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 ($P_{pl}\approx0.9P_{RF-G}$) and low energy Maxwellian distribution of CX hydrogen atoms with temperature $T_H\approx350$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 $E_{\perp H}\geq1.0$keV). The additional conditioning contribution of the high energy CX flux of neutrals was evidenced.

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 collision 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.

MOTIVATION / 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 parallel wave-numbers, $k_{||}\approx$ 6-10m^{-1}, (*dipole phasing*). As a result, antenna-plasma coupling efficiency is very high, η>0.9. Here the antenna-plasma coupling efficiency is defined as a normalized fraction of the generator power coupled to the plasma, $\eta=P_{RF-pl}/P_{RF-G}$.
- Usually, FW with high $k_{||}$-values is a non-propagative wave in low density ($n_e\sim10^{16}$-10^{18}m^{-3}) ICWC plasmas and ICRF antenna operates inefficient. To improve the antenna coupling to ICWC plasmas, several scenarios of FW excitation in low density plasmas were suggested and successfully tested [3]:
  - (i) phasing of the antenna current straps to excite FW with low $k_{||}$ values (*monopole phasing*)
  - (ii) FW-SW-IBW mode conversion (MC) in RF plasmas with two ion species
  - (iii) operation at High Cyclotron Harmonics (HCH), typically $\omega=10\omega_{ci}$ by reducing the toroidal magnetic field value.

EXPERIMENTAL RESULTS

AUG ICWC DISCHARGE COMPARISON: HCH ($\omega=10\omega_{ci}$) vs ICR ($\omega=\omega_{ci}$)

- All (4) available ICRF antennas with two current straps in each: *(i)* f=30MHz, *(ii)* monopole phasing (1 active strap per antenna) →**Fig.1**, *(iii)* P_{RF}=100-470kW, *(iv)* $p_{HE}\approx(2$-$4)\times10^{-4}$mbar, *(v)* trace hydrogen content $p_{H2}<10^{-6}$mbar
- **HCH, $\omega=10\omega_{cH+}$ @ B_T=0.2T:** *(i)* high antenna coupling ($\eta\approx0.9$), *(ii)* Maxwellian low energy flux of CX H-atoms ($T_H\approx E_{\perp H}\approx$300-350eV)
- **Fundamental ICR, $\omega=\omega_{cH+}$ @ B_T=2.0T:** *(i)* lower antenna coupling $\eta\approx0.65$, *(ii)* non-Maxwellian high energy flux of CX H-atoms (local energy $E_{\perp H}\approx$0.8-2.0keV) → Figs.2-3 and Table 1
- The additional wall conditioning contribution in high B_T was clearly evidenced for the first time [4]

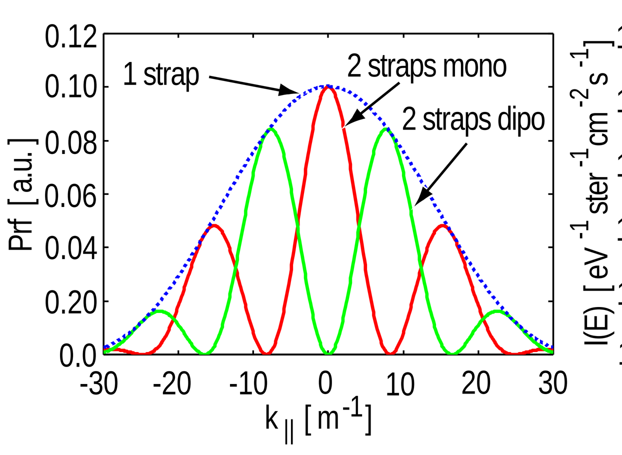

Figure 1: $k_{||}$-spectrum of the RF power radiated by AUG ICRF two-strap antenna in vacuum for (i) one active strap per antenna and for (ii) different phasing between two active straps.

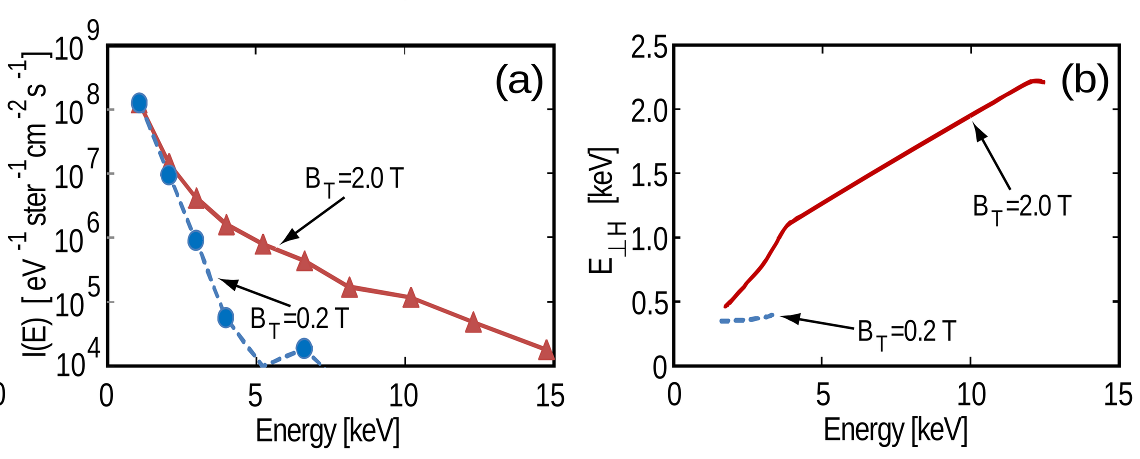

Figure 2: NPA detected energy spectra of the CX H-atom flux from ICWC plasmas (a) and deduced local energy of H-atoms (b) in high B_T=2.0T (#29004) and in low B_T=0.2T (#29012), respectively.

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).

Toroidal magnetic field (T)	2.0	0.2
He partial pressure (mbar)	$\approx2\times10^{-4}$	$\approx2\times10^{-4}$
H_2 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 , η (r.u.)	≈0.65	≈0.9
Total coupled RF power (kW)	≈300	≈170
Local energy of CX H-flux (eV)	≥1000	≈350

NUMERICAL MODELING

1. SIMULATION OF ICRF PLASMA PRODUCTION IN B_T PRESENCE

Plasma simulator – TOMATOR 0-D transport code [5] – 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^{++}) in helium-hydrogen gas mixture. It takes into account: (1) elementary collision reactions (excitation/radiation, ionization (by ***e***- and ***i***-impact), dissociation, recombination, charge exchange, elastic collisions), (2) particle losses due to the finite plasma dimensions, (3) charged particle/energy confinement losses in the magnetic configuration, (4) active pumping, gas injection, particle recycling, (5) RF heating of ***e*** and H^+, (6) losses due to plasma impurities.

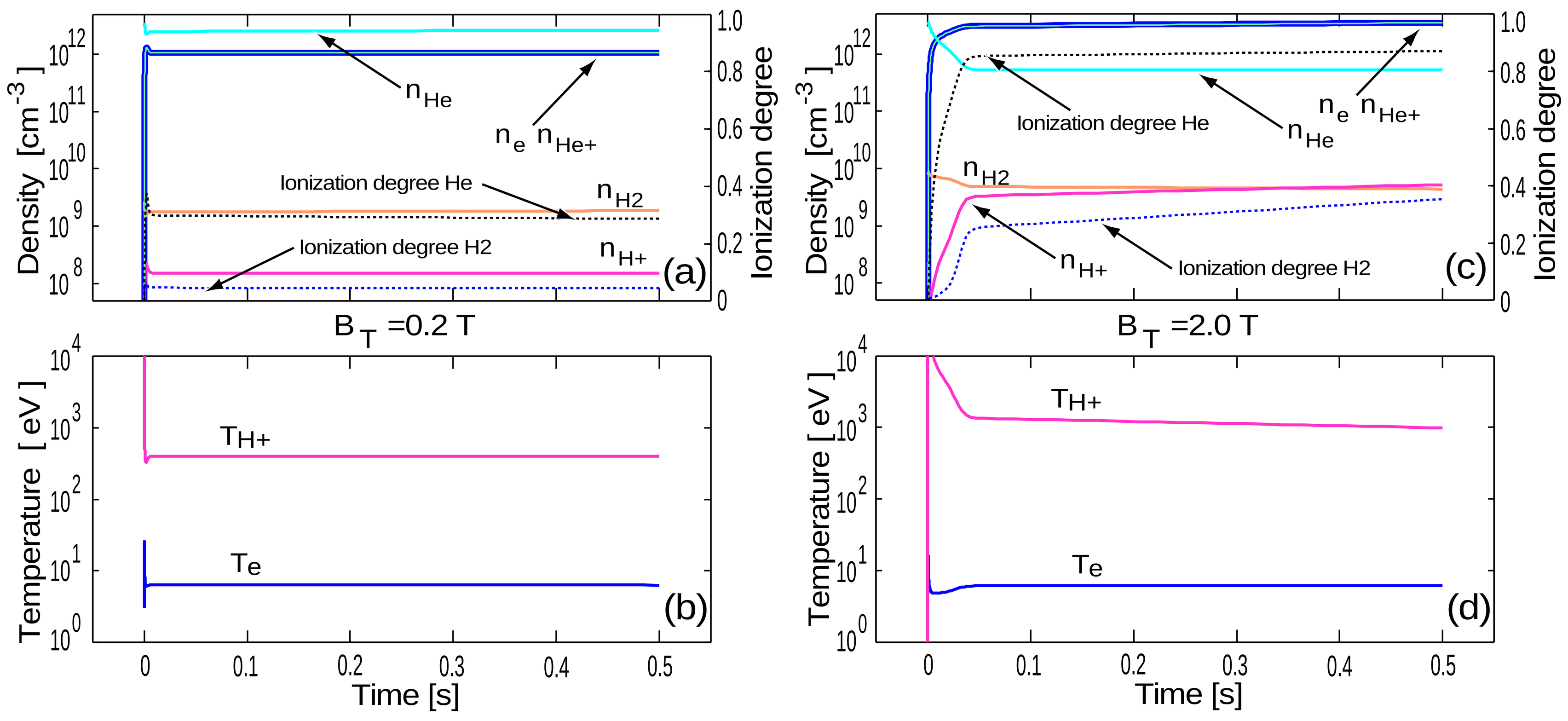

Figure 3: *TOMATOR simulation of ICWC plasma production in AUG-like machine in low B_T=0.2T (graphs (a)-(b)) with input parameters: $p_{He}=2\times10^{-4}$mbar, $p_{H2}=1.5\times10^{-7}$mbar, P_{tot}=175kW, P_{H+}/P_{tot}=0.04 and in high B_T=2.0T (graphs (c)-(d)) with input parameters: $p_{He}=2\times10^{-4}$mbar, $p_{H2}=5\times10^{-7}$mbar, P_{tot}=300kW, P_{H+}/P_{tot}=0.8.*

SUMMARY OF PLASMA SIMULATION

- For the given helium pressure, energy of protons and coupled RF power (Table 1), low density plasmas with warm protons (B_T=0.2T) and high energy protons (B_T=2.0T) may be simulated only at (i) ultra-low H_2-concentration in helium, (ii) dominant *electron* heating in the low B_T and (iii) dominant *proton* heating in the high B_T.
- High energy protons generated in the high B_T-case contribute to gas ionization and support discharge even with minor fraction of the power coupled to electrons.
- 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 ($\approx$3%). The latter may be beneficial for wall conditioning.

2. MODELING OF PLASMA WAVE DYNAMICS IN ICRF BAND

Plasma wave dynamics and RF power deposition profiles for all plasma species were modeled with a 1-D Dispersion Equation Solver [6]. It solves the dispersion equation for Maxwellian or bi-Maxwellian plasmas accounting for all Larmor radius corrections and collision absorption mechanisms 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*.

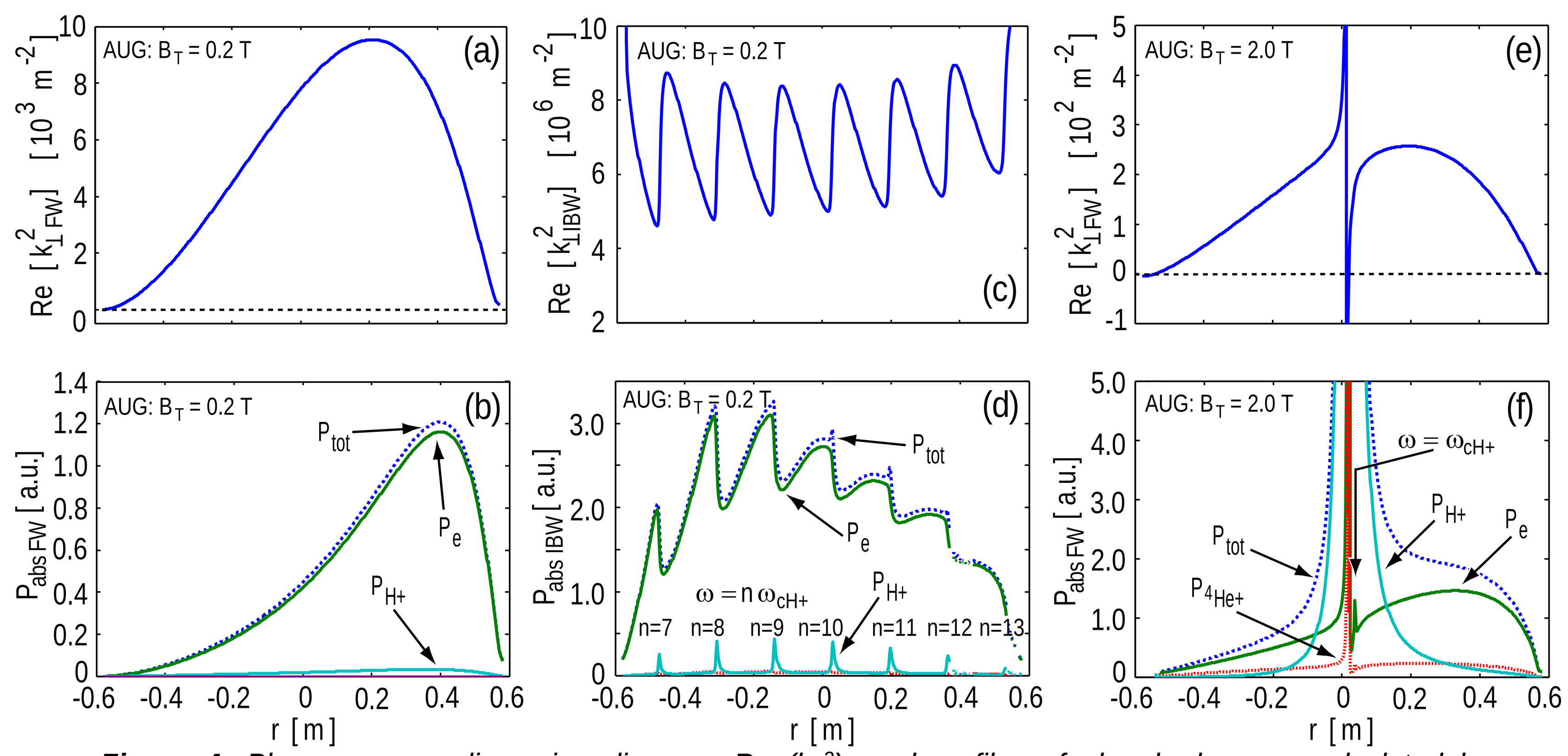

Figure 4: *Plasma waves dispersion diagram, Re ($k_\perp^2$), and profiles of absorbed power calculated by dispersion equation solver for the case of AUG helium plasmas containing minor (≤0.4%) concentration of protons in low B_T=0.2T (graphs (a)-(d)) and high B_T=2.0T (graphs (e)-(f)). RF parameters: f=30MHz, antenna monopole phasing: $k_{||}$=1.34m^{-1} for FW and $k_{||}$=5m^{-1} for IBW (Fig.1). Plasma parameters predicted by plasma simulator (Fig.3).*

SUMMARY OF RF MODELING

- FW with low $k_{||}$ values propagates in low density plasmas ($n_{e0}\approx(1$–$3)\times10^{18}$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.
- **RF power absorption at HCH (B_T=0.2T):** (i) *Electron-dominant* absorption via electron-neutral collisions for both, FW ($P_e\sim0.96P_{tot-FW}$, Fig.4b) and IBW (($P_e\sim0.93P_{tot-IBW}$, Fig.4d); Landau ***e***-damping is negligible, $\omega/(k_{||}v_{Te})\sim$40-400; (ii) Maximum of P_e for FW is shifted towards LFS (Fig.4b) and correlates with non-homogeneous plasma CCD-image; (iii) Protons are heated mainly through FW non-resonant collision damping ($P_{coll-H+}\sim0.03P_{tot-FW}$, Fig.4b); resonant IC absorption of IBW at high cyclotron harmonics for protons has a minor effect ($P_{HCH-H+}\sim0.03P_{tot-IBW}$, Fig.4d).
- **RF power absorption at ICR (B_T=2.0T):** (i) *Ion-dominant* absorption via ion cyclotron damping of FW at the fundamental ICR for protons with minor concentration ($P_{ICR-H+}\sim0.78P_{tot-FW}$, Fig.4f) responsible for generation of high energy proton flux; (ii) Electrons absorb minor fraction of RF power via non-resonant electron-neutral collisions ($P_e\sim0.16P_{tot-FW}$, Fig.4f).

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REFERENCES

[1] A. Lyssoivan et al., *Plasma Phys. Control. Fusion* **54**, 074014 (2012).
[2] B. Beaumont et al., Proceedings 23 IEEE/NPSS Symposium on Fusion Engineering, San Diego, CA, 2009.
[3] A. Lyssoivan et al., *Journal of Nuclear Materials* **415**, S1029-S1032 (2011).
[4] D. Douai, this conference.
[5] T. Wauters et al., *Plasma Phys. Control. Fusion* **53**, 125003 (2011).
[6] D. Van Eester et al., *Plasma Phys. Control. Fusion* **35**, 1189 (1993).