RF Physics of ICWC Discharge at High Cyclotron Harmonics

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Abstract. Recent experiments on Ion Cyclotron Wall Conditioning (ICWC) performed in tokamaks TEXTOR and ASDEX Upgrade with standard ICRF antennas operated at fixed frequencies but variable toroidal magnetic field demonstrated rather contrasting parameters of ICWC discharge in scenarios with on-axis fundamental ion cyclotron resonance (ICR) for protons, $\omega = \omega _{cH^+}$, and with its high cyclotron harmonics (HCH), $\omega = 10\omega _{cH^+}$. HCH scenario: very high antenna coupling to low density RF plasmas ($P\approx 0.9P_{RF-G}$) and low energy Maxwellian distribution of CX hydrogen atoms with temperature $T_H\approx 350$ eV. Fundamental ICR: lower antenna-plasma coupling efficiency (by factor of about 1.5 times) and generation of high energy non-Maxwellian CX hydrogen atoms (with local energy $E_{\perp H^+} \geq 1.0$ keV). In the present paper, we analyze the obtained experimental results numerically using (i) newly developed 0-D transport code describing the process of plasma production with electron and ion collisional ionization in helium-hydrogen gas mixture and (ii) earlier developed 1-D Dispersion Relation Solver accounting for finite temperature effects and collision absorption mechanisms for all plasma species in addition to conventionally examined Landau/TTPM damping for electrons and cyclotron absorption for ions. The numerical study of plasma production in helium with minor hydrogen content in low and high toroidal magnetic fields is presented. The investigation of the excitation, conversion and absorption of plasma waves as function of $B_T$-field suggests that only fast waves (FW) may give a crucial impact on antenna coupling and characteristics of the ICWC discharge using standard poloidally polarized ICRF antennas designed to couple RF power mainly to FW. The collisional (non-resonant) absorption by electrons and ions and IC absorption by resonant ions of minor concentration in low $T_e$ plasmas is studied at fundamental ICR and its high harmonics.

Keywords: ICRF Antennas, ICRF discharge, Wall Conditioning, Tokamak

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INTRODUCTION

The Ion Cyclotron Wall Conditioning (ICWC) technique, based on Radio-Frequency (RF) discharge ignition and sustainment with conventional ICRF heating antennas [1] is envisaged for application in ITER using the ITER main ICRF heating and current drive system [2]. The conventional ICRF antennas with poloidal current straps are designed and optimized for heating of dense ($n_e>10^{19}$ m$^{-3}$) target plasmas via excitation of Fast Waves (FW) with high coupling efficiency, $\eta>0.9$. Here we define the antenna-plasma coupling efficiency as a normalized fraction of the generator power coupled to the plasma, $\eta = P_{RF-pl}/P_{RF-G}$. To improve the coupling of standard ICRF antennas to low density ICWC plasmas ($n_e\sim 10^{16} - 10^{18}$ m$^{-3}$), several scenarios of FW excitation in low density plasmas was suggested and successfully tested [3]: (i) monopole phasing of the antenna current straps to excite FW with low $k_||$ values, (ii) FW-SW-IBW mode conversion (MC) in RF plasmas with two ion species, (iii) operation at High Cyclotron Harmonics (HCH), typically $\omega \approx 10\omega _{cH^+}$ by reducing the toroidal magnetic field value.

This paper focuses mainly on a study of the RF physics aspects of ICWC discharges performed at low $B_T$ field (HCH regime) in comparison to high $B_T$ field in the presence of fundamental ICR for resonant ions.
EXPERIMENTAL RESULTS

The present ICWC experiments have been performed on the ASDEX Upgrade (AUG) tokamak in the following conditions. All (four) available ICRF antennas with two current straps in each antenna box were tuned to operate at frequency $f=30$ MHz with monopole or dipole phasing. The monopole configuration suggests energizing only one strap per antenna for technical reasons. The benefit of such scheme is radiating the RF power with low $k_\parallel$-spectrum (Fig.1) favorable for better antenna coupling to FW in low density RF plasmas. For comparison, two antennas with dipole phasing in each antenna box were also tested. Two values of the toroidal magnetic field were used: (i) high value $B_T=2.0$ T to simulate scenario with on-axis fundamental ICR for protons ($\omega=\omega_{\text{H}^+}$) and (ii) low $B_T=0.2$ T to operate ICWC discharge at HCH ($\omega=10\omega_{\text{H}^+}$). Contrary to stationary maintained low $B_T$ field in TEXTOR which allows performing long series of ICWC pulses at fixed duty cycle (simulation of ICWC in superconducting $B_T$) [4], the toroidal magnetic coils in AUG is powered by a fly-wheel generator in pulsed mode independently on the field value thus enabling to use only 10 s for RF pulses. ICWC discharges in pure helium ($p_{\text{He}}\approx(2-4)\times10^{-4}$ mbar) have been reliably generated at both $B_T$ values in the RF power range $100-470$ kW but with rather contrasting parameters. HCH scenario: very high antenna coupling in monopole phasing ($\eta\approx0.9$) and low energy flux of CX hydrogen atoms with Maxwellian-like energy distribution and local energy $E_\perp\approx T_H\approx350$ eV deduced from slope of the energy spectra (Fig.2). Fundamental ICR: lower antenna-plasma coupling efficiency (by factor of about 1.5 times) and generation of high energy non-Maxwellian H-atom flux with local energy $E_\perp\geq1.0$ keV. The additional wall conditioning contribution in high $B_T$ was clearly evidenced for the first time [5].

To analyze and understand the obtained contrasting results we will focus on parameters of two typical ICWC discharges performed at similar helium gas pressures and different $B_T$-fields as shown in Table 1. It should be noted that despite of the pure helium injection, the Residual Gas Analyzer registered a presence of minor amount of hydrogen in the AUG W-coated vessel. Similar regime in the TEXTOR C-coated vessel implied much higher hydrogen content [6]. This fact will also be taken into account in our further numerical analysis.

| TABLE (1). Parameters of two AUG ICWC shots (#29004 and #29012) performed at high and low $B_T$-fields respectively in helium with the trace hydrogen content (hydrogen release from the tungsten wall). |
|---------------------------------|-----------------|-----------------|
| **ICWC Discharge Parameters**   | **at $B_T=2.0$ T** | **at $B_T=0.2$ T** |
| He partial pressure (mbar)      | $\approx2\times10^{-4}$ | $\approx2\times10^{-4}$ |
| H₂ partial pressure (mbar)      | $<10^{-6}$ | $<10^{-6}$ |
| RF generator frequency (MHz)    | 30             | 30             |
| ICRF antenna phasing            | monopole (1 active strap/antenna) | monopole (1 active strap/antenna) |
| RF pulse length (s)             | 10             | 10             |
| Antenna coupling, $\eta$ (r.u.) | $0.65$         | $0.9$          |
| Total coupled RF power (kW)     | $\approx300$  | $\approx170$  |
| Loc. energy of CX H-flux (eV)   | $\geq1000$     | $\approx350$  |
NUMERICAL MODELING

Two types of numerical modeling were undertaken: (i) simulation of neutral gas ionization and plasma build-up in toroidal vessel in the presence of magnetic field and (ii) modeling of plasma wave dispersion equation and power deposition profiles for plasma species in low density plasmas in the ICRF band.

The simulation of plasma production in toroidal magnetic field was performed using recently developed TOMATOR 0-D transport code [6]. The plasma simulator is based on solution of the energy and particle balance equations for electrons, molecules (H$_2$), atoms (H, He) and ions (H$_3^+$, H$_2^+$, H$^+$, He$^+$, He$^{2+}$) in helium-hydrogen gas mixture. It takes into account (1) elementary atomic and molecular collision reactions, such as excitation/radiation, ionization (by electron and ion impact), dissociation, recombination, charge exchange and elastic collisions, (2) particle losses due to the finite dimensions of the plasma volume, (3) charged particle/energy confinement losses in the magnetic configuration, (4) active pumping, gas injection and particle recycling, (5) RF heating of electrons and protons and (6) a qualitative description of plasma impurities. The plasma simulation with parameters mentioned in Table 1 is presented in Fig.3.

![Graphs showing plasma production](image)

**FIGURE 3.** TOMATOR simulation of ICWC plasma production in AUG-like machine in low B$_T$=0.2 T (graphs (a)-(b)) with input parameters: P$_{He}$=2×10$^{-4}$ mbar, P$_{H2}$=1.5×10$^{-7}$ mbar, P$_{tot}$=175 kW, P$_{He}$/P$_{tot}$=0.04 and in high B$_T$=2.0 T (graphs (c)-(d)) with input parameters: P$_{He}$=2×10$^{-4}$ mbar, P$_{H2}$=5×10$^{-7}$ mbar, P$_{tot}$=300 kW, P$_{He}$/P$_{tot}$=0.8.

**Summary of plasma simulation:**

1. For the given helium pressure, energy of protons and coupled RF power (Table 1), low density plasmas with warm protons (B$_T$=0.2 T) and high energy protons (B$_T$=2.0 T) may be simulated only at (i) ultra-low H$_2$-concentration in helium, (ii) dominant electron heating in the low B$_T$ and dominant proton heating in the high B$_T$.

2. High energy protons generated in the high B$_T$-case contribute to the gas ionization and support discharge even with minor fraction of the power coupled to the electrons.

3. The electron dominant heating regime (low B$_T$) results in a low ionization degree (Fig.3a) and marginal contribution of the proton flux to a total flux of the particles bombarding the wall area (≈0.1%).

4. The ion (proton) dominant heating regime (high B$_T$) gives evidence for higher ionization degree (Fig.3c) and a noticeable contribution of high energy proton flux to the total particle flux bombarding the wall (≈3%). The latter may be beneficial for wall conditioning.

To provide a complementary insight into the plasma wave dynamics, modeling with a 1-D dispersion equation solver [7] was used. It solves the dispersion equation for Maxwellian or bi-Maxwellian plasmas accounting for all Larmor radius corrections and collision absorption mechanisms for all plasma species in addition to conventionally examined Landau/TTPM damping for electrons and cyclotron absorption for ions. The dispersion equation solver enables studying propagation and absorption of slow waves (SW), fast waves (FW) and ion Bernstein waves (IBW) at arbitrary cyclotron harmonic and for arbitrary wavelength. It provides the evolution of the wave flux for an isolated mode. Renormalizing the field to unity amplitude yields the relative absorption efficiency of the various species at a given location, as well as the relative strength of the absorption at different locations. It has the
drawback common to all dispersion solvers that no distinction is made between evanescence and damping on any traced wave mode.

The FW and IBW dispersion diagram and power deposition profiles for AUG ICWC plasmas with parameters taken from Table 1 and Fig.3 are shown in Fig.4 for low and high B_T cases, respectively.

**FIGURE 4.** Plasma waves dispersion diagram, Re ($k_{\perp}^2$), and profiles of absorbed power calculated by dispersion equation solver for the case of AUG helium plasmas containing minor ($\lesssim0.4\%$) concentration of protons in low $B_T=0.2$ T (graphs (a)-(d)) and high $B_T=2.0$ T (graphs (e)-(f)). RF parameters: $f=30$ MHz, antenna monopole phasing: $k_{||}=1.34$ m$^{-1}$ for FW and $k_{||}=5$ m$^{-1}$ for IBW (Fig.1). Plasma parameters predicted by plasma simulator (Fig.3).

Main conclusions from RF modeling:
1. FW with low $k_{||}$ values propagates in low density plasmas ($n_e\approx(1−3)\times10^{18}$ m$^{-3}$) in both, low and high $B_T$-cases (Re ($k_{\perp}^2$)$>0$, Fig. 4a,e) and provides high antenna coupling in the monopole phasing operation.
2. RF power absorption at HCH ($B_T=0.2$ T): (i) Electron-dominant absorption via electron-neutral collisions for both, FW ($P_e\approx0.96P_{tot-FW}$, Fig.4b) and IBW ($P_e\approx0.93P_{tot-IBW}$, Fig.4d); Landau e-damping is negligible, $\omega/(k_{\perp}c_T)\approx40$-400; (ii) Maximum of $P_{abs-e}$ for FW is shifted towards LFS (Fig.4b) and correlates with non-homogeneous plasma CCD-image; (iii) Protons are heated mainly through FW non-resonant collision damping ($P_{col-H+}\approx0.03P_{tot-FW}$, Fig.4b); resonant IC absorption of IBW at high cyclotron harmonics for protons has a minor effect ($P_{HCH-H+}\approx0.03P_{tot-IBW}$, Fig.4d).
3. RF power absorption at ICR ($B_T=2.0$ T): Ion-dominant absorption via ion cyclotron damping of FW at the fundamental ICR for protons with minor concentration ($P_{ICR-H+}\approx0.78P_{tot-FW}$, Fig.4f) responsible for generation of high energy proton flux; (ii) Electrons absorb minor fraction of the RF power via non-resonant electron-neutral collisions ($P_e\approx0.16P_{tot-FW}$, Fig.4f).

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