ELECTROMAGNETIC FIELDS AND HEAVY-ION ORBITING IN A LOW-TEMPERATURE PLASMA WITH A MAGNETIC PUMPING

K.P. Shamrai[1]*, E.N. Kudriavchenko*[2]
[1]*Institute for Nuclear Research, NAS of Ukraine, Kiev, Ukraine;*
[2]*Taras Shevchenko National University, Kiev, Ukraine*

The excitation of LF electromagnetic fields by various antennas in a magnetized plasma with a minor fraction of heavy ions is computed. The efficiency of heavy-ion acceleration owing to the parametric resonance in the ICR frequency range is examined. The effect of heavy-ion collisions with lighter ions and atoms is estimated.

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1. INTRODUCTION

Plasma methods for separation of multi-component substances by atomic mass, which use the ion cyclotron resonance (ICR) heating of a selected ion fraction, are being developed since the 1970th [1,2], in application to the isotope separation for medical and nuclear fusion technologies [2-5], to nuclear waste processing [6], etc. The low-frequency (LF) electromagnetic fields in the ICR frequency range can be excited by various antennas, such as the solenoidal [2,4], helical [3,7], and spiral [7] ones. Wave number spectra and impedances of some antennas were compared in Ref. 7. In Ref. 8, it was shown that the isotope separation selectivity can drop due to the parametric instability arising in quite strong LF fields.

In Ref. 6, ion acceleration was assumed to arise from both the electric force and the nonlinear Lorentz force. This parametric mechanism is a sort of magnetic pumping and differs from the usual ICR mechanism. However, it was discussed in Ref. 6 with a simple model that does not account for actual LF field patterns and ion collisions.

In this paper, the parametric mechanism is analyzed with more realistic model. The excitation of LF field by various antennas in a plasma, which is assumed to include a small fraction of heavy ions, is computed with the full electromagnetic code developed originally for helicon plasmas [9]. The orbits and the rates of heating and radial escape from the plasma of the heavy ions in these fields are examined. Collisions of the heavy ions with lighter ions and atoms are considered with a simple model.

2. THE MODEL AND LF FIELD PROFILES

A plasma mass separation facility is modeled as a plasma column located inside a metal chamber and immersed in a uniform magnetic field B_0 (Fig. 1(*a*)). We assume that the plasma column is produced somehow, e.g., with a helicon discharge as in DEMO plant [10], and is as large as in DEMO: $r_0 = 40$ cm, $L = 200$ cm, and $R = 100$ cm. A LF driving antenna of radius $r_A = 45$ cm contains an ac current of frequency ω and strength I_A. Figure 1(*a*) shows the azimuthally symmetric double-loop antenna (with loop spacing equal to *d*), whereas some azimuthally asymmetric antennas are shown in Fig. 2(*b*).

Consider the double-loop antenna (Fig. 1(*a*)) and a uniform plasma with the electron density and temperature $n_e = 1\times10^{11}$ cm^{-3} and $T_e = 4$ eV. The density of lighter ions (atomic mass $A_i = 30$ a.u.) much exceeds that of heavier ions ($A_H = 30$ a.u.), $n_i >> n_H$, and ion temperatures are $T_i \approx T_H = 0.2$–0.8 eV. The magnetic field ranges $B_0 = 100$–400 G, so that ions are magnetized: $\rho_i < \rho_H < 4.3$ cm. The Helmholtz-type antenna ($d = r_A$) contains in each loop the current ranging $I_A = 0.5$–4 kA, at a frequency within the ICR range for the heavier ions, $\omega \approx \omega_{cH}$, i.e., within the Alfvénic range for the lighter ions.

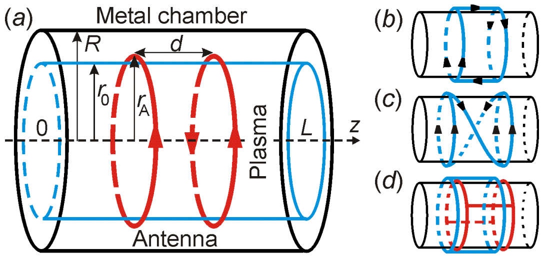

Fig. 1. Sketches of (a) the device, and of various driving antennas: (b) the Nagoya type III (Kharkov), (c) the helical, and (d) the phased Nagoya ones

The field amplitudes computed at $I_A = 1$ kA are considerable within axial antenna location only (Fig. 2). The E_θ-field is the strongest and exists in the plasma bulk. The E_r-field arises at the edge, due to plasma polarization, and the E_z-field is small. The B_z-field is well uniform in the bulk, due to the Helmholtz antenna configuration, and comparable in magnitude with B_0. The B_r-field is also considerable, whereas the B_θ-field is very small. Thus, the plasma has a negligible influence on the LF fields whose main components are practically the same as in the vacuum case. The LF power absorption is very small: the plasma loading resistance amounts to a few μΩ only. The reason is that the Alfvénic waves are too long in this parameter range to fit into the plasma column: $\lambda_A = 2\pi/k_A \sim 70$ m where $k_A = \omega_{cH}/v_A$ (v_A: Alfvénic velocity).

3. ORBITING OF HEAVY IONS

The motion of heavy ions in the LF fields was first examined with collisions neglected, using the equation

$$\ddot{\mathbf{r}} = (e/M_H)\mathbf{E}(\mathbf{r},t) + (e/M_H c)\left[\dot{\mathbf{r}}\times\mathbf{B}_0 + \dot{\mathbf{r}}\times\mathbf{B}(\mathbf{r},t)\right], \quad (1)$$

that takes account of the nonlinear Lorentz force. The ion orbits computed for driving frequencies $\omega \sim \omega_{cH}$, at the antenna current $I_A = 1$ kA and initial conditions $r(0) = 10$ cm, $z(0) = 100$ cm, $v_r(0) = v_z(0) = 0$, $v_\theta(0) = v_{TH} = (T_H/M_H)^{1/2}$ ($T_H = 0.2$ eV), are shown in Fig. 3. As seen, monotonic in time acceleration occurs not only at the ICR frequency, but also within a finite resonance range near.

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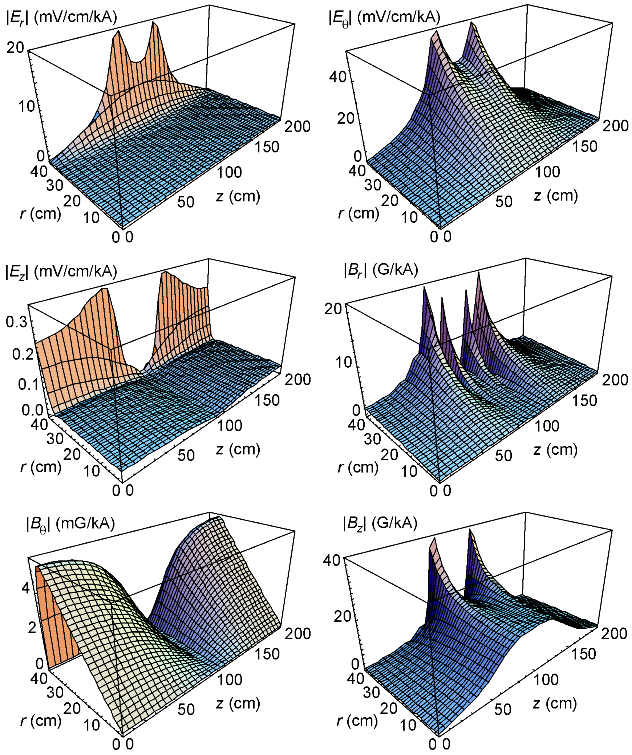


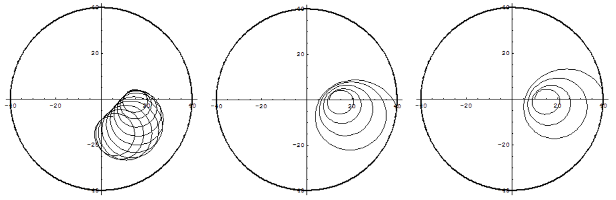
Fig. 2. Profiles of the LF field components, at $I_A = 1$ kA

Orbiting of unconfined ions is pretty peculiar: along with gyroradius growth, the guiding center moves to the periphery until the ion escapes to the wall. This originates from nonlinear (parametric) nature of acceleration under magnetic pumping. Indeed, with neglect of the nonlinear Lorentz force in Eq. (1) the ions are confined in plasma at any frequency. Nonlinearity is also apparent from the fact that the resonance, though much weaker, occurs near the sub-harmonic of the ICR frequency (Fig. 4).

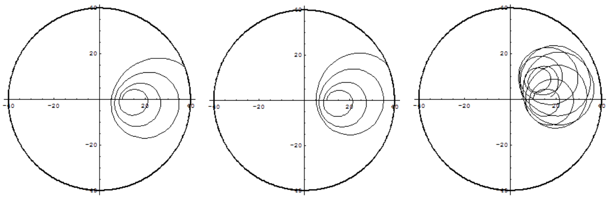
The effect of ion escape was found to depend only slightly on orientation of the initial perpendicular ion velocity. Also, at $\omega \approx \omega_{cH}$ escaping are even the ions with initially small velocities and near-axis positions.

It is suitable to characterize the resonance ion motion by the escape rate, i.e., by the inverse time of ion escape to the wall. The escape rate as function of the pump frequency is shown in Fig. 5(*a*), for the above parameters. As seen, the resonance near the ICR frequency is intense and broad-band, whereas the resonance near the ICR sub-harmonic is much weaker and narrow-band. Both the resonance intensity and bandwidth grow, approximately linearly, with the antenna current, as seen from Fig. 5(*b*). Note that the bandwidth relates to the mass separation selectivity, which is an important characteristic in the isotope separation problem, by the relation

$$\Delta\omega/\omega \approx \Delta M/M. \tag{2}$$

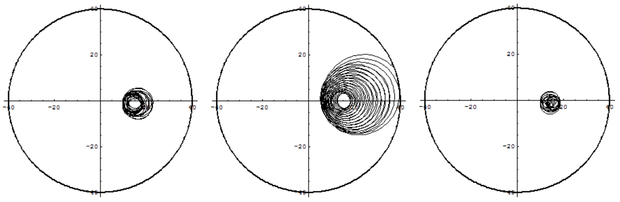


$\omega/\omega_{cH} = 0.90$ $\omega/\omega_{cH} = 0.95$ $\omega/\omega_{cH} = 1.00$



$\omega/\omega_{cH} = 1.05$ $\omega/\omega_{cH} = 1.10$ $\omega/\omega_{cH} = 1.15$

Fig. 3. Heavy-ion orbits at pump frequencies near ω_{cH}



$\omega/\omega_{cH} = 0.45$ $\omega/\omega_{cH} = 0.50$ $\omega/\omega_{cH} = 0.55$

Fig. 4. Heavy-ion orbits at frequencies near (1/2)ω_{cH}

At a fixed antenna current, the resonance bandwidth can be reduced, without substantial loss in the resonance intensity, by increasing the magnetic field B_0 (Fig. 6(*a*)). The escape rates computed at $B_0 = 400$ G and various I_A show qualitative similarity to those at lower B_0 (cf. Figs. 5(*a*) and 6(*b*)). At a fixed antenna current, both the resonance bandwidth and intensity decrease with the magnetic field increase, the former approximately in the inverse proportion whereas the latter by a weaker law.

4. MODELING HEAVY-ION COLLISIONS

The effect of heavy-ion collisions with lighter ions and atoms was examined in a simple model, by adding the friction force $\mathbf{F}_{fr} = -(\nu_{Hi} + \nu_{Ha})\dot{\mathbf{r}}$ in the RHS of Eq. (1) (ν_{Hi} and ν_{Ha} are respective collision frequencies). This model, however, neglects the angular particle scattering. A typical ion orbit and the escape rates computed at $B_0 = 400$ G and the above mentioned initial conditions are shown in Fig. 7. As seen, the friction delays but does not stop the ion escape to the wall. However, the resonance intensity falls and the bandwidth spreads substantially.

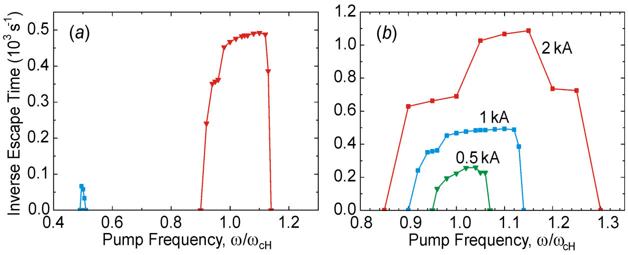


Fig. 5. (a) Escape rates at the fundamental harmonic and the sub-harmonic of the ICR resonance, and (b) the effect of the antenna current on the fundamental resonance

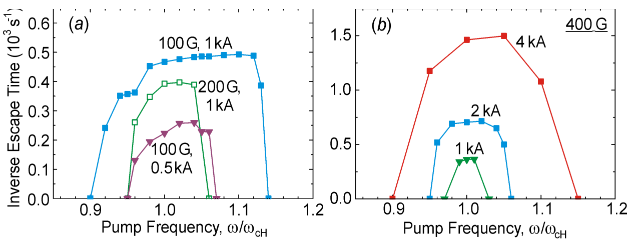
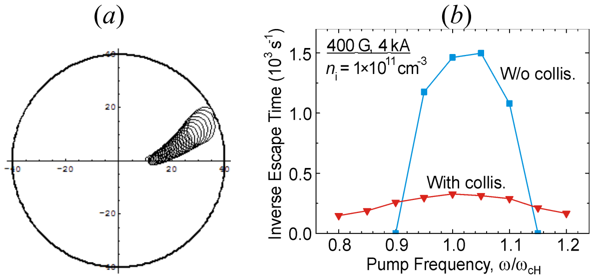


Fig. 6. (a) The effect of magnetic field on the fundamental resonance, and (b) the escape rates at $B_0 = 400$ G



(*a*) (*b*)

Fig. 7. (a) The ion orbit under influence of collisions, and (b) comparison of escape rates with and w/o collisions, at $B_0 = 400$ G and 0.5-mTorr neutral gas pressure

5. PUMPING WITH OTHER ANTENNAS

We have also examined the LF field excitation and ion orbiting with the azimuthally asymmetric driving antennas shown in Figs. 1(*b*)–(*d*). Obviously, the fields of these antennas are well nonuniform azimuthally. As a result, the ions with certain initial azimuthal positions, θ_0, are confined in plasma, i.e., are not escaping to the wall. The phased antenna, in contrast to the Nagoya and helical ones, provides some gain in the ion escape rate, as compared with the double-loop antenna with the same I_A, but for ions with favorable values of θ_0 only.

7. DISCUSSION AND CONCLUSIONS

The field excitation in the Alfvénic frequency range is only slightly affected by plasma and results in a weak power absorption. Thus, the magnetic pumping would not be disturbing for the main, plasma-making discharge.

The magnetic pumping gives rise to the radial heavy-ion escape to the wall at driving frequencies within a resonance band near the ICR frequency and much narrower band near the ICR sub-harmonic. Thus, the ion separation tool may operate within either frequency band and with the ion collector placed radially.

With increasing antenna current, both the resonance intensity and bandwidth grow. For the isotope separation, the former effect may enhance the process productivity, whereas the latter one may worsen the mass selectivity. For nuclear waste processing, which needs only rough mass separation, both effects may be profitable.

With increasing magnetic field, the resonance bandwidth decreases, approximately linearly, whereas the resonance intensity drops only slightly.

The collisional friction delays but does not stop the heavy-ion escape to the wall, provided that the plasma density, neutral gas pressure and magnetic field are such that the total collision frequency is kept well below ω_{cH}. Thus, the operation at higher magnetic fields is preferential for increasing both the process productivity, by increasing the plasma density, and the mass selectivity.

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ЭЛЕКТРОМАГНИТНЫЕ ПОЛЯ И ОРБИТЫ ТЯЖЕЛЫХ ИОНОВ В НИЗКОТЕМПЕРАТУРНОЙ ПЛАЗМЕ С МАГНИТНОЙ НАКАЧКОЙ

К.П. Шамрай, Е.Н. Кудрявченко

Рассчитано возбуждение НЧ- электромагнитных полей различными антеннами в плазме с малой добавкой тяжелых ионов. Исследована эффективность ускорения тяжелых ионов вследствие параметрического резонанса в ИЦР диапазоне частот. Оценен эффект столкновений тяжелых ионов с более легкими ионами и атомами.

ЕЛЕКТРОМАГНІТНІ ПОЛЯ ТА ОРБІТИ ВАЖКИХ ІОНІВ У НИЗЬКОТЕМПЕРАТУРНІЙ ПЛАЗМІ З МАГНІТНОЮ НАКАЧКОЮ

К.П. Шамрай, Є.М. Кудрявченко

Розраховано збудження НЧ- електромагнітних полів різними антенами в плазмі з малою добавкою важких іонів. Досліджено ефективність прискорення важких іонів внаслідок параметричного резонансу в ІЦР діапазоні частот. Оцінено ефект зіткнень важких іонів з легкішими іонами та атомами.