Removal of impurity ions from a plasma during Alfvén-wave absorption

R. A. Demirkhanov, A. G. Kirov, L. F. Ruchko, and A. V. Sukachev

(Submitted 2 March 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **37**, No. 8, 381–383 (20 April 1983)

Experiments in the R-0 stellarator show that the radial transport of impurities can be effectively modified during Alfvén-wave heating. The concentration of impurity ions decreases when the frequency of the rf field is equal to the cyclotron frequency of these ions.

PACS numbers: 52.55.Gb, 52.50.Gj, 52.25.Fi, 52.35.Bj

Previous experiments in the R-0 stellarator have shown that effective plasma heating can be achieved by means of rf fields in the megahertz range,[1] and it is possible to simultaneously excite steady-state entrainment currents and control the radial transport of the plasma.[2] In these experiments, an Alfvén wave was excited near the $\omega = k_{\parallel}(r)v_A(r)$ resonant surface[3]; as this wave was damped by electrons, it transferred energy and momentum to them. Another possibility is a cyclotron mechanism for the damping of the Alfvén wave, by partially ionized impurity ions under the condition $\omega = \omega_{BI} \ll \omega_{Bi}$, where ω_{BI} and ω_{Bi} are the cyclotron frequencies of the impurity ions and of the ions of the main gas, respectively. In this case the Alfvén wave transfers energy and momentum to the impurity ions, thereby influencing their radial transport. Impurity transport during the introduction of particles, momentum, and energy from external sources was studied theoretically in Refs. 4 and 5. We are now beginning to see the first experiments on the impurity behavior during ion cyclotron heating[6] and during gas injection.[7]

In this letter we report a study of the impurity behavior during Alfvén-wave heating of the plasma in the R-0 stellarator (some of these results were reported in Ref. 8), which has the following basic characteristics: $R = 50$ cm, $a = 5$ cm (respectively the major and minor radii of the quartz discharge chamber), $B_0 \leqslant 8$ kG, and $\bar{\iota} \leqslant 0.8$. An rf circuit consisting of eight helical conductors wound around the entire surface of the torus excited an rf field with $m = 2$ and $n = 2$ (m and n are respectively the poloidal and toroidal wave numbers) with a frequency $f = 1.45$ MHz and a pulse length $\tau = 5$ ms. By adjusting the phase of the rf oscillator we were able to excite a wave which propagated along the direction of the toroidal magnetic field and simultaneously opposite the poloidal magnetic field (a $+$ wave), or a wave propagating in the opposite direction (a $-$ wave), or a standing wave (a $\pm$ wave).

The experiments were carried out without ohmic heating. The plasma density was measured by a microwave interferometer with $\lambda = 2$ mm, and the plasma energy was measured with a diamagnetic pickup. For measurements of the electron temperature $\langle T_{e\sigma} \rangle$, a small toroidal current, which did not alter the discharge parameters ($P_{om} \ll P_{rf}, z_{\text{eff}} \approx 2$), was excited in the plasma. The impurity was simulated by injecting an admixture of N_2, He, or Ne ($n_I/n_i \leqslant 5\%$) at the same time as the working gas (H_2 or D_2). At $T_e = 10$–30 eV and $n_e = (2$–$10) \times 10^{13}$ cm^{-3} the intensity of the emission in

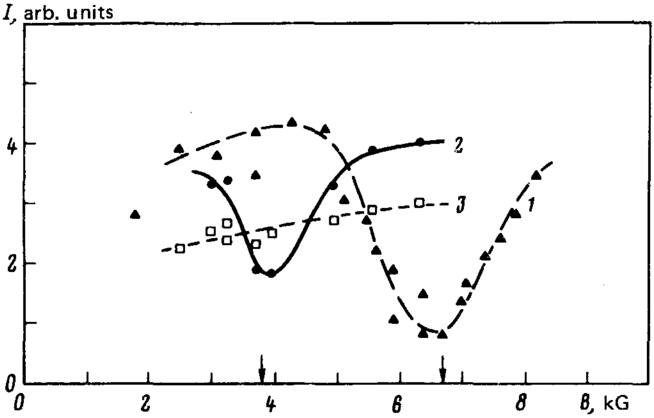

FIG. 1. Intensity of the emission in impurity ion lines from the center of the plasma column vs the magnetic field. 1—N III 4514 Å, $n_N/n_D \approx 4.5\%$, $D_2 + N_2$, $p = 7.7 \times 10^{-4}$ Torr, $x = 0.2$, traveling rf wave (–); 2—He II 4686 Å; 3—Ne II 4392 Å, $n_{He}/n_D \approx 1.5\%$, $n_{Ne}/n_D \approx 1\%$, $D_2 + He + Ne$, $p = 8.1 \times 10^{-4}$ Torr, $x = 0.2$, rf standing wave (±). The arrows show the resonant values of the magnetic field for the He^{+1} and N^{+2} ions.

the He II line ($\lambda = 4686$ Å) and the N III line ($\lambda = 4514$ Å) in the R-0 stellarator is determined primarily by the ion lifetime, and this parameter region was accordingly selected for studying the effect of an rf field on impurity ion transport.

The experiments showed that as the magnetic field is changed the emission inten-

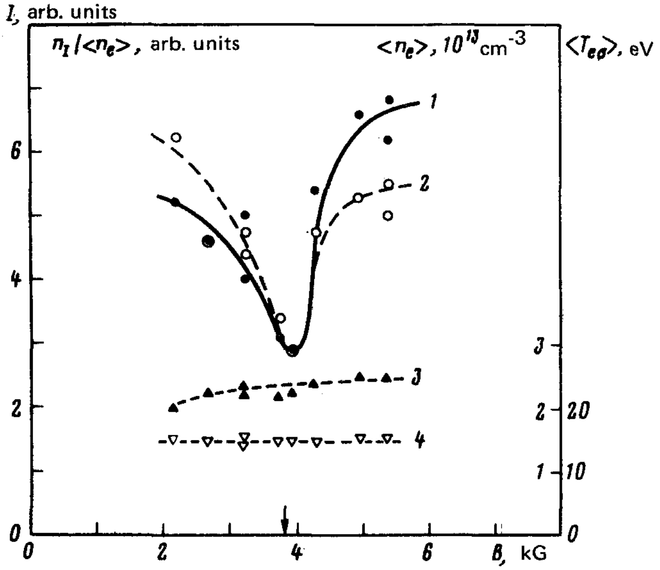

FIG. 2. 1—Intensity of the emission in the He II 4686 Å line from the center of the plasma column; 2—relative density of He^{+1} ions; 3—plasma density; 4—electron temperature. $n_{He}/n_H \approx 4\%$, $H_2 + He$, $p = 6.8 \times 10^{-4}$ Torr, $x = 0.2$, traveling rf wave (–). The arrow shows the resonant value of the magnetic field for He^{+1} ions.

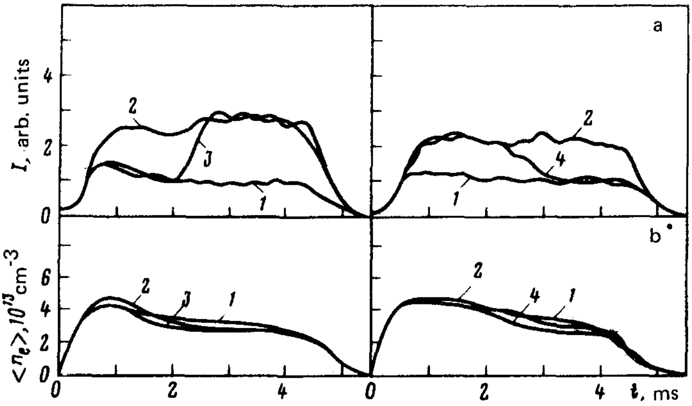

FIG. 3. Intensity of the emission in the He II 4686 Å line from the center of the plasma column (a) and plasma density (b) in the case of a constant magnetic field (1, 2) and a time-varying field (3, 4). 1—$B = 4$ kG$\approx B_{\text{res}}$; 2—$B = 5$ kG; 3—the magnetic field increases during the discharge, from $B = 3.5$ kG to $B = 5$ kG; 4—the field decreases from $B = 5$ kG to $B = 3.2$ kG. $n_{\text{He}}/n_{\text{H}} \approx 3.8\%$, H_2 + He, $p = 7.2 \times 10^{-4}$ Torr, $\varkappa = 0.4$, rf standing wave ($\pm$).

sity of the admixed ions, He II and N III, and thus the densities of these ions fall off significantly when the cyclotron resonance condition, $\omega = \omega_{BI}$, is satisfied for these ions (Fig. 1). There are no structural features in the line emission of Ne II ions (Fig. 1) or of O II, Si II, and Si III ions, which are not at resonance with the rf field. As the propagation direction of the rf wave is changed, the effect—the decrease in the impurity density in the plasma—remains.

The increase in the radial impurity transport does not substantially affect the confinement of the main plasma species, as can be seen from the behavior of the plasma density (curve 3 in Fig. 2) and the temperature (curve 4) as functions of the magnetic field. Also shown in this figure is the behavior of the relative density of He^{+1} ions, calculated from the measurements of $\langle T_e \rangle$ and $\langle n_e \rangle$.

Figure 3 shows the time evolution of the He II line emission intensity as the magnetic field is changed. Oscilloscope traces 1 and 2 correspond to the case of a constant magnetic field during the entire rf field pulse. Trace 1 corresponds to the cyclotron resonance $\omega = \omega_{BI}$ ($B \approx 4$ kG), and the emission in the He II lines is significantly weaker than at $B = 5$ kG (trace 2). When the rf pulse is shifted to the front of the magnetic field pulse, which is a sine half-wave, the emission intensity is low at the beginning of the discharge, while the field is near its resonant value, and it increases with increasing magnetic field (trace 3). When the magnetic field decreases during the discharge (the rf pulse is at the trailing edge of the magnetic field pulse) the emission intensity starts off high and then decreases while the field approaches the resonant value (trace 4).

In summary, these experiments show that rf fields which excite Alfvén waves in a plasma can simultaneously cause an effective heating of the plasma and reduce the equilibrium density of an impurity for which the cyclotron resonance condition, $\omega = \omega_{Bi}$, holds.

I wish to thank L. Ya. Malykh for assistance in these experiments.

[1] A. G. Kirov, L. F. Ruchko, A. V. Sukachov, *et al.*, in: Ninth European Conference on Controlled Fusion and Plasma Physics, Vol. 1, Oxford, 1980, p. 18.
[2] R. A. Demirkhanov, A. G. Kirov, L. F. Ruchko, and A. V. Sukachev, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 31 (1981) [JETP Lett. **33**, 28 (1981)].
[3] A. G. Kirov, L. F. Ruchko, and A. V. Sukachov, in: Second International Symposium on Heating in Toroidal Plasmas, Vol. 2, Como, 1980, p. 689.
[4] S. K. Wong, Phys. Fluids **21**, 299 (1978).
[5] P. B. Parks, K. H. Burrell, and S. K. Wong, Nucl. Fusion **20**, 27 (1980).
[6] TFR Group, Preprint EUR-CEA-FC-1131, 1981.
[7] K. H. Burrell, S. K. Wong, and T. Amano, Nucl. Fusion **20**, 1021 (1980).
[8] R. A. Demirkhanov *et al.*, in: Ninth International Conference on Plasma Physics and Controlled Fusion Research, IAEA-CN-41/J-I-2, Baltimore, 1982.

Translated by Dave Parsons
Edited by S. J. Amoretty