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Fast wave heating in a mirror during plasma build-up

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Abstract. A heating method for partially ionized plasma has been described in Ref. [V.E.Moiseenko Sov. J. Plasma Phys. **12**, 427 (1986)]. It exploits the collisional damping of fast waves that is large owing to the high rate of charge exchange collisions. Since the time of heating is limited by the duration of neutral gas ionization, the heating needs to be strong enough to achieve a high final ion temperature. This heating method has been studied numerically in the framework of MHD-like (magneto-hydrodynamic) equations in inhomogeneous cylindrical plasma. The influences of the ratio of the mean free path of the neutral atoms to the plasma radius, the initial ion concentration, the characteristics of the interaction of the neutral atoms with the chamber wall and other parameters on the plasma heating dynamics are examined. A scenario for RF plasma heating in one central cell of the multi-mirror device GOL-3 (Novosibirsk, Russia) is developed, in which the final ion temperature exceeds the ion oscillation energy in the RF field by one order of magnitude. The energy efficiency is high; only a small portion of the power is transferred by the neutral atoms to the chamber wall.

PACS: 52.50.Qt Plasma heating by radio-frequency fields; ICR, ICP, helicons - 52.65.Kj Magnetohydrodynamic and fluid equation.

Short title: V.E. Moiseenko et al: Fast wave heating in a mirror during plasma build-up

1 Introduction

Standard methods for RF (radio frequency) heating of plasmas in magnetic confinement devices for fusion are based on collisionless mechanism for absorption of the wave energy [1,2]. The reason is that the collision rates are low in fully ionized hot plasma. In partially ionized plasma, the rate of charge exchange collisions, in contrast to that of Coulomb collisions, remains significant all the way up to the fusion regime. This opens for a possibility of collisional heating during plasma build up [3].

In a partially ionized hydrogen plasma, the largest rate coefficient is for atomic resonant charge exchange [4]. At medium and high energies it is at least one order of magnitude larger than the cross sections for elastic collisions [5,6]. At small energies some pitch-angle scattering of ions may occur.

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However, in RF discharge all the particles have at least the energy of oscillations, and if it exceeds the certain level (approximately 100 eV) pitch angle scattering can be neglected. The ionization of hydrogen atoms is determined mainly by the electron impact ionization. Since the electron mass is small, electron impact ionization provides no momentum transfer, and recombination is negligible when the ionization is intense. Since elastic collision rate is small, ionization and recombination do not change the pitch-angle, the ion distribution can acquire high perpendicular-parallel anisotropy.

RF heating by collisions has notable advantages. While collisionless heating affects strongly only a small group of resonant particles and distorts the shape of the distribution function, collisional heating involves all particles and the distribution function shape is not seriously distorted. Collisional heating is not associated with any type of wave-particle resonance resulting in Landau damping or cyclotron damping. It can be realized without any connection to collisionless damping of the wave. This provides flexibility for the choice of the heating frequency and parallel wave number spectrum of the antenna currents.

Since the time of heating is limited by the period of neutral gas ionization, the heating needs to be strong enough to achieve a high final ion temperature. The fast waves, particularly the fast magnetosonic wave, could be used because they are strongly damped by charge exchange collisions.

Kinetics of the RF charge exchange heating in infinite homogeneous plasma has been theoretically studied in Ref. 3, where it was shown that the final distribution function of ions is Maxwellian in the velocity space perpendicular to the steady magnetic field. The ion temperature reaches [3] the value $T_i = 2\sigma W_{RF}$ where W_{RF} is the oscillation energy of ions in the RF field, $\sigma = S_c / S_i$, S_c and S_i are the charge exchange and ionization rate coefficients. Since the ionization rate in hydrogen plasma is one order less than the charge exchange rate, the final ion temperature is much higher than the RF oscillation energy.

In such a RF heating scheme the dynamics of the neutral gas plays an important role. During heating the temperature of atoms approaches the ion temperature. High temperature atoms are not magnetically confined and can escape across the plasma column. This effect is important and not accounted for in the infinite uniform plasma model. A goal of the present study is to investigate the influence of radial plasma non-uniformity on the characteristics of RF charge exchange heating.

2 Theoretical model of RF charge exchange heating

The RF charge exchange heating is described by the following system of kinetic equations for the atomic and ion components:

$$\frac{\partial f_i}{\partial t} + \frac{q}{m} \left(\mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B} \right) \frac{\partial f_i}{\partial \mathbf{v}} = L_{ia}, \quad (1a)$$

$$\frac{\partial f_a}{\partial t} + \mathbf{v} \cdot \nabla f_a = L_{ai}; \quad (1b)$$

where q is charge of the ions, m is the ion (atom) mass, $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields, and f_i and f_a are ion and neutral gas distribution functions,

$$L_{ia} = -L_{ai} = S_i n_i f_a + f_a \int \sigma_c |\mathbf{v}' - \mathbf{v}| f_i(\mathbf{v}') d^3 \mathbf{v}' - f_i \int \sigma_c |\mathbf{v}' - \mathbf{v}| f_a(\mathbf{v}') d^3 \mathbf{v}'; \quad (2)$$

are the collisional operators for ion-atom and atom-ion collisions accounting charge exchange and ionization processes. Here n_i is the ion density. It is assumed that the electric field is perpendicular to the steady magnetic field.

In strong magnetic field, the time of plasma diffusion across the magnetic field is significantly larger than the heating duration, the local processes are dominant and the convection term $\mathbf{v} \cdot \nabla f_i$ can be neglected.

Equations (1) do not contain the velocity component parallel to the magnetic field. For this reason the velocity space is considered to be two-dimensional.

From the kinetic equations (1a) and (1b) it is possible to obtain a system of balance equations by the standard procedure of integration in the velocity space with the following weights: unity, $\mathbf{v}$,

$mv^2/2$, for ions and unity, v_r , $mv^2/2$, $mv^2v_r/2$ for neutral gas. This resulting system of equations reads

$$\frac{\partial n_i}{\partial t} = S_i n_a n_i, \quad (3a)$$

$$\frac{\partial \mathbf{V}_i}{\partial t} = \frac{e}{m} \mathbf{E} + \frac{e}{mc} \mathbf{V}_i \times \mathbf{B} + (S_c + S_i)(\mathbf{e}_r \Gamma_a - n_a \mathbf{V}_i), \quad (3b)$$

$$\frac{\partial p_i}{\partial t} = (S_c + S_i) n_i (E_a + n_a W_{RF}) - S_c n_a p_i, \quad (3c)$$

$$\frac{\partial n_a}{\partial t} + \frac{1}{r} \frac{\partial(r \Gamma_a)}{\partial r} = -S_i n_a n_i, \quad (3d)$$

$$m \frac{\partial \Gamma_a}{\partial t} + \frac{\partial}{\partial r} E_a = -(S_i + S_c) m n_i \Gamma_a, \quad (3e)$$

$$\frac{\partial E_a}{\partial t} + \frac{1}{r} \frac{\partial(r Q_a)}{\partial r} = S_c n_a (p_i + n_i W_{RF}) - (S_c + S_i) n_i E_a, \quad (3f)$$

$$\frac{\partial Q_a}{\partial t} + \frac{\partial H}{\partial r} = -(S_i + S_c) n_i Q_a; \quad (3g)$$

where n_i is the ion density, $\mathbf{V}_i$ is the ion oscillating velocity in RF field, $p_i = \int d^2 \mathbf{v} \frac{m(\mathbf{v} - \mathbf{V}_i)^2}{2} f_i$ is

the ion pressure, $E_a = \int d^2 \mathbf{v} \frac{m \mathbf{v}^2}{2} f_a$ is the energy of the neutral component, $\Gamma_a = n_a V_a$ is the radial flux of the atoms, $W_{RF} = m V_i^2 / 2$,

$$Q_a \equiv \int \frac{m \mathbf{v}^2}{2} v_r f_a d^2 \mathbf{v}$$

is the energy flux of atoms, and

$H \equiv \int \frac{m \mathbf{v}^4}{4} f_a d^2 \mathbf{v}$. In the framework of our model, the evolution of the ionization rate S_i is prescribed, where different parameter ranges will be investigated.

Since the MHD approach operates in the space limited to a few low order polynomial moments of the distribution function, the energy dependence of $\sigma_c |\mathbf{v}' - \mathbf{v}|$ cannot be accounted rigorously. To make the system of equations closed, it is assumed that $\sigma_c |\mathbf{v}' - \mathbf{v}|$ depends on the average energy $W_{av} = W_i + E_a / n_a$: $\sigma_c |\mathbf{v}' - \mathbf{v}| \approx S_c = \sigma_c(W_{av}) \sqrt{2W_{av}/m}$. Note also that the ion energy $W_i = p_i / n_i + W_{RF}$ is always not less than the energy of oscillations. Since $\sigma_c |\mathbf{v}' - \mathbf{v}|$ is varying slowly, the error in this approximation is reasonably small.

Equation (3b) determines the ion velocity. It consists of an oscillational part caused by alternating electric field and a small drift part in the azimuthal direction resulted from the action of friction force with the neutral gas. This equation is the only equation in which pure oscillational terms are retained.

To close the system of equations (3) the quantity H needs to be specified. In paper [3] it is shown that the atom and ion distribution functions in the RF heated plasma are close to Maxwellian. In such a case we obtain

$$H \equiv 2E_a^2 / (m n_a); \quad (4)$$

A plasma non-uniformity perturbs the distribution function, and the perturbation is proportional to $z = v_{Ta} / (a S_c n_i)$ where a is the plasma radius and $v_{Ta} = \sqrt{2E_a / (m n_a)}$ is the thermal velocity of the atoms. The parameter z is the ratio of the mean free path of the atoms to the plasma radius. A small

mean free path for charge exchange is considered in the present study, i.e. $z \ll 1$, and formula (4) is used in the system of equations (3).

The term $S_c n_a n_i W_{RF}$ is responsible for the RF heating and appears in the ion pressure equation (3c) and the atomic gas energy equation (3f). In both equations this term has a positive sign, what provides both ion and neutral gas heating. Its proportionality to the charge exchange rate S_c reflects the collisional nature of such heating.

The regularity conditions on the axis $r = 0$ are:

$$\Gamma_a = 0, \quad (5a)$$

$$Q_a = 0; \quad (5b)$$

and the boundary conditions are chosen as:

$$\Gamma_a = \alpha \sqrt{n_a E_a / (2\pi m)}, \quad (6a)$$

$$Q_a = \beta E_a \sqrt{E_a / (2\pi m n_a)}; \quad (6b)$$

The parameter α is the particle outflow coefficient and describes the particle loss at the boundary, while β , the energy outflow coefficient, describes the energy loss. If $\alpha = 0$ particles are fully reflected from the chamber wall, and if $\beta = 0$, the energy does not drain. The case $\alpha = \beta = 1$ corresponds to free leakage of neutral gas through the boundary.

The number of the conditions corresponds to the order of the system of the equations (3d-3g) in the radial coordinate. This justifies the inclusion of the power flux equation into the system. Being the equation for the highest moment of the distribution function, this equation is for an odd moment and there is a need to make an assumption for higher (even) moment to close the system. The assumption for even moments is easier to find and substantiate.

To find the ion oscillation velocity V_i the alternating electric field E should be prescribed. Instead of this we prescribe the space-time dependence of W_{RF} since only through this quantity V_i comes to other equations. For this reason equation (3b) is omitted.

In the system of equations (3), we introduce the normalized quantities $\eta_{i,a} = n_{i,a} / n_0$, $\varepsilon = W_{RF} / W_0$, $\zeta = S_i / S_{i0}$, $\tau = S_{i0} n_0 t$, $\rho = r / a$, $\gamma = \Gamma_a a m S_{i0} / W_0$, $\pi_i = p_i / W_0 n_0$, $e_a = E_a / (W_0 n_0)$, $\vartheta = Q_a a m S_{i0} / W_0^2$ and $\sigma = S_c / S_{0i}$, where n_0 is the sum of the initial gas and plasma densities. The constants S_{i0} and W_0 are chosen so, that the dimensionless quantities ζ and ε are close to unity in average. In the normalized equations,

$$\frac{\partial \eta_i}{\partial \tau} = \zeta \eta_a \eta_i, \quad (7a)$$

$$\frac{\partial \pi_i}{\partial \tau} = (\zeta + \sigma) \eta_i e_a - \sigma \eta_a \pi_i + (\zeta + \sigma) \eta_a \eta_i \varepsilon, \quad (7b)$$

$$\frac{\partial \eta_a}{\partial \tau} + \frac{C}{\rho} \frac{\partial}{\partial \rho} (\rho \gamma) = -\zeta \eta_a \eta_i, \quad (7c)$$

$$\frac{\partial \gamma}{\partial \tau} + \frac{\partial}{\partial \rho} e_a = -(\zeta + \sigma) \gamma \eta_i, \quad (7d)$$

$$\frac{\partial e_a}{\partial \tau} + \frac{C}{\rho} \frac{\partial}{\partial \rho} (\rho \vartheta) = \sigma \eta_a \pi_i - (\zeta + \sigma) \eta_i e_a + \sigma \eta_a \eta_i \varepsilon, \quad (7e)$$

$$\frac{\partial \vartheta}{\partial \tau} + 2 \frac{\partial}{\partial \rho} \left(\frac{e_a^2}{\eta_a} \right) = -(\zeta + \sigma) \vartheta \eta_i; \quad (7f)$$

the parameters of the heating problem are the diffusion parameter $C = W_0 / (m_i a^2 S_{i0}^2 n_0^2)$, the space-time behavior of the collision rates ζ and σ , the oscillation energy profile ε and the boundary loss coefficients α and β .

The following initial conditions are used: The initial normalized ion density and the pressure profiles are parabolic or cubic, i.e. $1 - \rho^2$ or $(1 - \rho)^2(1 + 2\rho)$, and the initial atomic profiles are chosen constant. The initial profiles of the atomic gas flux and the energy flux are set linear and are obeying the boundary conditions.

The system of balance equations (7) is solved numerically by a finite difference method. A staggered space grid is used that provides separated nodes for vector components and scalar quantities. The Crank-Nikolson scheme with first order Runge-Kutta corrections for nonlinear terms is implemented. The rate of convergence of this scheme is proportional to the square of the mesh node number and is in inverse proportion to the square of the time step.

3 Numerical results

An example of a numerical solution of the system of equations (7) is shown in Figure 1. For the computation, the following parameters have been used. The initial plasma density is small and an almost unionized low temperature gas fills the cylindrical volume. The shapes of ion density and pressure are chosen cubic, the oscillation energy is constant along a plasma radius and the diffusion parameter of atomic gas has a moderate value $C = 0.01$. The boundary loss coefficients values are $\alpha = \beta = 0.14$.

During RF heating, the ion density and pressure increase almost simultaneously. When most of the atoms have become ionized, the heating saturates. The overall ion energy evolution is similar to the infinite uniform plasma case, but the behavior of the atomic gas is significantly different. The initial ion density with a maximum at the axis results in a non-uniform atomic gas heating. In the central part of the plasma column the atomic temperature increases faster than at the periphery. The atomic diffusion tends to balance and compensate this temperature gradient. At the plasma periphery, this results in a compression of the cold neutral gas and in a formation of a neutral gas density peak. After that, this density peak travels towards the center with gradually decreasing amplitude owing to the ionization.

The RF heating of the atoms is due to mutual friction between ions and atoms, and as a result both species are heated. Initially, the atomic gas energy increases due to the RF heating. The atomic gas energy reaches a maximum and then goes down because of neutral gas burnout. The temporal evolutions of the ion and the neutral gas temperatures are shown in Figure 2. The ion and the neutral gas temperatures time behavior are almost similar as a result of the charge exchange processes. At the initial stage of the RF heating the temperature profiles are central, as shown in Figure 2a. Later on they become more flat (Figure 2b). This is connected with the density peak that appears at the periphery and after that moves towards the center. The track of this peak is seen in Figure 2c.

In the case of infinite uniform plasma the normalized ion temperature reaches the value 20. In non-uniform plasma the final space averaged ion temperature is only slightly lower (Figure 2b).

The magnitude of the diffusion parameter C is important for the global energy balance. The influence of C on the final ion density and pressure profiles is shown in Figure 3. In case of negligibly small diffusion ($C = 10^{-6}$), the final ion density and pressure profiles are flat for the reason of the homogenous initial gas density and the chosen uniform distribution of RF oscillation energy for the case shown in Figure 3. The final ion pressure is almost equal to the final pressure in the infinite uniform plasma heating case. The heating efficiency decreases with further increase of the diffusion parameter (see Figure 3). In the “threshold” case $C = 0.01$ the energy efficiency of the RF heating is reasonably high and reaches the value 0.8. The ratio of average plasma pressure achieved in this case to the pressure achieved in the case of small diffusion, i.e. $C = 10^{-6}$, is 0.7. With further increase of C the heating quality worsens. Thus, the range $C \leq 0.01$ is useful for the heating.

The influence of the boundary loss coefficients α and β is illustrated by Fig.4. These coefficients influence the near-boundary plasma: An increase of these coefficients decreases the final plasma density and temperature. The plasma density distribution is insensitive to the value of the boundary loss coefficient β , as seen in Figure 4. The reason for this is that the heat flux at the boundary does not directly influence the particle balance.

For the presented set of calculations the ionization rate is high. In practice it can be lower at small plasma densities and increase with the ionization degree. To model this scenario it is assumed that $\zeta = 0.3 + 1.95\eta_i^2$. The value of the normalized charge exchange σ becomes higher because the average value of the ionization rate is smaller. The final plasma parameters in this regime are shown in Figure 5. The increase of heating time results in increased plasma pressure. However, since the diffusion coefficient remains the same, longer heating time causes larger plasma losses.

If the energy of oscillation is non-constant and decreases in time, for instance $\varepsilon = 1 - \tau/60$, the plasma density remains almost unchanged (see Figure 6). As expected, the plasma pressure decreases proportionally to the energy delivered to plasma by the RF field.

When the initial ionization degree is small, its magnitude determines only the time delay of the RF heating, but not the final plasma profiles, see Figure 7. If the ionization degree is high (50% in the plasma center) at the start of the RF heating, the final ion density and pressure profiles becomes more central. The overall loss of the RF heating efficiency compared with the low ionization degree case is reasonably small, as seen in Figure 7.

The oscillation energy profile significantly influences the RF heating (see Figure 8). Besides a flat oscillation energy profile, two profiles $\varepsilon = \sin^2(\pi\rho)$ and $\varepsilon = 1 - (1 - \rho)^2(1 + 2\rho)$ have been investigated. Both of them nullify at the axis $\rho = 0$. The first profile has a maximum at $\rho = 0.5$ and the second profile has a maximum at the boundary. In both cases, two neutral gas density peaks are generated near the boundary and at the axis. The reason for this is the low rate of RF heating of the neutral gas at those locations. The final temperature profile typically follows the RF oscillation energy profile with some smearing caused by the energy transport by the neutral gas.

The time evolution of fluxes towards the wall is shown in Figure 9. The temporal maximum of the neutral gas outflow is associated with the density peak formation at the plasma periphery. The temporal maximum of the energy outflow is in correspondence with the atomic energy peak near the periphery (see Figure 1). The energy efficiency of the RF heating is

$$\eta_\varepsilon = \psi_i / (\psi + w_l);$$

where

$$\psi_i = 2\pi \int_0^1 \pi_i \rho d\rho;$$

is the final ion pressure and

$$w_l = 2\pi \int_0^{\tau_{end}} q_b d\tau;$$

is the lost energy and q_b is the energy flux to the wall. It reaches the value 0.8 for the case in Figure 9.

4 Application to GOL-3 mirror trap

GOL-3 is a multi-mirror device with a plasma radius 3-5 cm, and a high plasma density about $n_0 = 10^{14} - 10^{15} \text{ cm}^{-3}$ [7]. The possibility to use RF charge exchange heating in this device is crucially dependent on the value of the diffusion parameter C . As our calculations have shown, efficient RF heating could be achieved if $C \leq 0.01$. The parameter C is proportional to the RF oscillation energy and is inversely proportional to the plasma density squared. Thus, for a given value of the plasma density an upper limit exists for the RF oscillation energy. For GOL-3 parameters of the plasma density the limiting RF oscillation energy varies from 1eV to 100eV, and thus an efficient RF charge exchange heating is possible only in dense plasma with $n_0 \sim 10^{15} \text{ cm}^{-3}$.

Application of the RF charge exchange heating is here analyzed for one central cell of the GOL-3 device. To minimize the axial variation of the confining magnetic field inside the plasma bunch, the RF heating should be arranged near the magnetic field minimum. In GOL-3 5 cm away from the midplane, the magnetic field has increased by about 20%, and the mirror effect establish some parallel energy, but in average not more than 10% of the perpendicular energy. The parallel energy can therefore be neglected within the accuracy margins of the model. A favourable effect of the mirror field is that almost all RF heated ions of the bunch are expected to be deeply trapped in the magnetic mirror which increases the plasma lifetime.

Temporal evolutions of space averaged ion density and temperature are shown in Figure 10 for different initial gas pressures. In the high-density regime the plasma temperature rises up to 1.4-1.8 keV during 0.5-1.5 microseconds of the RF heating pulse. For the RF oscillation energy level $W_{RF} = 100$ eV in a 10 cm long plasma bunch with 5 cm radius and peak density 10^{15} cm^{-3} , the power that delivered to plasma is $P_{RF} = 2\pi a^2 L W_0 n_0^2 S_{i0} \int_0^1 \eta_a \eta_i (1 + 2\sigma) \epsilon \rho d\rho \approx 100 \text{ MW}$ when the neutral gas and plasma densities are of the same order. Notice here that high power in short pulses has been used previously in non-linear plasma heating experiments [8].

In the model the parameters C and σ depends on the ionization rate coefficient S_i . The ionization rate coefficient is determined mainly by the electron impact ionization mechanism and depends on the electron temperature. The electron impact ionization rate coefficient has a maximum about $3 \cdot 10^{-14} \text{ m}^3/\text{s}$ at electron energy 100eV and the value of $0.5 \cdot 10^{-14} \text{ m}^3/\text{s}$ at $T_e = 10 \text{ eV}$ [9]. The time evolution of GOL-3 ion temperature during RF heating for different values of S_i is shown in the figure 11.. Decrease of the final ion temperature on ionization rate increase can be explained by the decrease of σ . The role of the boundary conditions becomes more important in the case of small S_i for the reason of increase of the diffusion parameter C and, therefore, generation of significant outflow of the neutral atoms to the wall. This also results in decrease of the final ion temperature. However, in both cases the decrease is not dramatic and, a sufficient ion heating has been observed in all cases. An experimental variation of the oscillation energy W_0 allows one to achieve an optimal heating efficiency by balancing the rate of the neutral atoms diffusion and the influence of σ .

The considered heating method is based on collisional wave damping and does not involve cyclotron or Landau damping. Thus, it is not sensitive to the magnetic field strength. The criteria on the frequency choice are the fulfillment of the wave propagation condition and sufficient wave damping within the plasma bunch. The antenna choice would have to be made by modeling the wave propagation, and preliminary estimates for the fast magnetosonic wave excitation indicate a possible scenario with a strap type antenna and with a heating frequency in the 10 MHz range.

Conclusions

An RF heating method for partially ionized plasma that exploits charge exchange collisional dumping of the fast wave has been studied in inhomogeneous cylindrical plasma. An extended system of MHD equations with an equation for heat flux (required for the closure of the problem) has been derived from the kinetic equations and has been used in the numerical model. The model predicts heating in a wide range of plasma parameters. The heating process is accompanied by complex dynamics of the neutral gas. It is shown, that if the diffusion parameter C of the neutral gas in the plasma is less than 0.01 the heating dependence on other parameters is not sensitive, and the heating efficiency exceeds 80%.

A scenario for charge exchange RF heating in one central cell of the multi-mirror GOL-3 device (Novosibirsk, Russia) is developed, in which the final ion temperature exceeds the ion oscillation energy in the RF field by one order of magnitude. The energy efficiency is high and only a small portion of the power is transferred by the neutral atoms to the chamber wall in the case of high plasma density.

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Figure captions

Fig. 1. Dynamics of RF charge exchange heating. The parameters are: $C = 0.01$, $\sigma = 10$, $\alpha = \beta = 0.14$, $\varepsilon = 1$, and the initial conditions are: $\eta_i^{\max} = 10^{-4}$, $\pi_i^{\max} = 0.02\eta_i^{\max}$, $\eta_a = 1$, $e_a = 10^{-5}$.

Fig. 2. Radial profiles of normalized ion Θ_i and neutral gas $\Theta_a = e_a / \eta_a$ temperatures at two instants a) $\tau=9$ and b) $\tau=25$. Time evolutions of Θ_i and Θ_a are shown in c). The parameters and initial conditions are the same as in Fig. 1.

Fig. 3. Final ion density and pressure profiles for different values of the diffusion coefficient C . Same parameters and initial conditions as in Fig. 1.

Fig. 4. Final ion density and pressure profiles for different boundary condition parameters. Other parameters and the initial conditions are as in Fig. 1.

Fig. 5. Final ion density and pressure profiles for varying in time ionization rate (curve 2) in comparison with the standard regime (curve 1). Other parameters and the initial conditions are as in Fig. 1.

Fig. 6. Final ion density and pressure profiles for varying in time energy of oscillation (curve 2) in comparison with the standard regime (curve 1). Other parameters and the initial conditions are as in Fig. 1.

Fig. 7. Final ion density and pressure profiles for different initial ion density. The sum of atomic and ion density is kept constant, i.e. $\eta_i + \eta_a = 1$. Same parameters and other initial conditions are as in Fig. 1.

Fig. 8. RF heating with two cases of non-flat RF oscillation energy profile. a) RF oscillation energy shape b) Final normalized ion temperature profile c) Final normalized ion density profile.

Curve 1 is for $\varepsilon = \sin^2(\pi\rho)$ and curve 2 is for $\varepsilon = 1 - (1 - \rho)^2(1 + 2\rho)$.

Fig. 9. Boundary fluxes during heating. Same parameters and initial conditions as in Fig. 1.

Fig. 10. Time evolution of space averaged ion temperature and density for different initial gas pressures in GOL-3. The parameters are $\sigma = 10$, $\alpha = \beta = 0.35$, $W_{rf} = 100\text{eV}$ and the initial conditions are $\eta_i^{\max} = 10^{-4}$, $\pi_i^{\max} = 0.02\eta_i^{\max}$, $\eta_a = 1$, $e_a = 10^{-5}$.

Figure 11 Time evolution of space averaged ion temperature for different ionization rate coefficients. The parameters $\alpha = \beta = 0.35$, $W_{rf} = 100\text{eV}$ and the initial conditions are, $n_0 \sim 10^{15}\text{cm}^{-3}$, $\eta_i^{\text{max}} = 10^{-4}$, $\pi_i^{\text{max}} = 0.02\eta_i^{\text{max}}$, $\eta_a = 1$, $e_a = 10^{-5}$.

Figure 1 Dynamics of RF charge exchange heating. The parameters are: $C = 0.01$, $\sigma = 10$, $\alpha = \beta = 0.14$, $\varepsilon = 1$, and the initial conditions are: $\eta_i^{\max} = 10^{-4}$, $\pi_i^{\max} = 0.02\eta_i^{\max}$, $\eta_a = 1$, $e_a = 10^{-5}$.

Figure 2 Radial profiles of normalized ion Θ_i and neutral gas $\Theta_a = e_a / \eta_a$ temperatures at two instants a) $\tau=9$ and b) $\tau=25$. Time evolutions of Θ_i and Θ_a are shown in c). The parameters and initial conditions are the same as in Figure 1.

Figure 3 Final ion density and pressure profiles for different values of the diffusion coefficient C . Same parameters and initial conditions as in Figure 1.

Figure 4 Final ion density and pressure profiles for different boundary condition parameters. Other parameters and the initial conditions are as in Figure 1.

Figure 5 Final ion density and pressure profiles for varying in time ionization rate (curve 2) in comparison with the standard regime (curve 1). Other parameters and the initial conditions are as in Figure 1.

Figure 6 Final ion density and pressure profiles for varying in time energy of oscillation (curve 2) in comparison with the standard regime (curve 1). Other parameters and the initial conditions are as in Figure 1.

Figure 7 Final ion density and pressure profiles for different initial ion density. The sum of atomic and ion density is kept constant, i.e. $\eta_i + \eta_a = 1$. Same parameters and other initial conditions are as in Figure 1.

a)

b)

c)

Figure 8 RF heating with two cases of non-flat RF oscillation energy profile. a) RF oscillation energy shape b) Final normalized ion temperature profile c) Final normalized ion density profile. Curve 1 is for $\varepsilon = \sin^2(\pi\rho)$ and curve 2 is for $\varepsilon = 1 - (1 - \rho)^2(1 + 2\rho)$.

Figure 9 Boundary fluxes during heating. Same parameters and initial conditions as in Figure 1.

Figure 10 Computation of time evolution of space averaged ion temperature and density for different initial gas pressures in GOL-3. The parameters are $\sigma = 10$, $\alpha = \beta = 0.35$, $W_{rf} = 100 \text{ eV}$ and the initial conditions are $\eta_i^{\max} = 10^{-4}$, $\pi_i^{\max} = 0.02 \eta_i^{\max}$, $\eta_a = 1$, $e_a = 10^{-5}$.

Figure 11 Computation of time evolution of space averaged ion temperature for different ionization rate coefficients. The parameters $\alpha = \beta = 0.35$, $W_{rf} = 100 \text{ eV}$ and the initial conditions are, $n_0 \sim 10^{15} \text{ cm}^{-3}$, $\eta_i^{\max} = 10^{-4}$, $\pi_i^{\max} = 0.02 \eta_i^{\max}$, $\eta_a = 1$, $e_a = 10^{-5}$.