

# Heating of a three-component current-free plasma by Alfvén waves in the Uragan-2 stellarator

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A hydrogen-deuterium plasma has been heated at ion cyclotron resonance. An anomalously rapid heating of nonresonant ions has been observed. A dense ( $\gtrsim 10^{13} \text{ cm}^{-3}$ ), current-free plasma can be produced and heated through the simultaneous use of two rf oscillators at different frequencies.

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One of the most promising methods for heating plasmas in large toroidal confinement systems is the method of ion cyclotron resonance (ICR) for plasmas containing ions of two species. Here a collisionless linear mechanism is used to transfer energy from the rf field to a small group of resonant ions, and then the bulk of the ions (the

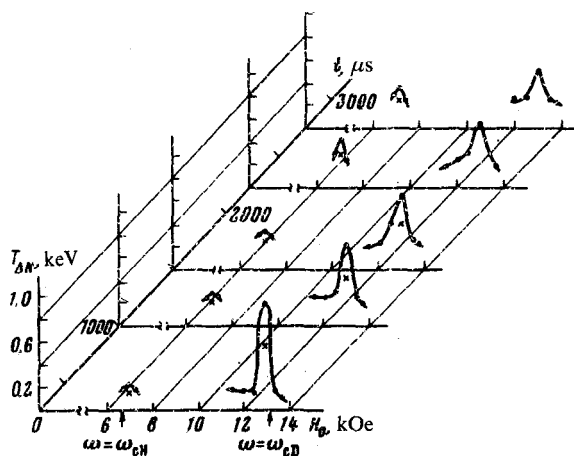


FIG. 1. Dependence of the average energy of the hydrogen ions,  $T_{\text{IH}}(0)$ , and of the deuterium ions,  $T_{\text{ID}}(x)$ , on the longitudinal magnetic field  $H_0$  during the rf pulse ( $\tau_{\text{rf}} = 4.3$  ms).

nonresonant ions) are heated by the resonant ions through Coulomb collisions.<sup>1</sup>

In this letter we are reporting the observation of an anomalously rapid (collisionless) heating of a hydrogen plasma containing a small admixture (up to 10%) of deuterium ions by Alfvén waves (ion cyclotron waves) under ICR conditions for either the deuterium ions ( $\omega \approx \omega_{\text{CD}}$ ) or hydrogen ions ( $\omega \approx \omega_{\text{CH}}$ ). The experiments were carried out in the Uragan-2 racetrack stellarator<sup>2</sup> ( $\bar{a} \approx 7$  cm,  $R = 110$  cm,  $L = 1035$  cm,  $l = 3$ ,  $H_0 \sim 20$  kOe,  $\iota \sim 0.9$ ).

In a first series of experiments, rf power ( $P_{\text{rf}} \approx 300$  kW,  $f \approx 10$  MHz) was fed to the launching device (a loop antenna), which radiated an rf field with a broad spectrum of longitudinal wave harmonics ( $\lambda_z \approx 10^2 - 10^3$  cm). A plasma of density  $\bar{n}_e \sim (4 - 10) \times 10^{12}$  cm<sup>-3</sup> was produced over a broad range of longitudinal magnetic fields for conditions corresponding to the resonant excitation of Alfvén waves. The field range included the ICR regions for both hydrogen ions and deuterium ions,  $\Omega_{\text{H}} = \omega/\omega_{\text{CH}} = 0.4 - 1$ . A substantial heating of the plasma ions was observed at  $H_0 \approx 7$  kOe and  $H_0 \approx 13$  kOe, which are approximately the cyclotron values for the protons and deuterons (Fig. 1). The energy distributions determined for the hydrogen and deuterium ions from the charge exchange of neutrals in the ICR regions corresponding to the two ion species are both highly non-Maxwellian (Fig. 2). In heating at the resonance  $\omega \approx \omega_{\text{CD}}$ , the deuterium energy distribution has a tail at higher energies than does the proton energy distribution. A study of the time dependence of the energy distributions showed, however, that the average proton energy  $T_{\text{IH}}$  exceeded the average deuteron energy  $T_{\text{ID}}$  essentially throughout the plasma heating, for both the hydrogen and deuterium ICR conditions (Fig. 1). Some typical average ion energies and plasma densities (the plasma density was measured with an interferometer operating at the wavelength  $\lambda = 8$  mm) are  $T_{\text{IH}} \sim 1$  keV at  $\bar{n}_e \sim 10^{12}$  cm<sup>-3</sup> for the resonance  $\omega \approx \omega_{\text{CD}}$  and  $T_{\text{IH}} \sim 400$  eV and  $T_{\text{ID}} \sim 300$  eV at  $\bar{n}_e \sim 2 \times 10^{12}$  cm<sup>-3</sup> for the resonance  $\omega \approx \omega_{\text{CH}}$ . Under ICR conditions for deuterium, the hydrogen ions are heated for a time  $t < 0.1$  ms, which is far shorter than the scale time for Coulomb energy exchange between the deuterium and hydrogen ions ( $\tau_{\text{D-H}} \sim 4$  ms at  $n_e \sim n_H \sim 4 \cdot 10^{12}$  cm<sup>-3</sup> and  $T_{\text{D}} \gtrsim 300$  eV). Under these particular experiment conditions, the field amplitude of the wave in the plasma is  $\bar{H}_r \sim 15$

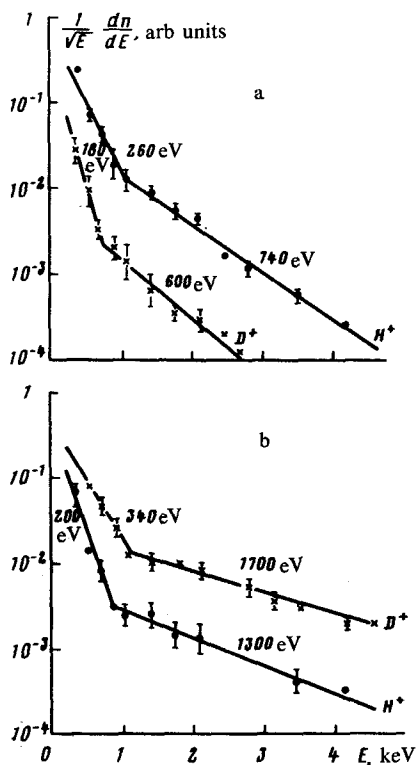


FIG. 2. Proton and deuteron energy distributions measured under ICR conditions. a— $H_0 = 7$  kOe,  $t = 2.0$  ms; b— $H_0 = 13$  kOe,  $t = 0.1$  ms.

kOe in both ICR regions. At such rf fields, the directed velocity of the deuterons in the region of their cyclotron resonance,  $u_{\perp} k_{\perp} c \tilde{H}_{\perp} / 4\pi n_D e \sim 5 \cdot 10^7$  cm/s, is higher than the thermal velocity of the plasma ions,  $v_{Ti}$ . Under these conditions, small-scale beam instabilities are driven in the plasma by the relative oscillations of either ions of different species or ions and electrons. These instabilities have a typical (growth rate  $\gamma$  and a frequency  $\omega$  on the order of the ion plasma frequency  $\omega_{pi}$ , and their wavelengths are  $\lambda_{\perp} \sim u_{\perp} / \omega_{pi}$  (Refs. 3 and 4). At  $u_{\perp} \lesssim v_{Ti}$ , parametric ion cyclotron instabilities are driven<sup>5,6</sup> ( $\omega \sim n\omega_{ci}$ ,  $\lambda_{\perp} \sim u_{\perp} / \omega_{ci}$ ). The scattering of plasma particles by the turbulent fluctuations of the electric field, which result from these plasma instabilities in the Alfvén waves, leads to a rapid turbulent heating of the plasma, at a rate determined by the turbulence level. This turbulence level is particularly high when the ion-ion instabilities reach a high level. The anomalously rapid heating observed for both of the ion species may be caused by either Čerenkov and cyclotron absorption and emission of plasmons or (under strong turbulence conditions) the finite correlation time of the unstable was: “stochastic” heating.

In a second series of experiments we studied the heating of a dense ( $\bar{n}_e \gtrsim 10^{13}$  cm<sup>-3</sup>) current-free plasma during the simultaneous operation of two rf oscillators at different frequencies. The first oscillator, matched to the loop antenna ( $f_1 \approx 10$  MHz,  $P_1 \sim 300$  kW), was used to produce the initial plasma under conditions corresponding to the excitation of Alfvén waves ( $H_0 \approx 10$  kOe,  $\Omega_{IH} \approx 0.44$ ). This plasma was heated

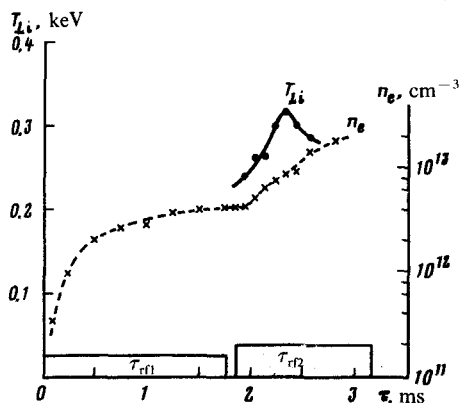


FIG. 3. Time dependence of the density of the resulting plasma,  $\bar{n}_e$ , and of the hydrogen ion temperature  $T_{iH}$  during the operation of two rf oscillators.

by a second rf oscillator ( $f_2 \approx 20$  MHz,  $P_2 \approx 1$  MHz). The rf power from this oscillator was pumped into the plasma under conditions corresponding to the excitation of ion cyclotron waves ( $\Omega_{2H} \approx 0.83$ ) by a slot antenna, which radiated an rf field with a narrow harmonic spectrum ( $\lambda_z \approx 30$ –80 cm). The use of two rf oscillators at the cyclotron resonance for the hydrogen ions led to the production of a current-free plasma with  $T_{iH} \approx 330$  eV and  $\bar{n}_e \approx 10^{13}$  cm $^{-3}$ . The proton energy distribution in this case turned out to be approximately Maxwellian throughout the heating time (there were no high-energy tails on the distributions). Effective plasma heating by the second oscillator was observed, however, only if this oscillator was turned on after the end of the pulse from the first oscillator, so that the rf pulses from the two oscillators did not overlap (Fig. 3). When the pulses did overlap in time, the efficiency of the heating by the second oscillator was substantially reduced. An explanation for this effect must await further experiments.

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<sup>2</sup>V. Z. Amelin *et al.*, *Ukr. Fiz. Zh.* **21**, 422 (1976).

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