RADIO-FREQUENCY WALL CONDITIONING FOR STEADY-STATE STELLARATORS

***Yu.S. Kulyk*[1], *V.E. Moiseenko*[1], *T. Wauters*[2], *A. Lyssoivan*[2]**

[1]Institute Institute of Plasma Physics of the NSC KIPT, Kharkov, Ukraine;

[2]Laboratory for Plasma Physics-ERM/KMS, Association EURATOM - BELGIAN STATE, Brussels, Belgium

Results of numerical modelling of a pulsed discharge used for wall conditioning and sustained by excitation of slow waves at frequencies below the ion cyclotron are presented. The analysis carried out with usage of a self-consistent model that simulates plasma production. The numerical calculations have shown that at the plasma build-up stage, the atoms are generated mainly owing to dissociation of hydrogen molecules by electron impact. When the RF power is off the dissociative recombination of molecular ions with electrons comes to play that is an additional source of atomic hydrogen.

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INTRODUCTION

Plasma production in the ion cyclotron range of frequencies (ICRF) is a possible way to sustain wall conditioning discharge in stellarators [1]. The ICRF heating increase plasma temperature, and plasma electron make ionization of neutral gas by electron impact. At small values of the plasma density, the slow wave is responsible for plasma production. With increase of the plasma density the slow wave is damped propagating to the centre of the plasma column. At high values of plasma density, the Alfvén resonances come to play.

The ICRF antennas are mainly oriented for the fast wave excitation, but the slow wave is important for energy transfer to plasma electrons and plasma production. For SW excitation, the frame antenna could be more effective than strap ICRF antennas. The frame antenna differs from a strap antenna by presence of longitudinal (with respect to the magnetic field) currents.

A discharge sustained by excitation of slow waves at frequencies below the ion cyclotron is used for wall conditioning [2]. The transfer of energy from the wave to the electrons is due to binary collisions. In the discharge, plasma is generated with a density substantially less than the density of neutral hydrogen gas. Low ionization degree is necessary for efficient dissociation of molecules and production of hydrogen atoms. By interaction of the plasma ions and neutral hydrogen atoms with the inner wall surfaces, volatile substances are formed from the impurities covering the wall. The latter can be pumped out from the vacuum chamber. In such a discharge it is important that the plasma density is not high in order to decrease the probability of ionization of desorbed volatile impurities and increase the probability of their pumping.

A similar discharge, but at frequencies higher than ion cyclotron, has been analysed and experimentally tested in Ref. 3. The advantage of the scenario considered here is the lower frequency that facilitates generator and antenna design and lowers the costs of the RF equipment. On the other hand, a high steady magnetic field is necessary for considered scenario. This is provided in machines with the cryogenic magnetic coils.

For successful start-up of the discharge, it is necessary to provide overlapping of the slow wave global resonances. Following paper [3], this is difficult to arrange for low $k_{||}$ resonances. To excite the slow wave with high $k_{||}$, a double frame antenna is used here instead of the single frame antenna used in Ref. 3.

The self-consistent 1D code [4] simulating radio-frequency plasma production in stellarator type machines in the ion cyclotron range of frequencies is used to study such a discharge.

NUMERICAL MODEL

As a prototype, the self-consistent model for RF plasma production in atomic gas [4] is used, which has been developed earlier. A newly developed model is for molecular hydrogen. In addition to the part which calculates a boundary problem for Maxwell's equations, the self-consistent model has a part that calculates particle and heat transport. This part of the code uses the neoclassical diffusion and the elementary processes of plasma interaction with the neutral gas.

In the model the particle balance is determined by ionization of the hydrogen molecule. Among the elementary processes which are accounted for in the model are: ionization, dissociation, rotational and vibrational excitations. Charged particle losses due to dissociative recombination are also added to the particle balance. This is the only nonlinear term in the model. Above mentioned processes are taken into account in the energy balance equation for the plasma electrons. The module, which calculates the neutral hydrogen production rate is developed and included into the code.

The system of the balance equations for particles and energy reads:

$$\frac{3}{2}\frac{\partial(k_B n_e T_e)}{\partial t} = P_{RF} - k_B[\varepsilon_{vibr}\langle\sigma_{vibr}\mathrm{v}\rangle + \varepsilon_d\langle\sigma_d\mathrm{v}\rangle +$$

$$+\varepsilon_i\langle\sigma_i\mathrm{v}\rangle + \varepsilon_e\langle\sigma_e\mathrm{v}\rangle]n_e n_{H_2} - \frac{3}{2}k_B T_e\langle\sigma_{dr}\mathrm{v}\rangle n_e^2 -$$

$$-(C_a+1)\frac{k_B n_e T_i}{\tau_n} - \frac{k_B}{r}\frac{\partial}{\partial r}r\left(q_e + \Gamma_e T_e - \chi n_e\frac{\partial T_e}{\partial r}\right) - e\Gamma_e E_r,$$

$$\frac{dn_e}{dt} = \langle\sigma_i\mathrm{v}\rangle n_e n_{H_2} - \frac{n_e}{\tau_n} - \frac{1}{r}\frac{\partial}{\partial r}r\Gamma_e - \langle\sigma_{dr}\mathrm{v}\rangle n_e^2,$$

$$\int n_e dV + n_{H_2}V_V = const, \qquad (1)$$

where n_e is the plasma density, n_{H2} is the density of molecule hydrogen, T_e is the electron temperature, P_{RF}

is the RF power density of electron heating, k_B is the Boltzmann constant, $\langle\sigma_{vibr}\mathrm{v}\rangle$ is the vibrational excitation rate, $\langle\sigma_d\mathrm{v}\rangle$ is the electron impact dissociation rate, $\langle\sigma_e\mathrm{v}\rangle$ is the electron excitation rate, $\langle\sigma_i\mathrm{v}\rangle$ is the ionization rate, $\langle\sigma_{dr}\mathrm{v}\rangle$ is the dissociative recombination rate, the energy losses of electrons in inelastic collisions are denoted by ε: ε_{vibr}=0.5 eV, ε_d=12.4 eV, ε_e=15.6 eV, ε_i=13.6 eV [5], τ_n is the particle confinement time, V_V is the vacuum chamber volume, and $C_a=e\Phi_a/T_e\approx3.5$ is the ratio of the electron energy in the ambipolar potential to the electron thermal energy. Only electrons with energies higher than the potential energy $e\Phi_a$ leave the plasma.

EXAMPLES OF CALCULATIONS

The following parameters of calculations are chosen: the major radius of the torus is $R=3.5\cdot10^2$ cm; the radius of the plasma column is r_{pl}=40 cm; the radius of the metallic wall is a=60 cm; the toroidal magnetic field is B=3 T. The radial coordinate of the front surface of double-frame antenna (Fig. 1) is r_{ant}=45 cm; angle width of antenna is φ_{ant}=0.75, azimutal size of antenna is ϑ_{ant}=0.085. Antenna is simulated by the external RF currents $\mathbf{j}_{\mathrm{ext}}$ which satisfy the condition $\nabla\cdot\mathbf{j}_{\mathrm{ext}}=0$. The explicit expressions for the Fourier harmonics of the antenna currents are used in the Maxwell's equations.

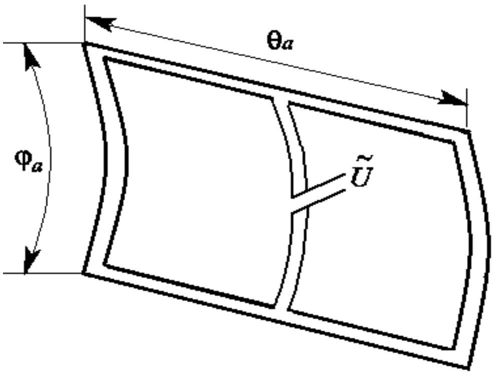

Fig. 1. Sketch of double-frame antenna

The first numerical experiments have shown that for the reason of good charged particle confinement in the stellarator, the continuous discharge with RF power about 10 kW produces dense plasma with low temperature. During plasma production the plasma temperature decreases, and the rate of atomic hydrogen generation reduces. The major part of the power goes to the inelastic collisions, i.e. vibrational and rotational excitation of molecules that do not contribute to the dissociation and atomic hydrogen production. The plasma density increases until the balance is established between the plasma losses and the build-up rate. But since the plasma confinement time is long, even in medium-size machines the plasma production rate is slow. The electron temperature falls to unacceptably low level. As a result, the highest rate of generation of atomic hydrogen is observed at the beginning of the discharge. This is not beneficial for generation of neutral hydrogen atoms which are necessary for wall conditioning.

The idea is to use a pulsed discharge with higher electron temperature during the pulse. The plasma density should grow up since the plasma production rate exceeds plasma losses. In pause between pulses the plasma density decay is provided by the dissociative recombination of the molecular ions. In this process the atomic hydrogen is also generated.

The results of the calculations with the double-frame antenna are presented in Figs. 2-4 which display the time evolution of electron temperature, plasma density and the atomic production rate. Figs. 5-7 display the profiles of plasma density, electron temperature and power deposition at the time moment $t=0.51\cdot10^{-2}$ s (the end of RF pulse).

In Figs. 2a, 2b, one can see that the plasma density increases very rapidly and does not saturate. When the discharge switches off the plasma density decreases as 1/t.

The electron temperature increases up to more than 20 eV, and, after shutdown of the RF pulse, the electron temperature quickly decreases (see Figs. 3a, 3b). This happens because the neutral gas takes the energy of electrons quickly via inelastic collisions.

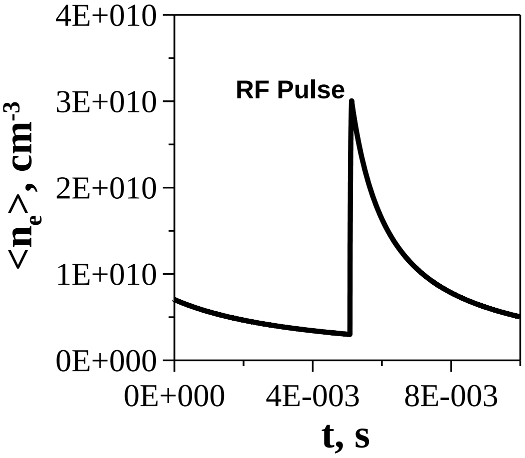

Fig. 2a. Time evolution of average plasma density during pulse period

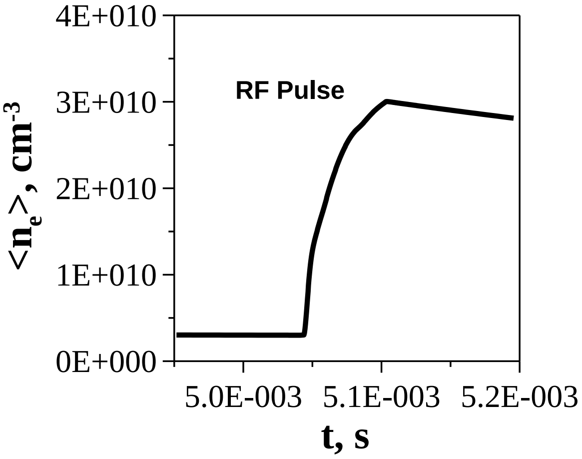

Fig. 2b. Time evolution of average plasma density during RF pulse

The dissociative recombination of molecular ions with electrons comes to play. Note here that the dissociative recombination is more effective at low temperatures.

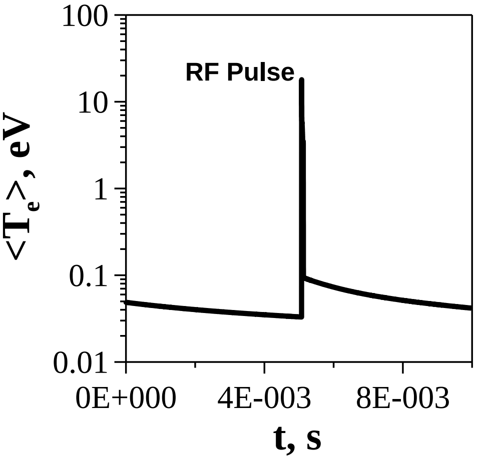

Fig. 3a. Time evolution of average electron temperature during pulse period

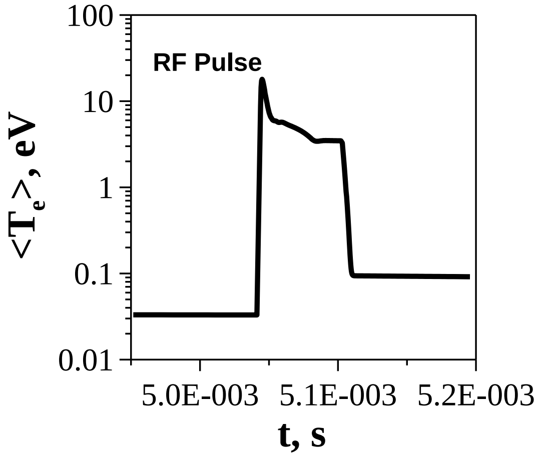

Fig. 3b. Time evolution of average electron temperature during RF pulse

Maximum generation of neutral atoms is observed during the RF pulse (see Fig. 4b). Without RF power neutral atom generation rate abruptly reduces due to the fact that the plasma temperature decreases and the electron impact dissociation becomes ineffective. But the generation of atoms does not stop because dissociative recombination comes to play.

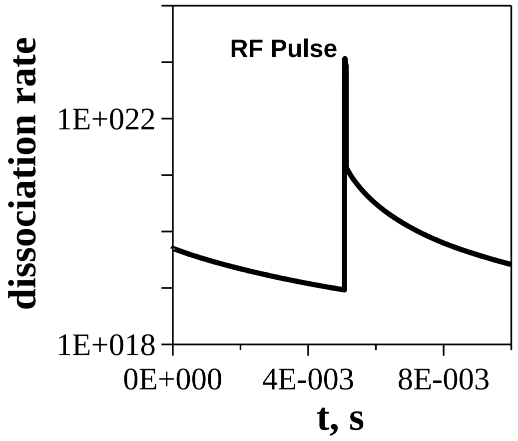

Fig. 4a. Time evolution of dissociation rate during pulse period

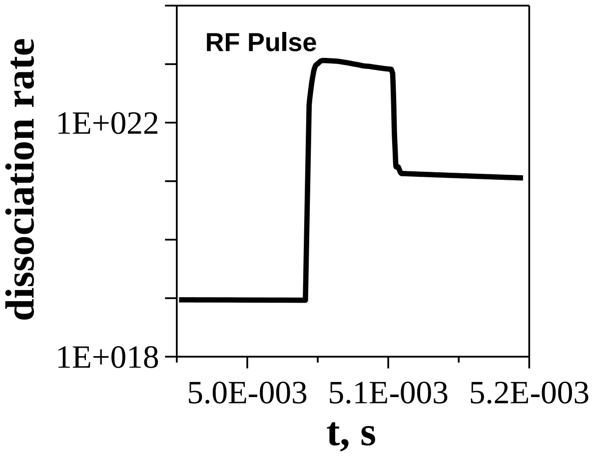

Fig. 4b. Time evolution of dissociation rate during RF pulse

The radial distributions are taken at the end of RF pulse. As seen from Fig. 5 the plasma fills the entire confinement volume, but plasma density radial profile has a small hole in the plasma column centre.

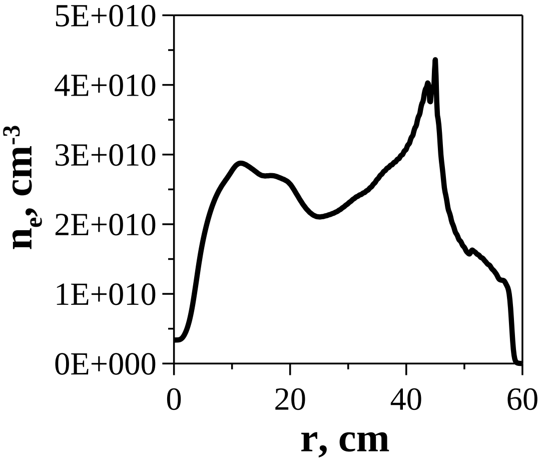

Fig. 5. Plasma density profile at time moment $t=0.51\cdot10^{-2}$ s (and of RF pulse)

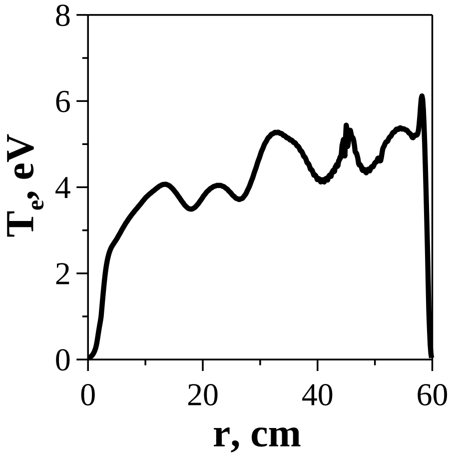

Fig. 6. Electron temperature profile at time moment $t=0.51\cdot10^{-2}$ s

The electron temperature in the confinement volume is higher than 4 eV (Fig. 6). The same temperature is observed at the plasma periphery, where the plasma confinement is poor. In the centre of plasma column the plasma production does not occur because the electron temperature is very low there. This is a result of weak power deposition at the central area (Fig. 7). But at all surrounding arias the plasma production is intensive.

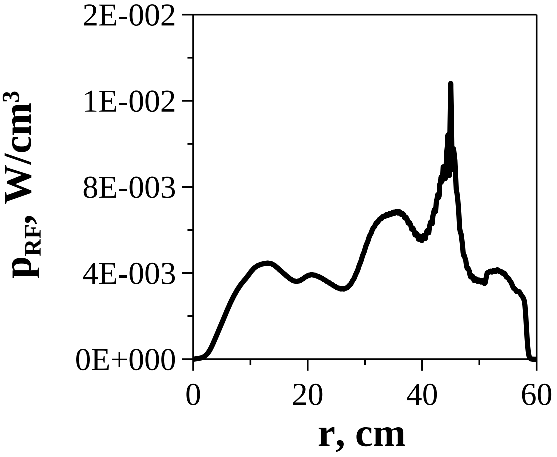

Fig. 7. Power deposition profile at time moment $t=0.51\cdot10^{-2}$ s

DISCUSSION

A scenario of RF discharge with periodic pulses is considered. Such discharge is created for the neutral atoms production, which are used to clean the wall surfaces of vacuum chamber.

Such RF discharge could be initiated in magnetic field that is advantageous for machines with superconducting magnets.

A double-frame antenna that excites the slow wave with suppressed excitation of long-wavelengths modes is used.

At the plasma build-up stage, the atoms are generated mainly owing to dissociation of hydrogen molecules by electron impact. But in addition, in the intervals between pulses, when the RF power is off, the dissociative recombination of molecular ions with electrons comes to play that is an additional source of atomic hydrogen.

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ВЫСОКОЧАСТОТНАЯ ОБРАБОТКА СТЕНОК ДЛЯ СТАЦИОНАРНЫХ СТЕЛЛАРАТОРОВ

Ю.С. Кулик, В.Е. Моисеенко, T. Wauters, A. Lyssoivan

Представлены результаты численного моделирования импульсного разряда для ВЧ-чистки стенок вакуумной камеры, поддерживаемого возбуждением медленной волны на частотах ниже ионной циклотронной. Численный анализ проводился с помощью самосогласованной модели, которая моделирует создание плазмы. Расчёты показали, что во время ВЧ-импульса атомы формируются в основном за счёт диссоциации молекул водорода электронным ударом. Когда ВЧ-питание выключено, вступает в роль диссоциативная рекомбинация молекулярных ионов с электронами, что является дополнительным источником атомарного водорода.

ВИСОКОЧАСТОТНА ОБРОБКА СТІНОК ДЛЯ СТАЦІОНАРНИХ СТЕЛАРАТОРІВ

Ю.С. Кулик, В.Є. Моісеєнко, T. Wauters, A. Lyssoivan

Представлені результати числового моделювання імпульсного розряду для ВЧ-чистки стінок вакуумної камери, підтримуваного збудженням повільної хвилі на частотах нижче іонної циклотронної. Числовий аналіз проводився за допомогою самоузгодженої моделі, що моделює створення плазми. Розрахунки показали, що під час ВЧ-імпульсу атоми формуються в основному за рахунок дисоціації молекул водню електронним ударом. Коли ВЧ-живлення вимкнено, вступає в роль дисоціативна рекомбінація молекулярних іонів з електронами, що є додатковим джерелом атомарного водню.