Dynamics of r.f. production of Stellarator plasmas in the ion cyclotron range of frequency

V.E. Moiseenko, A.I. Lysoivan, S.V. Kasilov, V.V. Plyusnin

Institute of Plasma Physics, National Science Center, Kharkov Institute of Physics and Technology, 310108 Kharkov, Ukraine

Abstract

The present study investigated numerically the process of r.f. production of plasma in the URAGAN-3M torsatron in the frequency range below the ion cyclotron frequency ($\omega < \omega_{ci}$). The dynamics of r.f. plasma build-up at the stages of neutral gas burnout and plasma heating were studied using a zero-dimensional transport code, in which the plasma confinement law was determined by large helical device scaling. Two models for input r.f. power were used. In the first case, the r.f. power absorbed by the electrons was computed by a one-dimensional r.f. code solving Maxwell's boundary problem equations. The mechanisms of electron heating through direct excitation of the slow wave (SW) by antennae as well as the conversion of fast wave (FW) into SW in the vicinity of Alfvén resonance (scenario of Alfvén heating) were taken into account in the computations. In the second case, an 'ideal' model of r.f. power deposition onto the electrons as a linear function of plasma density was employed. A noticeable difference in plasma production dynamics computed for these two cases was found. Better agreement with experimental data obtained from the URAGAN-3M torsatron was found for the first case resulting from combination of the one-dimensional r.f. and zero-dimensional transport codes.

1. Introduction

The production of non-ohmic plasmas using r.f. fields in the frequency range below the ion cyclotron frequency ($\omega < \omega_{ci}$) has been tested successfully on many toroidal machines of the present generation [1]. This r.f. method developed in Kharkov proved to be effective for dense plasma ($n_e > 10^{13}$ cm$^{-3}$) production for a large variety of operational regimes of thermonuclear devices. The results of numerical analysis showed the possibility of r.f. production of plasmas in reactor-scale machines as well as in the present devices [1–3]. Analysis of the basic physical mechanisms responsible for r.f. plasma production has been carried out extensively [1,2,4,5]. As a result of these efforts, a physical model describing qualitatively the process of r.f. plasma production in the ion cyclotron range of frequencies (ICRF) has been developed. It was found that the r.f. discharge passed through a number of consecutive stages: a pre-wave stage of neutral gas breakdown and initial ionization by antennae, r.f. near-field, and wave stages of electron heating by slow wave (SW) excited in the plasma volume either directly by antennae or as a result of Alfvén wave conversion in the vicinity of the local Alfvén resonance (AR).
In this paper, we report the initial results of a quantitative (numerical) description of the wave stages of plasma ICRF (\(\omega < \omega_c\)) production. The combination of a one-dimensional (1D) code for solving Maxwell’s boundary problem together with a zero-dimensional (0D) transport code was used to study the evolution of plasma parameters. The results of numerical modeling are compared with experimental data on r.f. plasma production in the URAGAN-3M torsatron using a frame type (FT) antenna [3].

2. Description of numerical models

2.1. 1D model

The r.f. fields in plasma excited by external FT antennae were calculated using a 1D r.f. code. The toroidal geometry was simulated by the cylindrical approximation via periodicity in the cylindrical axis direction. All equilibrium quantities were assumed to have no variations in the azimuthal direction. In this code, the azimuthal and longitudinal Fourier mode expansions were used. The quantity of Fourier modes taken into account was determined by the permissible level of relative error (about 0.5%). The typical mode number was about 3000. In this model, a dielectric tensor took into account the mechanisms of collisional dissipation as well as electron Landau and ion cyclotron absorption of the r.f. field energy. The ion gyroradius was assumed to be zero.

In the low density phase (\(n_e < 10^6 \text{ cm}^{-3}\)), the plasma density profile was considered to be homogeneous up to the wall. When the density was higher, the profile was considered as a splined curve defined by points. The points in the plasma column interior were taken from experimental measurements (see Ref. [6]). Outside the plasma column, only one point was introduced near the wall. The density value at this point was fixed, \(n_e = 10^6 \text{ cm}^{-3}\). The stationary magnetic field \(B\) was defined by the formula

\[
B = \varepsilon_0 B_0 \left[1 - r^2 R - \frac{1}{2} \left(1 - \frac{1}{\omega_c^2} \omega_2^2 \right) \right]
\]

The dependence \(B\) vs. \(r\) arises from averaging the dielectric tensor over the magnetic surface.

Antennae were modeled by external currents flowing along narrow strap conductors. For these currents, we introduced the requirement \(\nabla \cdot j = 0\), thus excluding from consideration the electrostatic mechanism of wave excitation. The size of the FT antennae was as follows: \(l_z = 70\) cm and \(l_o = 23\) cm (here \(l_z\) and \(l_o\) are the antenna dimensions in toroidal and poloidal directions respectively). The following URAGAN-3M parameters which were typical of the plasma production stage were employed in the computations: major radius \(R = 100\) cm, wall radius \(r_w = 19\) cm, average plasma radius \(\bar{a} = 12\) cm, toroidal magnetic field \(B_0 = 0.47\) T, central electron and ion temperatures \(T_e(0) = T_i(0) = 20\) eV, \(\omega / \omega_c = 0.78\). The FT antenna was positioned at the radius \(r_s = 16\) cm.

It should be noted that the frequency for Alfvén wave heating by this antenna is close to the ion cyclotron frequency because the URAGAN-3M torsatron is a small device.

2.2. 0D model

The dynamics of plasma build-up at the stages of neutral gas (H\(_2\)) burnout and plasma heating was studied using a 0D transport code, in which the plasma confinement law was defined by large helical device (LHD) scaling. The set of transport equations included the equations of energy balance of electrons, ions and atoms as well as particle balance. The electron energy balance included the r.f. power term, energy losses due to radiation and ionization, Coulomb energy exchange with ions, and transport losses described by LHD scaling. The ion energy balance included the energy exchange with electrons and atoms due to Coulomb and charge exchange collisions as well as transport losses. The atom energy balance included energy exchange with ions and energy flux with velocity of sound to the wall of the vacuum chamber. The charged particle balance included the ionization term and the loss term evaluated from LHD scaling. The dynamics of the system with a constant number of particles \((n_e + n_a = \text{const})\) was considered, i.e. the ‘hot’ ions lost at the wall were replaced in the confinement volume by the ‘cold’ atoms (assumption of complete recycling). Parameters typical of neutral gas
r.f. breakdown \((n_e \approx 10^6 \text{ cm}^{-3}, T_e \approx 3 \text{ eV}, T_i \approx T_n = 0.03 \text{ eV} \text{ and } n_n \approx (0.03-3.0) \times 10^{13} \text{ cm}^{-3})\) were used as initial data.

It should be noted that the r.f. power term in the electron energy balance equation is proportional to the antennae loading resistance \(R_p\):

\[
P_{rf} = \frac{(1/2)I_{rf}^2 R_p(n_e).
\]

Here \(I_{rf}\) is the amplitude of the antenna r.f. current (in calculations assumed to be constant during plasma build-up). To describe more correctly the rise in plasma density during wave stages of plasma r.f. production, the dependence of loading resistance vs. plasma density \(R_p(n_e)\) was calculated by the 1D r.f. code. The dependence \(P_{rf}(n_e)\) obtained in this way was then substituted into the 0D transport code.

It should be noted that the present consideration is rather simplified and has some restrictions. The major limitations are that the plasma must be transparent for neutrals and the r.f. power must be deposited into the plasma core. The first requirement limits the value of plasma density. The second requirement is not satisfied when peripheral r.f. power deposition takes place.

3. Results of calculation

Fig. 1 shows the computed loading resistance \(R_p\) vs. plasma density (curve 1). The r.f. power per particle, \(P_{rf}/(V_p n_e)\), is presented by curve 2. The oscillating nature of the deposited r.f. power is a result of excitation of various types of global resonance in the plasma caused by fast Alfvén waves, fast magnetosonic waves, slow waves and conversions between them. To describe analytically the behavior \(P_{rf}(n_e)\), the oscillations of the absorbed r.f. power have been neglected in the present calculations. This approach allowed us to represent the dependence of the r.f. power in the following form (see curve 3 in Fig. 1):

\[
P_{rf} = \left(\frac{n_e}{n_e^*}\right)^{0.78} P_0
\]

where \(P_0\) is the maximum r.f. power level. This r.f. term was substituted into the electron energy balance equation of the 0D model. The temporal evolution of the computed plasma density dependence was compared with experimental data for plasma r.f. production in the URAGAN-3M. Fig. 2 shows the dynamics of the rise in plasma density measured through different chords during plasma production by the FT antennae (RF-1 pulse). From this pulse, we analyzed the line-averaged density signal (central chord 3) in the time interval marked by the arrows. The evolution of the computed and experimental values of plasma density during the plasma production phase is demonstrated in Fig. 3. It is seen that the computed curve 1 describes satisfactorily the experimental dynamics of the rise in plasma density.
results which fit adequately the experimental data obtained in the URAGAN-3M torsatron. Use of the ‘ideal’ model of r.f. power deposition gives the same practical result, but the temporal evolution of the plasma density is quite different from that observed experimentally.

As follows from the calculations, the ‘ideal’ regime of r.f. power input is more efficient than the FT antenna regime; for the same r.f. power level it provides faster ionization of neutral gas (Fig. 3). Therefore antennae should be optimized to approach the ‘ideal’ regime. However, it should be noted that the same effect can be achieved by increasing the direct r.f. power.

The study revealed good properties of FT antennae for plasma densities up to \( n_e \approx 5 \times 10^{12} \text{ cm}^{-3} \). However, in the URAGAN-3M experiments the plasma density is limited to \( n_e \leq 1.5 \times 10^{13} \text{ cm}^{-3} \). To describe this effect, a more accurate numerical model is required. Therefore, the problem of antenna design for dense plasma build-up in the ICRF is relevant. A similar analysis should be performed for future antennae in order to study their properties at the pre-ionization and moderate density stages of plasma build-up.

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References


