Ionization collapse of rf plasma filament in dense gas

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Direct experimental observations reveal an "explosive" growth to "extremely high" values of the electron density of a plasma filament produced in a dense gas by an intense rf field.

In a discharge caused in a compressed gas by an intense rf field, the ionized region breaks up into filamentary plasma formations which are distributed regularly or randomly, as was shown in Refs. 1–3. These "rf plasma filaments" are thin at the scale of the electromagnetic wavelength. In general, their long dimensions are oriented along the electric vector of the rf field. Extremely limited information is available about the properties of the plasma in these filamentary structures, and the mechanism for their formation is essentially unknown. The time-varying plasma entities observed in rf discharges have recently attracted considerable interest because of theoretical predictions[4] of an explosive increase in the properties of the plasma, followed by a saturation of the growth,[5,6] in solitary-filament structures. The extremely high values of the electron density predicted by the theory—substantially higher than the critical density $n_c = m(\omega^2 + \nu^2)/4\pi e^2$ (ω is the field frequency, and ν is the electron collision rate)—and the extremely high electron temperatures ($T_{e\max} \gtrsim 10$ eV) suggest that a filamentary discharge is a unique plasma formation, with no analogs among the rf discharges which have been described in the literature. In this letter we are reporting the first direct experimental measurement of the properties of an rf plasma filament. These measurements were carried out at a high time resolution, so it is also possible to draw conclusions about the rise time and lifetime of the filament.

The experimental layout is shown in Fig. 1. The working gas was argon or xenon.

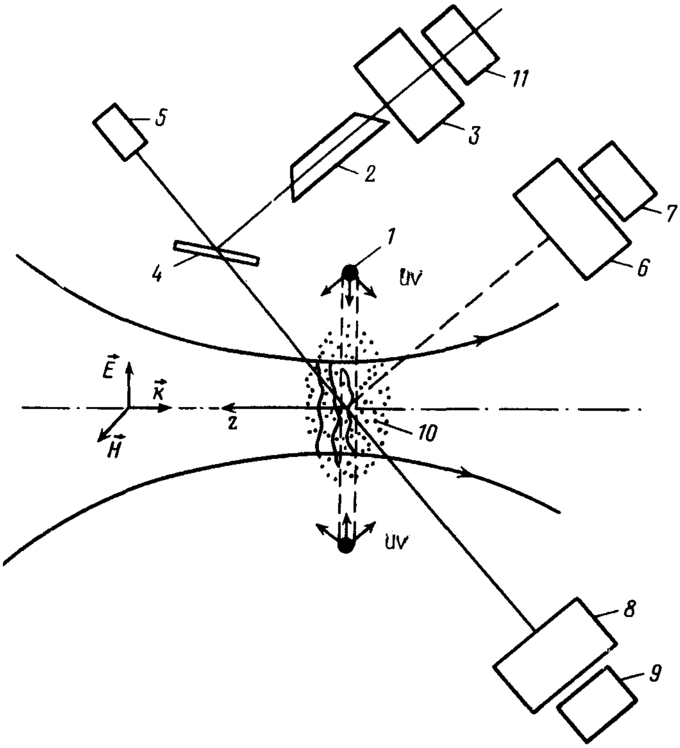

FIG. 1. Experimental layout. 1—Annular source of UV ionizing radiation; 2—tube with glow discharge; 3,6,8—MDR-3 monochromators; 4—beam splitter, 5—diode laser; 7,9,11—photomultipliers; 10—region in which microwave radiation interacts with ionized gas.

An annular source of ionizing radiation created a slab of nearly homogeneous plasma with an electron density $n_{e0} = 10^{12}$ cm^{-3}. A beam of linearly polarized electromagnetic waves was directed into the ionized gas [at a pressure $70 \leqslant p$ (torr) $\leqslant 760$]. The wavelength was $\lambda \cong 2$ cm, the pulsed power $p \leqslant 500$ kW, and the pulse length $\tau \leqslant 100$ μs. A certain time after the electromagnetic pulse was applied we detected a bright flash of light in an originally weakly ionized (with a degree of ionization $\leqslant 5 \times 10^{-7}$) and faintly glowing region. Photography (time-integrated and streak photography) revealed that the flash is associated with the appearance of filamentary plasma formations with a transverse dimension $d \leqslant 0.3$ mm. Their characteristic lifetime (emission time) is on the order of 2–3 μs.

To determine the electron density in the filament, we used spectral diagnostic methods: a passive method involving detection of the intrinsic emission in the visible part of the spectrum and an active method, involving a probing of the ionized region by a diagnostic laser beam in the IR range. Each of these methods was used to determine the electron density on the basis of the Stark broadening of lines[7] detected in the emission or absorption spectrum.

Lines in the spectrum of the intrinsic emission, which was of the nature of a flash

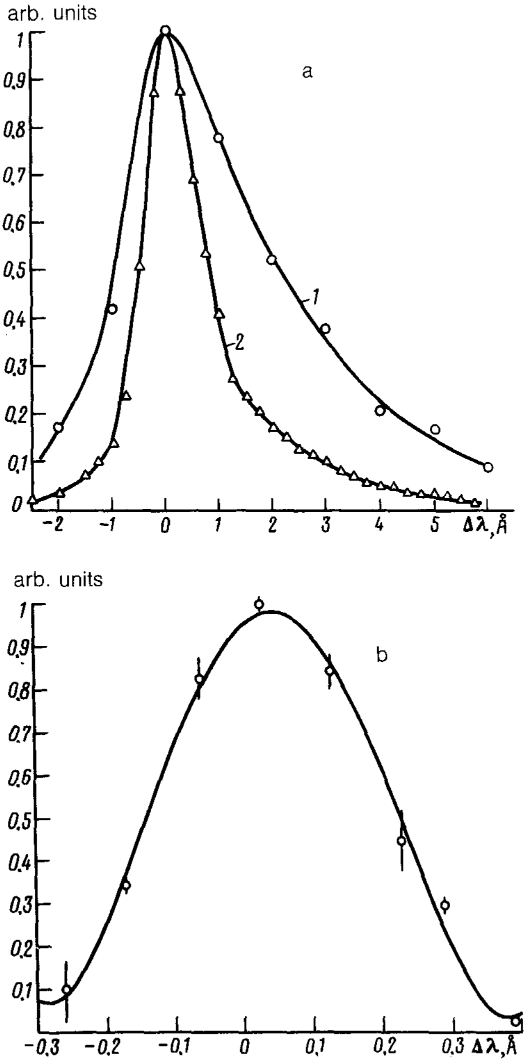

FIG. 2. a: Profiles of emission lines measured at $p = 300$ torr and $S = 40$ kW/cm^2. 1—In argon, ArI ($\lambda_0 = 703$ nm); 2—in xenon, XeI ($\lambda_0 = 467.1$ nm). b: Profile of absorption line in argon from a metastable level [the $^3P_0(4s_3)$–$^3D_1(4p_7)$ transition; $\lambda_0 = 866.8$ nm].

coinciding with the appearance of the plasma filaments, were singled out by an MDR-3 monochromator and detected by a photomultiplier (Fig. 1). Figure 2(a) shows the typical shapes of the lines ArI (7030 Å) and XeI (4671 Å), which are seen to be greatly broadened and asymmetric. Assuming that the brightly emitting filaments are the radiation source (and the absorption region), in which the lineshape is formed, and using the Stark constants of these lines, we can calculate the electron density n_e. The densities found as a result for the two gases (Ar and Xe) were approximately the same, $n_e \approx 5 \times 10^{16}$ cm^{-3}.

In the active spectroscopic method we used a tunable "diode" laser operating in a frequency interval spanning the line ArI (8668 Å) [the $^3P_0(4s_3)$–$^3D_1(4p_7)$ transition]. The extremely high spectral resolution of this method ($\delta\lambda < 0.01$ Å) is unquestionably an advantage; the time resolution is satisfactory ($\delta t \leqslant 0.1$ μs), as is the spatial resolution ($\delta r \approx 5$ mm), which is set by the size of the diagnostic beam. The high sensitivity of this method is another advantage. For the measurements, the laser beam was broken up into two parts, one of which entered the vacuum chamber and passed through the ionized region under study. The second beam went through a glow discharge in a tube filled with argon [the reference signal, which corresponds to the unshifted (null) position of the absorption line]. Figure 2(b) shows a typical profile of the absorption line. Figure 3 shows curves of n_e, calculated from the half-width of the line, versus the initial pressure and the radiation power density. We wish to stress that the spectral methods which we used yield values of n_e which are averages over both the number of lines in the observation region and the lifetime of these lines.

In summary, these measurements show that the electron density in a filament increases from an initial level $n_{e0} \approx 10^{12}$ cm^{-3} to values $n_e > 2 \times 10^{16}$ cm^{-3} (when the displacement of the gas is taken into account, the degree of ionization could approach unity), which are substantially higher than n_c ($n_c \leqslant 10^{15}$ cm^{-3}), in a time $\tau \leqslant 0.5$ μs. These results thus confirm that it is possible to realize a collapsing (explosive) evolution (ionization collapse) of an rf plasma filament in a dense gas. The plasma densities reached in the process are so high that the resonance conditions for ion plasma waves (or ion acoustic waves) can be satisfied, so a parametric mechanism for the dissipation of the rf energy becomes possible. We would also like to point out two important

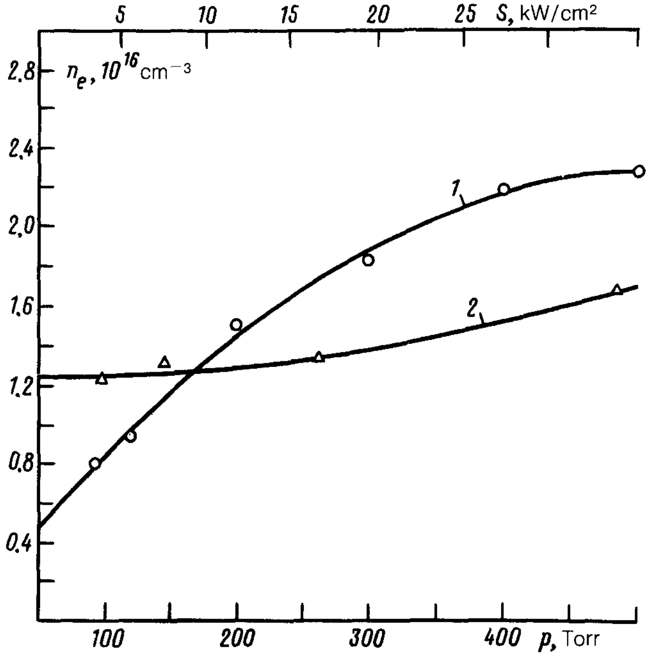

FIG. 3. Curves of n_e versus (1) the initial gas pressure, at $S = 20$ kW/cm^2, and (2) the power density S at $p = 200$ torr.

circumstances which unavoidably accompany the development of the filaments and which are capable of exerting a substantial effect on the overall course of the ionization processes. First, the combination of a high density and a high electron temperature (the average value of T_e measured in these experiments was a few electron volts) makes plasma filaments a source of intense UV light. Second, the substantial and local evolution of energy (on the order of 100 J/cm^3, according to estimates) over such short times ($\leqslant 0.5\ \mu$s) should lead to the excitation of strong shock waves.

[1] G. M. Batanov *et al.*, in *Proceedings of the Lebedev Physics Institute*, Vol. 160, Nauka, Moscow, 1985, p. 174.

[2] G. L. Bogomolov *et al,*, Zh. Eksp. Teor. Fiz. **93**, 519 (1987) [Sov. Phys. JETP **66**, 295 (1987)].

[3] A. L. Vikharev *et al.*, Zh. Eksp. Teor. Fiz. **94** (4), 136 (1988) [Sov. Phys. JETP **67**, 724 (1988)].

[4] A. V. Kim and G. M. Fraĭman, Fiz. Plazmy **9**, 604 (1983) [Sov. J. Plasma Phys. **9**, 352 (1983)].

[5] E. Ya. Kogan and B. Yu. Kuzin, Zh. Prikl. Mekh. Tekh. Fiz. **3**, 28 (1988).

[6] I. B. Bokolishvili *et al.*, Preprint 86, Institute of Applied Mathematics, Academy of Sciences of the USSR, 1989.

[7] H. R. Griem, *Spectral Line Broadening by Plasmas, Academic,* New York, 1974.

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