

Monte Carlo simulation of ICRF discharge initiation at $\omega_{LHR} < \omega$

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Introduction

The radio-frequency (RF) plasma production technique in the ion cyclotron range of frequency (ICRF) is applied for wall conditioning (ICWC) in superconducting fusion machines ($T_e = 3 - 5 \text{ eV}$, $n_e < 10^{12} \text{ cm}^{-3}$), for RF-assisted start-up in tokamaks and for target plasma production ($n_e = 10^{13} \text{ cm}^{-3}$) in stellarators [1].

To investigate plasma initiation by ICRF antennas the Monte Carlo code RFdinity1D was developed and presented in [2]. The code was improved recently on several of its aspects concerning 3D binary collision physics, implementation of Coulomb collisions and electron losses due to drifts and recombinations. A description with focus on its improvement compared to the previous version will be given in next section, simulation results and comparison with experiments on TEXTOR are presented in the third and fourth section.

Model Description

The 1D code describes the motion of electrons around the torus along one toroidal magnetic line by two velocity components: a component perpendicular ($v_\theta = \sqrt{v_x^2 + v_y^2}$) and parallel (v_z) to the magnetic field line. This report presents simulations for one-strap and two-strap antenna electric field (monopole phasing). The electric field profile E_z for each strap is approximated by the sum of two Gaussians with opposite sign centered around the two gaps between the strap and the antenna box. The shape of the profile is based on vacuum field simulations for the ITER antenna by Lysoivan [1]. The electrons are accelerated by the parallel component of the RF electric field E_z (with respect to B_T) in front of the antenna and are initially uniformly distributed along the length of the magnetic field line with initial velocities sampled from a low energy Maxwell distribution ($T_{e,0} = 0.5 \text{ eV}$).

The collisions of electrons with hydrogen molecules are treated according to a Monte Carlo Collision schema (MCCS) [3]. The electron specific free path length is calculated by

$$\lambda^{MC} = -\frac{1}{n_{H_2}\sigma_T(\varepsilon_i) + n_e\sigma_{rec}(\varepsilon_i)} \log(1 - \xi), \quad (1)$$

where n_{H_2} and n_e are the hydrogen and electron densities, $\sigma_T(\varepsilon_i)$ is the sum of the electron impact collision cross sections of *ionization*, *excitation* and *dissociation* reactions for the electron energy ε_i , $\sigma_{rec}(\varepsilon_i)$ is the electron ion recombination cross section, and ξ is a random number

($0 \leq \xi < 1$). Upon the collision, the collision type is determined according to MCCS and the scattering angle is calculated with respect to the type of the collision [3]. In case of an ionization collision, the energy of the ejected electron strongly depends on the energy of the incoming electron, implemented in the model according to [3].

The electron-ion Coulomb collisions are calculated according to Takizuke-Abe [4], and are included in the simulation once the electron density reaches $n_e = 10^{14} \text{ m}^{-3}$. The ion population, uniformly distributed over the torus, is considered to be Maxwellian, with temperature corrected after each coulomb collision.

Simulating breakdown

Plasma initiation is governed by electron impact ionization. At low densities, when recombination and drift losses are insignificant the electron density (n_e) time evolution follows the equation

$$\frac{dn_e}{dt} = n_e n_{H_2} \langle \sigma(\varepsilon) v \rangle_{e,H_2}^{ion} = n_e v_{ion}, \quad (2)$$

where $n_{H_2} \langle \sigma(\varepsilon) v \rangle_{e,H_2}^{ion}$ is the ionization rate v_{ion} .

Figure 1(a) gives three simulated electron density evolutions in time for the electric field with one strap in a TEXTOR torus size. The simulations with $E_0 = 12 \text{ kV/m}$ and $E_0 = 20 \text{ kV/m}$ at $f = 29 \text{ MHz}$ reach a stable density level of $n_e \approx 6 \cdot 10^{18} \text{ m}^{-3}$ within 1ms. The density saturation occurs due to two effects: i) the recombination reactions become frequent and balance out the ionization reactions, ii) the drop of the hydrogen density n_{H_2} in the considered closed system with constant number of particles reduces the $e - H_2$ collision frequency. The threshold density when the Coulomb collisions ($n_e = 10^{14} \text{ m}^{-3}$) are taken into account is highlighted in Fig. 1(a) (black dashed line). It is clear that at this stage the electron-ion Coulomb collisions do not have a significant effect on the evolution of n_e (see Fig. 1(a)). However at higher electron density the electron energy distribution converges into a Maxwell distribution with an energetic tail. The critical density for both slow waves (SW) excitation ($\omega = \omega_{p,e}$) $n_{e,crit}^{SW(\text{cut-off})}$ and the low hybrid resonance ($\omega = \omega_{LHR}$) $n_{e,crit}^{SW(LHR)}$ are as well indicated. A first principle validity limit of the present code version is considered to be $n_{e,crit}^{SW(\text{cut-off})}$. It is expected that upon slow wave excitation the E_{\parallel} field will diverge from the vacuum field. On approaching the LHR, where E_{\parallel} becomes very strong the vacuum field cannot be used further and simulation results beyond this density with the present code version are not valid. The numerical definition of the breakdown moment in simulations was nevertheless put at the upper validity limit $n_{e,crit}^{SW(LHR)}$, based on [5].

Simulated dependencies on Electric field strength and frequency

E -scan and f -scan simulations at $p_{H_2} = 0.05 \text{ Pa}$ with TEXTOR torus dimensions and a hypothetical one strap antenna with dimensions corresponding to one strap of the TEXTOR double strap antenna are shown in Figure 1(b). The points represent a surface of v_{ion} (See eq. (2)) in the E - f plane. The f -scan suggests a decreasing v_{ion} with increasing frequency in the ICRF range of

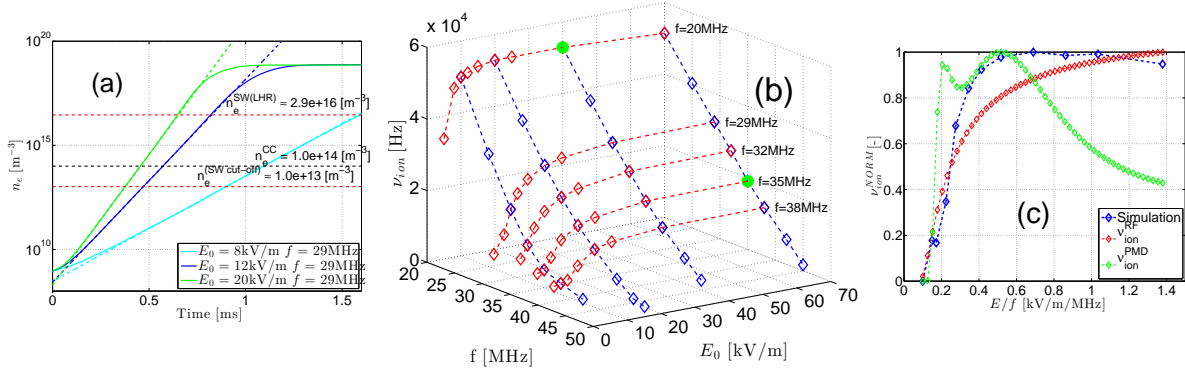


Figure 1: Parametric discharge initiation scans for TEXTOR torus size dimensions for electric field of one strap: (a) n_e as a function of time with exponential fits (Eq. (2)) at $p_{H_2} = 0.05$ Pa, (b) Surface of v_{ion} in E - f plane at $p_{H_2} = 0.05$ Pa, (c) Normalized ionization rate v_{ion}^{NORM} as function of E_0/f for theoretical formulas v_{ion}^{RF} and v_{ion}^{PMD} together with simulated values at $p_{H_2} = 0.01$ Pa.

interest. Furthermore, it is clear that for fixed frequency the values of v_{ion} remain close to unchanged above 25 kV/m, suggesting the existence of an optimal minimal electric field strength above which the ionization rate v_{ion} and also the breakdown time remain constant. For the lower electric fields a rapid increase of v_{ion} is observed from a threshold E_0 where the plasma initiation becomes possible until the described optimal E_0 .

The shape for the simulated E -dependency can be partially explained based on the theory presented in [6], separating the ionization rate near the antenna v_{ion}^{RF} where electrons gain energy from the oscillating RF field, from the ionization rate far from the antenna region v_{ion}^{PMD} where electrons are considered to gain energy from the Ponderomotive force as illustrated in figure 1(c). The approximative theory predicts for both rates a dependency on the ratio of electric field strength and frequency E_0/f . The dependencies are plotted in Figure 1(c) together with simulations at $p_{H_2} = 0.01$ Pa, fixed frequency of 29 MHz and varying E_0 . All three curves were normalized for better legibility. The theoretical E_0/f dependency is however not sufficient to fully describe the v_{ion} dependency on E_0 and f . The ionisation rates for the two green highlighted points shown in Fig. 1(b) with equal E_0/f ratio, given in Table 1, differ by a factor $\sim 2,8$. The latter evidences the need to explore the v_{ion} dependency on E_0 and f by using more sophisticated models (for example RFDinity1D presented here).

E_0	f	E_0/f	v_{ion}
40	20	2,0	$5,283 \cdot 10^4$
70	35	2,0	$1,905 \cdot 10^4$

Table 1: The values of E_0 , f and v_{ion} for same ratio of E_0/f .

RF power scan and pressure scan and comparison with experiments

Simulations with the idealized monopole electric field for TEXTOR torus and antenna dimensions were performed to compare them with the experimental breakdown time (t_{bkdn}) dependencies on RF power and pressure obtained on TEXTOR.

The Figure 2(a) represents t_{bkdn} as a function of the electric field strength in the simula-

tions and the experiments. The experimental t_{bkdn} tendency is clearly reproduced by the simulations. The values for the experimental plot were estimated at best effort from the voltage at the feeding point of the strap via transmission line voltage measurements taking into account the radial exponential decay of the E_{\parallel} field in the torus. The saturation in the experiments occurs around $E_0 \simeq 20\text{ kV/m}$ ($P_{ANT} = 100\text{ kW}$) while the saturation in the simulations starts around $E_0 \simeq 10\text{ kV/m}$.

Experimental breakdown times t_{bkdn} as a function of pressure with constant antenna power $P_{ANT} = 100\text{ kW}$ at $f = 29\text{ MHz}$ are shown in Figure 2(b) (red curve) together with the simulations for $f = 29\text{ MHz}$ and two electric field amplitudes: $E_0 = 5\text{ kV/m}$ and $E_0 = 20\text{ kV/m}$. At higher E_0 , the t_{bkdn} is not expected to vary much (See Fig. 2(a)). Again the simulated trend matches the experimental one.

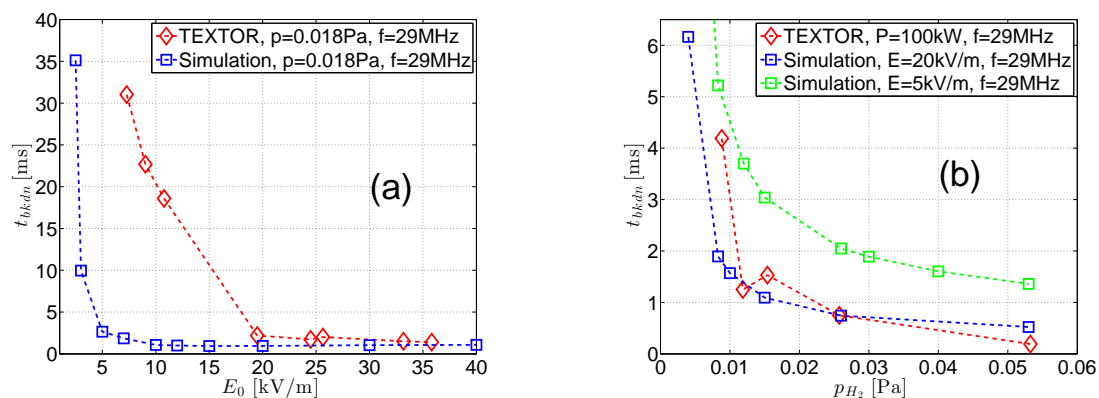


Figure 2: (a) Breakdown time as a function of electric field strength for simulation at $p_{H_2} = 0.018\text{ Pa}$ and $f = 29\text{ MHz}$ (blue line) and for experiment on TEXTOR at $p_{H_2} = 0.018\text{ Pa}$ and $f = 29\text{ MHz}$ (red line), (b) Breakdown time as a function of neutral pressure p_{H_2} at $f = 29\text{ MHz}$ and for two electric field amplitudes $E_0 = 5\text{ kV/m}$ and $E_0 = 20\text{ kV/m}$ (blue and green lines), the red lines represent experimental t_{bkdn} on TEXTOR.

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