JETP LETTERS VOLUME 17, NUMBER 10 20 MAY 1973

OBSERVATION OF INCREASE OF HIGH-FREQUENCY FIELD IN A RESONANT INHOMOGENEOUS-PLASMA LAYER

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Submitted 30 March 1973
ZhETF Pis. Red. 17, No. 10, 541 - 544 (20 May 1973)

We report here an experimental observation of a sharp increase in the azimuthal magnetic field H_ϕ of an ion-cyclotron wave in the region of the so-called resonant layer [1] of an inhomogeneous plasma. In this layer, the square of the longitudinal refractive index $n_\parallel = k_\parallel c/\omega$ is close in value to the component $\varepsilon_1 = -\omega_{pi}^2/(\omega^2 - \omega_{Hi}^2)$ of the dielectric tensor ($n_\parallel^2 \simeq \varepsilon_1$, $\omega < \omega_{Hi}$).

The strong increase of the radial electric field of the wave $E_r \simeq H_\phi/n$ in a resonant layer, analogous to the effect of "swelling" of the field in an inhomogeneous plasma in the region of hybrid resonances [2], was investigated theoretically in [3, 4]. In the vicinity of this layer there can occur a strong absorption of the wave as a result of Cerenkov [3], cyclotron [5], or collision [4] damping. In a number of experiments [6 - 8], they observed strong absorption of waves of frequency $\omega < \omega_{Hi}$ in a plasma, and it was assumed that this absorption is due to the presence of a resonant layer.

The existence of a resonant layer can be used to obtain strong alternating electric fields in a plasma and thereby heat it turbulently. The data reported here were obtained in experiments in which such a possibility is investigated.

The plasma was produced by a strong-current straight discharge in hydrogen at initial pressure $\sim 10^{-3}$ mm Hg, discharge pulse duration $\sim$ 15 μsec, inside diameter of quartz discharge tube 6.2 cm, and distance between electrodes 88 cm. The electric circuit of the plasma source is similar to that described in [9]. The discharge was produced in a quasi-constant longitudinal magnetic field H. The oscillations were excited in the plasma with a Stix coil consisting of eight sections of 8.5 cm diam. The axial period $2\pi/k_\parallel$ of the high-frequency (HF) field generated by the coil was 20 cm. The coil was the inductance of a surge circuit with natural frequency $\omega/2\pi = 6.6$ MHz. The maximum amplitude of the alternating longitudinal magnetic field H_z on the axis reached 200 Oe in vacuum.

The HF field was turned on $\sim$10 μsec after the end of the discharge-current pulse. The character of the radial distribution of the plasma density n(r) at that instant (Fig. 1a) was determined on the basis of a simultaneous observation of the transmitted and reflected microwave signals (the latter in an interferometer scheme) with wavelengths 8.1, 4.0, and 2.2 mm. In the frequency region $\omega \sim \omega_{Hi}$, the plasma absorbed up to 70% of the energy stored in the circuit. The field H_z was appreciably increased thereby (by 2 - 3 times), thus demonstrating that a wave was excited in the plasma.

The radial distribution of H_ϕ was measured with a magnetic probe of 2 mm diam, which was moved along the discharge-tube diameter in a quartz tube (4 mm o.d.) in a space between two neighboring sections of the exciting coil. A plot of $H_\phi(r)$ at a constant magnetic field of 4650 Oe ($\omega = 0.9\omega_{Hi}$) is shown in Fig. 1b. For the same case, Fig. 1c shows the radial dependence of the phase difference $\Delta\theta$ of the field components H_ϕ and H_r (the latter was measured with a miniature magnetic probe located alongside the probe used to measure H_ϕ). The $H_\phi(r)$ plot is characterized by a jumpwise increase of H_ϕ in the vicinity of $r_0 \simeq 1.5$

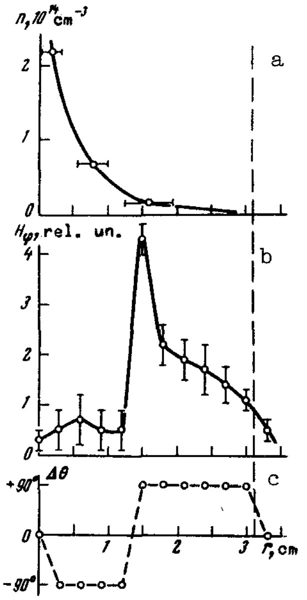

Fig. 1. Radial distribution of plasma density (a), of field H_ϕ (b), and of phase shift between H_r and H_ϕ (c) at H = 4650 Oe. The vertical dashed line marks the position of the tube wall

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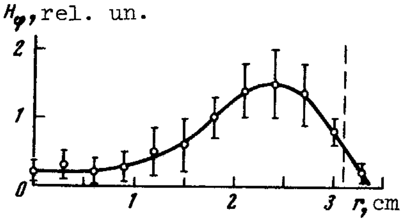

Fig. 2. Radial distribution of field H_ϕ at H = 3000 Oe.

cm. As follows from Fig. 1c, $\Delta\theta$ experiences in this place a 180° jump. At $r > r_0$, the direction of rotation of the vector of the transverse magnetic field of the oscillations, determined from $\Delta\theta$, corresponds to an ion-cyclotron wave. Thus, no ion-cyclotron wave is observed at $r < r_0$.

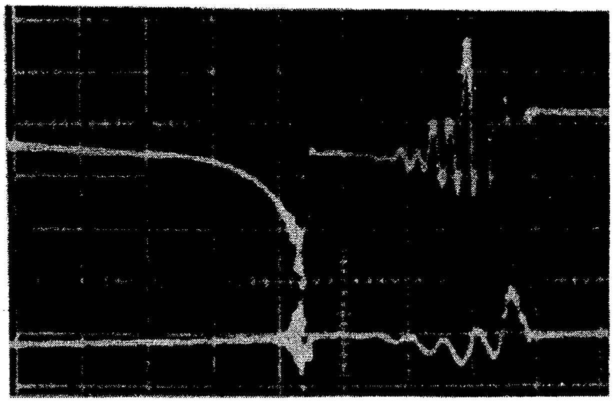

Fig. 3. Upper trace - superimposed oscillograms of direct-discharge current and HF current in the exciting coil; lower trace - diamagnetic signal. Sweep 5 μsec/div.

The aggregate of the data shown in Fig. 1 leads to the conclusion that the jumpwise change of H_ϕ in the vicinity of $r_0 = 1.5$ cm is due to the resonance $n_\parallel^2 \simeq \varepsilon_1$. The plasma density calculated from this equation for the conditions of Fig. 1, $n \simeq 1.0\times10^{13}$ cm^{-3}, is close to the density $n(r_0) \simeq 1.7\times10^{13}$ cm^{-3} determined from Fig. 1a.

As expected, the singularity in the $H_\phi(r)$ dependence does not appear at H = 3000 Oe ($\omega = 1.4\omega_{Hi}$), when the equality $n_\parallel^2 \simeq \varepsilon_1$ is not satisfied for any value of n (Fig. 2, H_ϕ is plotted to the same scale as in Fig. 1).

It follows from a comparison of Figs. 1b and 2 that the field H_ϕ in the resonant layer increases by approximately one order of magnitude. The maximum amplitude of H_ϕ in the resonant layer reached 500 Oe in absolute magnitude. The corresponding order of magnitude of the radial electric field was 700 V/cm. The maximum transverse current velocity is $u_r \simeq k_\parallel c H_\phi / 4\pi n e = 4\times10^7$ cm/sec and greatly exceeds the suggested thermal velocity of the ions ($\lesssim 3\times10^6$ cm/sec). Turbulent heating of the plasma should therefore occur in the vicinity of the resonant layer [10]. When the HF field was turned on, the transverse plasma pressure increased rapidly ($\lesssim 1$ μsec), as registered with a magnetic probe (Fig. 3). Under the conditions of Fig. 1b ($\omega < \omega_{Hi}$), this increase reached 7×10^{15} eV/cm^3. Under the conditions of Fig. 2 ($\omega > \omega_{Hi}$) the increase of the transverse pressure was much smaller. It can therefore be assumed that the increase of the internal plasma energy is due at least in part to heating of the plasma by the strong HF field in the resonant layer observed by us.

We are deeply grateful to I. Yu. Adamov and V. I. Kononenko for help with the work and to A. V. Longinov and K. N. Stepanov for a discussion of the results and valuable advice.

[1] T. H. Stix, Phys. Fluids 3, 19 (1960); T. H. Stix, Theory of Plasma Waves, McGraw, 1962.
[2] V. E. Golant and A. D. Piliya, Usp. Fiz. Nauk 104, 413 (1971) [Sov. Phys.- Usp. 14, 413 (1972)].
[3] V. V. Dolgopolov and K. N. Stepanov, Nuclear Fusion 5, 276 (1965).
[4] V. V. Dologpolov and K. N. Stepanov, Zh. Tekh. Fiz. 36, 1003 (1966) [Sov. Phys.-Tech. Phys. 11, 741 (1966)].
[5] M. P. Vasil'ev, L. I. Grigor'eva, V. V. Dolgopolov, B. I. Smerdov, K. N. Stepanov, and V. V. Chechkin, ibid. 34, 1231 (1964) [9, 953 (1965)].
[6] V. V. Chechkin, M. P. Vasil'ev, L. I. Grigor'eva, and B. I. Smerdov, ibid. 31, 1033 (1961) [6, 755 (1962)].
[7] J. Adam, F. Alvarez de Toledo, P. H. Rebut, and A. Torossian, 2-me Colloque International sur les Interactions Entre les Champs Oscillants et les Plasmas, Saclay, 15 - 19 Jan. 1968, Vol. 1, p. 77.
[8] A. Jigoshi, J. Fujita, S. Sakakibara, N. Inoue, and C. Leloup, Kakayugo Kenkyu 25, 61 (1970); J. Phys. Soc. Japan 31, 315 (1971).
[9] L. V. Dubovoi and V. P. Fedyakov, Zh. Eksp. Teor. Fiz. 53, 789 (1967) [Sov. Phys.-JETP 26, 485 (1968)].

[10] L. I. Grigor'eva, A. V. Longinov, A. I. Pyatak, V. L. Sizonenko, B. I. Smerdov, K. N. Stepanov, and V. V. Chechkin, Plasma Physics and Controlled Nuclear Fusion Research, 1971, Vol. III, IAEA, Vienna, 1971, p. 573.

HYDROGEN LASER IN VACUUM ULTRAVIOLET AT ATMOSPHERIC PRESSURE

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Submitted 2 April 1973; resubmitted 16 April 1973
ZhETF Pis. Red. 17, No. 10, 545 - 548 (20 May 1973)

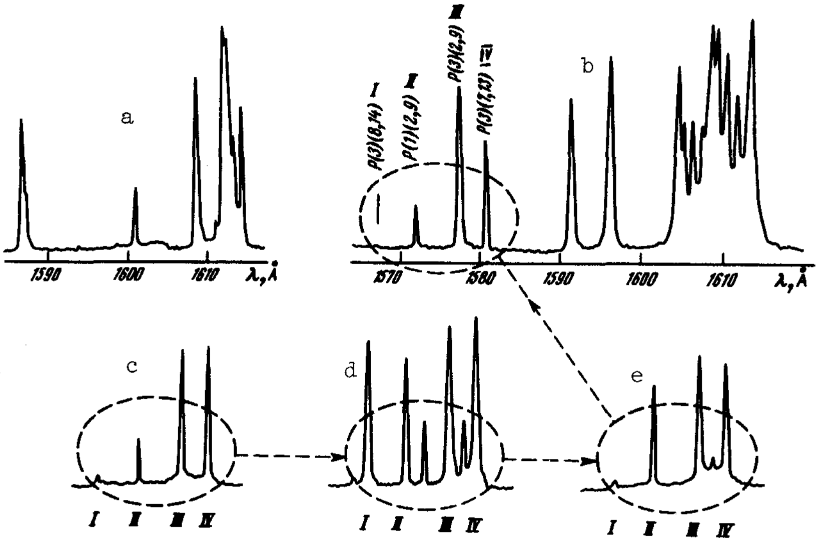
The first observation of superradiance in the vacuum ultraviolet on transitions of molecular hydrogen and deuterium at atmospheric pressure is reported. When the pressure is increased, intensity anomalies are observed in the superradiance spectrum for transitions terminating on vibrational levels near the dissociation limit of the H_2 molecule. Ten new laser transitions were observed.

Quantum electronics methods are being extended to the vacuum ultraviolet (VUV) band by developing pulsed VUV coherent-radiation lasers of high power [1, 2] and by finding new methods of multiplying the frequencies of high-power pulses in the visible band [3, 4]. One of the promising trends is to increase the power of H_2 lasers by increasing the pressure and changing over to four-level operation [5]. We report here significant progress made in this direction.

To obtain lasing at atmospheric pressure, we used a transverse discharge in a working volume $0.006 \times 1 \times 35$ cm^3 of a Blumlein flat transmission line measuring 35 × 60 cm with variable profile and wave resistance 5 Ω through an asymmetrically placed commutator with solid dielectric. The combination of high current density, $j = 10^5$ A/cm^2 with satisfactory spatial uniformity of the plasma improves greatly the conditions of laser excitation in a transverse discharge with a narrow channel. The electrodes were copper foil strips 50 μ thick with polished edges, glued between segments of polished glass at a distance 1 ± 0.05 cm. Visual indication of the short-wave radiation was through a uranyl-glass window with a control glass plate secured 15 cm away from the laser channel inside a vacuum cell.

In the entire investigated pressure interval, up to 1 atm, unidirectional radiation is observed, with divergence ∿2° in the plane of the working channel and ∿1° in the perpendicular plane, at a line voltage somewhat higher than the threshold value V_{thr}. The threshold voltage at atmospheric pressure, $V_{thr} = 28$ kV, is only double the value at $p = 0.1$ atm.

The spectra of the laser cell emission on the electronic transition $B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$ of molecular hydrogen and deuterium at a gas pressure 1 atm were registered with the VMS-1 instrument with wavement-measurement accuracy 0.1 Å. Microphotograms of the emission spectra are shown in the figure. The observed radiation does not satisfy the line-intensity relations



Microphotograms of superradiance spectra of hydrogen and deuterium: a) D_2, 0.6 atm, V = 80 kV; b) H_2, 1 atm, 80 kV; c) H_2, 0.1 atm, 20 kV kV; d) H_2, 0.1 atm, 40 kV; e) H_2, 0.3 atm, 80 kV.