plasma is foreseen to be achieved in 2014. It will be the world largest fusion device of the stellarator type, with an inherent feature of the possibility of continuous non-pulsed operation. The main scientific objective of the W7-X programme is to experimentally demonstrate the good plasma confinement properties that this device is predicted to have. In order to prove particle confinement in W7-X and extrapolate the results to a stellarator-reactor, a source of fast ions with the energy $\sim 50 - 100$ keV is required. For that purpose ion cyclotron resonance heating system is foreseen to be installed in W7-X.

In this paper, we outline possible ICRH scenarios relevant for hydrogen (OP-1) and deuterium (OP-2) phases of W7-X operation. Using a small fraction of helium-3 ions heated at the fundamental IC resonance is feasible for both OP-1 and OP-2 phases if tuning the antenna frequency to the lowest value available with TEXTOR generators, $f = 25$MHz. A qualitative study of the heating efficiency in (^{3}He)-H plasmas relevant for the initial phase of W7-X operation is performed using the 1D full-wave code TOMCAT. A module, which allows accounting for the stellarator magnetic field variation, has been successfully implemented in TOMCAT. Good agreement between two approaches has been shown for $X[^3\mathrm{He}] < 3.5\%$. Using the modified TOMCAT solver, it was shown that for the typical conditions of W7-X operation single-pass absorption in (^{3}He)-H plasmas is maximized at $X[^3\mathrm{He}] \approx 2.2\%$ and reaches the level $p_{\mathrm{total}} \approx 67\%$ with the ion heating fraction ~0.76. The presented results will serve as a basis for future more sophisticated 2D and 3D modeling of ICRH heating in W7-X.

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REFERENCES

1. R.C. Wolf, the Wendelstein 7-X Team, *Fusion Engineering and Design* **83**, 990-996 (2008).
2. P. Helander et al., *Plasma Phys. Control. Fusion* **54**, 124009 (2012).
3. J. Ongena et al.., "The Dedicated ICRH System for the Stellarator Wendelstein 7-X", this conference.
4. D. Van Eester and R. Koch, *Plasma Phys. Control. Fusion* **40**, 1949-1975 (1998).
5. D. Van Eester et al., *Plasma Phys. Control. Fusion* **54**, 074009 (2012).
6. Ye.O. Kazakov, T. Fülöp and D. Van Eester, *Nucl. Fusion* **53**, 053014 (2013).
7. T.H. Stix, *Nucl. Fusion* **15,** 737-754 (1975).
8. J. Ongena et al., *AIP Conf. Proc.* **1406**, 265-268 (2011).
9. A. Messiaen et al., "Coupling and Matching Study of the ICRF Antenna for W7-X", this conference.

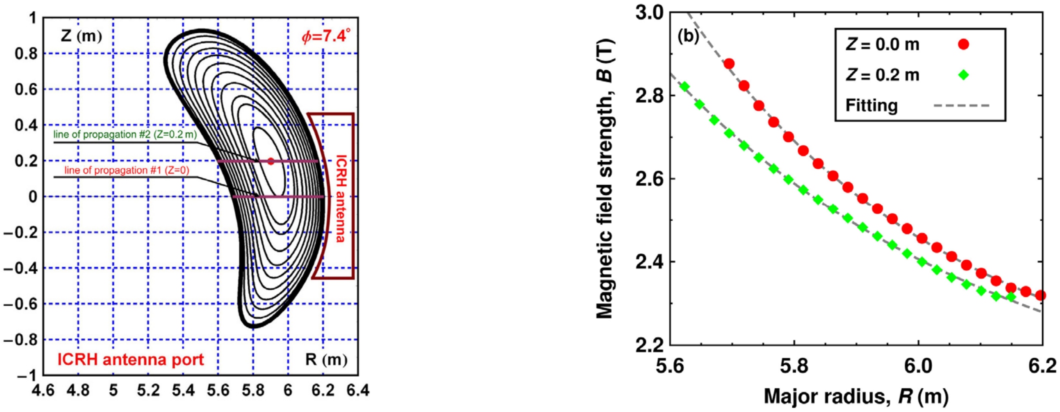

FIGURE 1. (a) Port for ICRH antenna in W7-X is reserved at the toroidal angle 7.4º facing the bean-shaped plasma. (b) Radial variation of the magnetic field strength along the lines of wave propagation $Z = 0.0$ m and $Z = 0.2$ m.

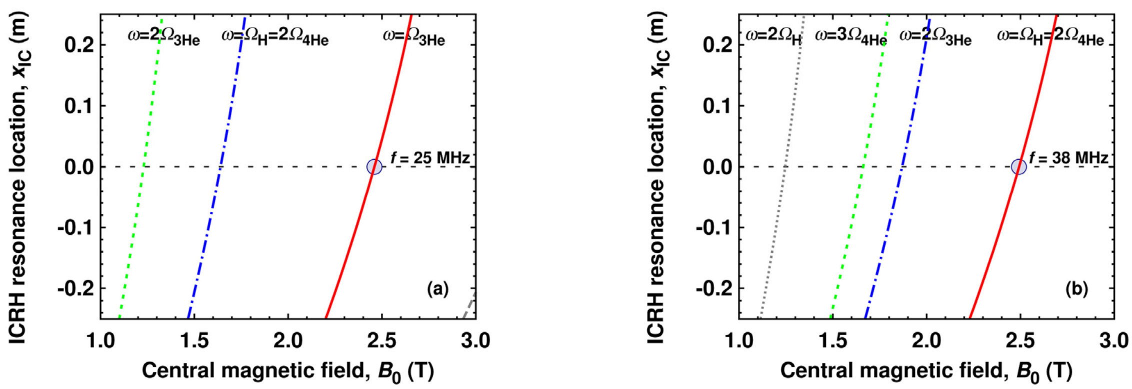

FIGURE 2. Locations of the ICRH resonance layers for different ion species vs. B_0 for the lowest, $f = 25$ MHz (a) and highest, $f = 38$ MHz (b) frequencies within frequency range available for TEXTOR generators, which will be used in W7-X.

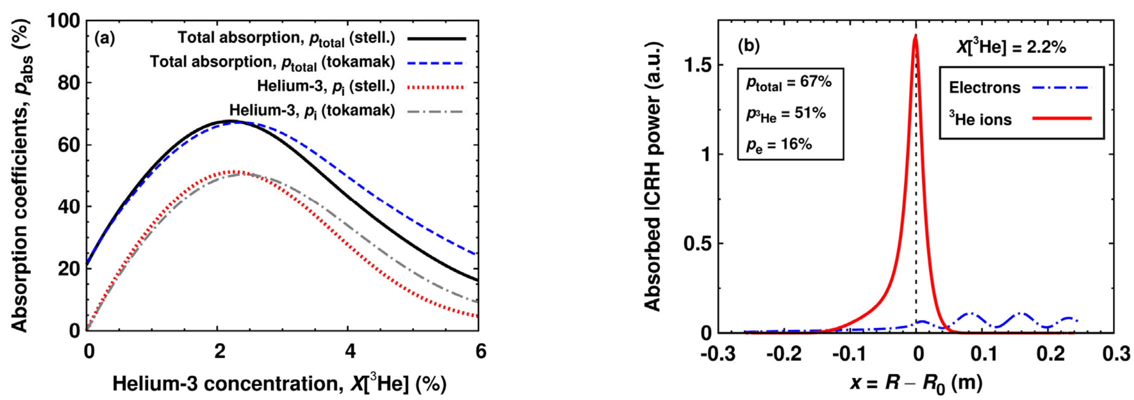

FIGURE 3. (a) Single-pass absorption coefficients in (^{3}He)-H plasma vs. the concentration of helium-3 ions evaluated with the baseline and modified versions of the TOMCAT solver. (b) Radial ICRH power deposition profiles for $X[^3He] = 2.2\%$.