Wave aspect of neutral gas breakdown with ICRF antenna in ICWC operation mode

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Abstract

Neutral gas breakdown by the standard ICRF antenna operated in the Ion Cyclotron Wall Conditioning (ICWC) mode is a major issue for the antenna safety and the RF discharge optimization. Consistent modelling with a 1-D full wave RF code and a 0-D transport code was undertaken to simulate the gas breakdown threshold for two AUG ICWC discharges in hydrogen with different antenna phasing in the light of slow (SW) and fast (FW) waves excitation. The present study clearly indicates that SW excitation in vicinity of the low hybrid resonance (LHR) at the antenna side, independently on antenna phasing, may be considered as the trigger for gas breakdown ($n_{e\text{-LHR}}/n_{e\text{-bd model}}$≈0.8–0.85). Monopole phasing suggests an additional benefit: low toroidal modes (n_{tor}=2) of the FW, excited at the gas breakdown moment ($n_e > 10^{16}$ m^{-3}), dramatically improve the antenna coupling, reduce the antenna RF voltage and, finally, promote fast, robust and safe breakdown compared to dipole phasing. The possible contribution to the gas ionization of the high energy resonant protons usually generated at ICR is also investigated.

Introduction

The ability of standard ICRF antennas to operate in the plasma production mode [1] is widely used in fusion machines for Ion Cyclotron Wall Conditioning (ICWC) in the presence of a high magnetic field [2]. The first (gas breakdown) phase of the ICWC discharge is considered as the most critical one with respect to the antenna RF voltage and loading due to the fast transition from vacuum to plasma conditions and therefore requires careful optimization. The typical gas breakdown shows up in a sudden but somewhat delayed drop in the applied antenna RF voltage and in a burst in the H_α emission (measured far away from the antenna port) [3]. Such a correlation is the sign of a safe initiation of the RF discharge and plasma formation outside of the antenna box. To develop an optimized ignition scenario, the gas breakdown conditions in the ICRF band have been studied intensively using single particle analytic descriptions [1,4] and numerical codes: 0-D transport [5] and 1-D Monte

Carlo [6]. Strong dependencies of the gas breakdown time on ICRF antenna phasing and toroidal magnetic field observed experimentally in ASDEX Upgrade (AUG) and TEXTOR could not be explained properly in the frame of these models without involving plasma wave physics.

In the present paper, we reanalyse the experimental data for the gas breakdown phase in terms of the slow waves (SW) and the fast waves (FW) excitation in low density RF plasmas. Consistent modelling with the 1-D full wave RF code TOMCAT [7] and the updated 0-D transport code TOMATOR [5] was undertaken to simulate the gas breakdown conditions. The RF code was used for calculating the RF fields and power deposition profiles per plasma species providing input data for the 0-D transport code to simulate the dynamics of the plasma production based on numerical solution of the energy and particle balance equations for the molecules, atoms, ions and electrons.

Numerical simulation of gas breakdown with ICRF antenna at different phasing

To benchmark the gas breakdown simulations, we used data for two AUG ICWC shots #27184 and #27185 performed in identical conditions: hydrogen gas at the same pressure p_{H2}=4.7×10^{-4} mbar, the same toroidal magnetic field B_T=2.32 T and the same RF power delivered to the antenna from RF generator, $P_{RF\text{-}G}$≈210 kW. At the operating frequency f=30 MHz and B_T=2.32 T the fundamental ICR layer for protons is located ≈0.28 m towards LFS (antenna side) from the torus axis. The only one difference in the two shots is the phasing between the RF currents in the antenna straps: dipole phasing in #27184 (two out-of-phased active straps) and monopole in #27185 (one active strap). The latter resulted in dramatically different $k_{\|}$-spectrum of the RF power radiated by the AUG ICRF antenna into the vacuum vessel: long wavelength spectrum ($k_{\|}$~0 neglecting image RF current) for the monopole phase and much shorter ($k_{\|}$≈8–9 m^{-1}) for dipole phase [8]. Two independent numerical definitions for the gas breakdown event were used in the 0-D code. The first one describes the gas breakdown as the moment when the modelled coupled RF power (dashed curves in Figs.1b,2b) changes its waveform from *linearly dependent on plasma density* to *constant value* following (i) the idealized hypothesis of maximal ionization rate during the initial stage of plasma production (n_e<<n_n) suggested by Moiseenko [9] and (ii) a realistic quick response of the coupled RF power to the ignition moment (solid green curves in Figs.1b,2b). The second definition is related to a hypothesis on strongly increased collisionality during the transition from single ionization events to an avalanche (gas breakdown moment) when energy losses or frequency for reactions between ionization and electron-ion collisions become equal [10]. The dynamics of simulated gas breakdown for the two discharges are shown in Figs.1,2 together with time-traces of the measured antenna RF voltage and the RF power delivered to the antenna and coupled to the produced plasma. Quite different time-behaviour of the density (Figs.1c,2c) and the temperature (Figs.1d,2d) for all plasma species (electrons and H^+, H_2^+, H_3^+ ions) as a function of different coupled power is clearly seen and results from different antenna phasing. A good correlation between the experimental and simulated breakdown time for both shots was achieved when the modelled coupled power, P_{pl}(model), was properly fitted with the measured coupled power, P_{pl}(exp), in level and waveform following the first, "RF physics", definition of the gas breakdown (Figs.1b,2b). Contrary to the second definition, the breakdown moment correlated with maximum of the energy losses and frequency for ionization reactions (Figs.1e,2e).

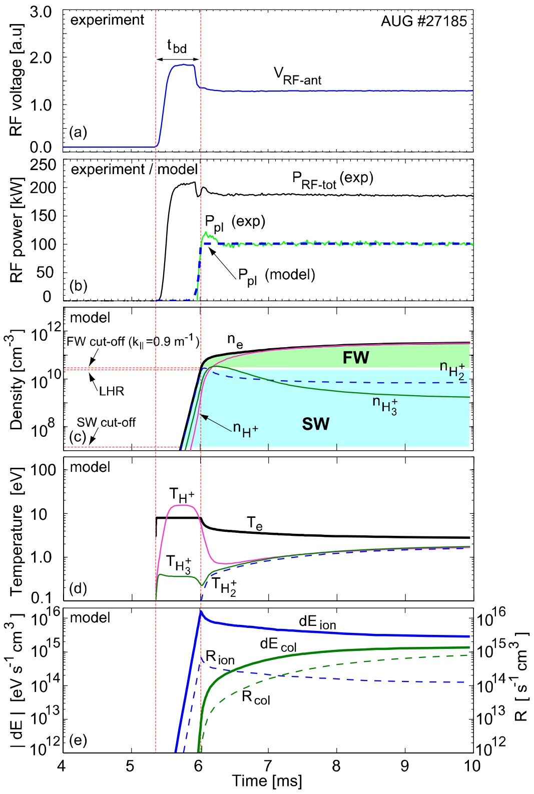

Figure 1. 0-D simulation of the H_2 breakdown with AUG ICRF antenna in **monopole** phasing (#27185): $B_T(0)=2.32$ T, $p_{H2}=4.7\times10^{-4}$ mbar, $P_{RF\text{-}ant}=210$ kW, $P_{pl}/P_{RF\text{-}ant}=0.48$, $P_{H+}=0.01P_{pl}$, f=30 MHz, $n_{e\text{-}bd\ model}\approx2.8\times10^{10}$ cm^{-3}.

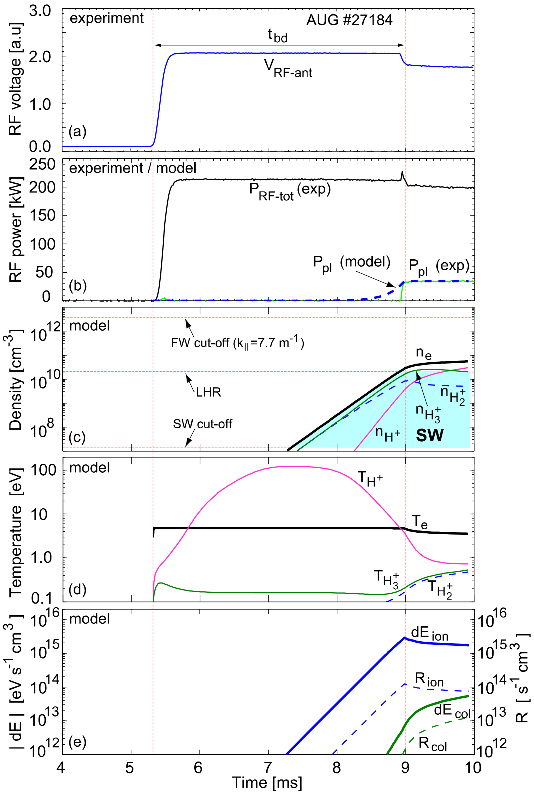

Figure 2. 0-D simulation of the H_2 breakdown with AUG ICRF antenna in **dipole** phasing (#27184): $B_T(0)=2.32$ T, $p_{H2}=4.7\times10^{-4}$ mbar, $P_{RF\text{-}ant}=210$ kW, $P_{pl}/P_{RF\text{-}ant}=0.17$, $P_{H+}=0.03P_{pl}$, f=30 MHz, $n_{e\text{-}bd\ model}\approx2.7\times10^{10}$ cm^{-3}.

Analysis of plasma wave excitation and absorption at breakdown conditions

The best agreement between simulated and experimental dynamics of plasma ignition was achieved after several consistent modelling iterations correcting the fraction of the coupled RF power to the electrons and protons used in the 0-D transport model by calculation of the absorbed power per species with the 1-D full wave RF code (Figs.3, 4). Several consequences from numerical analysis of the plasma wave excitation and the analytical estimates of their density thresholds [1] should be mentioned.

1. The SW excitation in a weakly ionized gas starts long before the breakdown event ($n_{e\text{-}SW(cut\text{-}off)}\approx1.1\times10^7$ cm^{-3}, $n_{e\text{-}SW(cut\text{-}off)}/n_{e\text{-}bd}\approx4\times10^{-4}$, Figs.1c,2c). The low hybrid resonance (LHR), at which the $E_{\|SW}$-field (along the B_T-field) becomes very strong (Figs.3b,4b),

enhances the *e-collisional* ionization and may be considered as the trigger for the gas breakdown at the antenna side independently on ICRF antenna phasing ($n_{e\text{-}SW(LHR)}$≈2.4×10^{10} cm^{-3}, $n_{e\text{-}SW(LHR)}/n_{e\text{-}bd}$≈0.85, Figs.1c, and $n_{e\text{-}SW(LHR)}$≈2.1×10^{10} cm^{-3}, $n_{e\text{-}SW(LHR)}/n_{e\text{-}bd}$≈0.8, Fig.2c).

2. Monopole phasing presents an additional benefit to the breakdown performance: low toroidal mode (n_{tor}=2) of the FW can already be excited at the LFS (antenna side): $n_{e\text{-}FW(cut\text{-}off)} \approx n_{e\text{-}bd\ model}$ (Fig.1c) and Re($k_{\perp FW}^2$)>0 (Fig.3a). This results in dramatically improved antenna coupling (Fig.1b), reduced antenna RF voltage (Fig.1a), and fast and robust breakdown compared to antenna dipole phasing, $t_{bd\text{-}mono} \approx 0.18 t_{bd\text{-}dipo}$.

3. The strong *e-collisional* absorption of the RF power (P_e>0.9P_{tot}) at the breakdown moment predicted by the 1-D RF code (Figs.3c,4c) results in dominant *e-impact* ionization. The fraction of the RF power absorbed by the IC accelerated resonant protons becomes too small, $P_{H+\ mono}$≈(0.01–0.03)P_{tot}, $P_{H+\ dipo}$≈(0.03–0.06)P_{tot}, to overcome a threshold for the *i-impact* ionization due to the rapidly increased concentration of the resonant ions in the ionized hydrogen gas on approaching the breakdown condition ($n_{H+}/n_{e\text{-}bd}$ ≈0.07, Fig.1c and $n_{H+}/n_{e\text{-}bd}$ ≈0.13, Fig.2c).

The present study clearly indicates that monopole phasing may be considered as the most reliable and safe scenario for the operation of ICRF antenna in the plasma production mode.

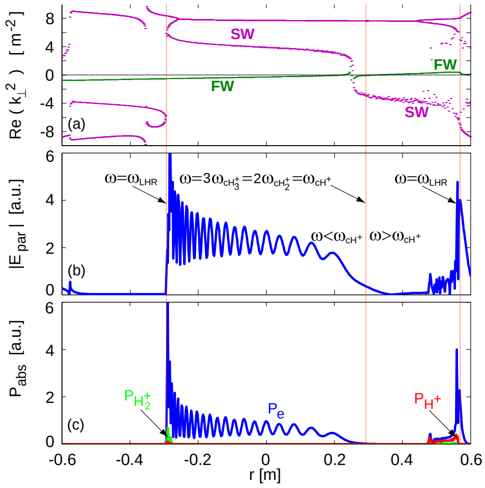

Figure 3. TOMCAT modelling predicted for the breakdown moment in H_2 with AUG ICRF antenna in **monopole** phasing (#27185): (a) plasma wave dispersion equations, (b) RF $E_{\parallel}$-field and (c) RF power deposition profiles.

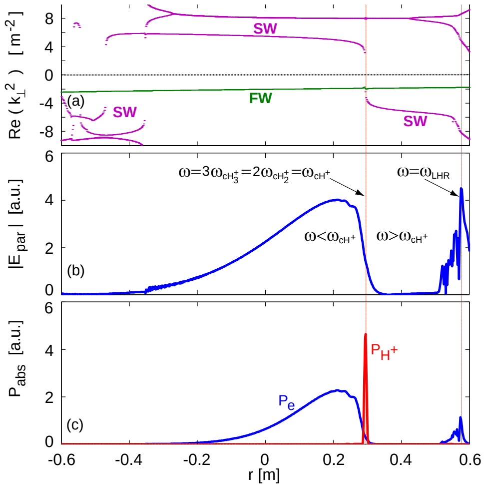

Figure 4. TOMCAT modelling predicted for the breakdown moment in H_2 with AUG ICRF antenna in **dipole** phasing (#27184): (a) plasma wave dispersion equations, (b) RF $E_{\parallel}$-field and (c) RF power deposition profiles.

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