Experimental investigation of nonstationary streamer formations in a microwave plasma column at high pressures

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Spectrometric investigations of a microwave plasma column at high pressures in Kapitza devices are described. The procedures used to measure, with spatial and temporal resolution, the column emission in the ultrasoft x-ray, vacuum-ultraviolet, and visible bands and to diagnose the filament plasma by laser scattering are described. It is found that irregular microsecond spikes of vacuum-ultraviolet radiation and ultrasoft x rays are emitted from streamer formations in a plasma filament having an average temperature less than one eV. The emission takes the form of short-lived filaments with average effective electron temperature up to several electron volts.

Investigations of a freely floating plasma column produced by a powerful microwave field in a cavity at high gas pressure were carried out under the direction of Academician P. L. Kapitza for more than two decades up to his death in 1984. The first detailed description of the production and the basic properties of the column was published by Kapitza in 1969.[1] The research results reported in that article have shown that the column is a rather complicated plasma formation and that traditional diagnostic methods are inadequate for a complete picture of the physical phenomena in a plasma column. These difficulties were pointed out by Kapitza himself in later papers[2,3] devoted to investigations of the column. During the first stage of the research, in particular, it was impossible to explain unequivocally such phenomena as the presence of an appreciable continuous background emission in the extreme ultraviolet, the peculiarities in the distribution of the spectral-line brightness in pure gases and their mixtures, the onset of both coarse- and fine-structure instabilities at different microwave powers absorbed by the column, and a number of other phenomena. More specifically, measurements of radiation from a plasma column in hydrogen, using a Geiger counter and an ionization chamber, have shown that the radiation intensity in the wavelength range 1050–1250 Å reaches $5\cdot 10^{15}$ photons/s, which is 10^6–10^8 higher than the intensities of the recombination radiation and bremsstrahlung of a plasma having an electron temperatured $T = 0.5$ eV (Ref. 1) as well as of the H^- continuum.[4]

Results of somewhat later spectral measurements performed with a vacuum spectrometer and recorded with a Geiger counter are shown in Fig. 1a (curve 1). Analysis[4] shows that this spectrum is due to the broadband emission of molecular hydrogen and to a continuum that extends from the transmission limit of the LiF counter window into the long-wave region. For comparison, curve 2 of Fig. 1 shows the spectrum, measured by the same procedure, of a dc arc discharge in deuterium having a plasma electron temperature $T_e = 1$ eV, an electron density $n_e = 10^{16}$ cm^3, and the same characteristic dimensions as the microwave discharge. Comparison of the curves shows that the arc emission does not contain a noticeable continuum background in the extreme ultraviolet.

The succeeding diagnostic investigations were aimed at obtaining additional information on the discharge properties. In particular, to determine the nature of the filament emission in the extreme ultraviolet, methods were developed for plasma diagnostics with high spatial and temporal resolution in the vacuum ultraviolet (VUV) and in the ultrasoft x-ray (USX) bands, and also for column diagnostics by laser-emission scattering.

The experiments were performed under the direction of P. L. Kaptiza for a number of years, mainly in two installations, viz., N-220 (wavelength 19 cm, discharge power up to 15 kW) and the larger N-550 (wavelength 58 cm, discharge power up to 45 kW). They could be filled with different gases or mixtures at pressures up to 9 atm (small installation), and up to 4 atm (large installation). Most experiments were performed in hydrogen and deuterium. The construction of the N-220 installation is described in Refs. 1 and 2. The N-550 operates on the same principles. Many calibration measurements in the VUV were performed with a microwave system built later with a slit entry port[3,5] (wavelength 19 cm, discharge power up to 100 kW).

The measurement methods and the experimental results were recorded only in laboratory reports, dissertations,[6–10] brief preliminary communications and conference papers,[11–19] heretofore not published in detail. The present paper partially fills this gap.

1. MEASUREMENTS BY LASER SCATTERING

The laser-beam scattering method is used quite extensively to measure the electron temperature of a plasma,[20] but the diagnostic setup for the study of the plasma column had to satisfy a number of specific requirements. The position of the plasma pinch in the cavity was stabilized by rotating the gas, but nevertheless the plasma column oscillated somewhat irregularly about an equilibrium position near the cavity axis. The amplitude of these oscillations was approximately 1 cm, the diameter of the plasma column in the central cross section was of the same order, and the characteristic column-displacement velocity ranged from 0.1 to 1 m/s. The plasma column was therefore probed by the laser pulse only at that instant when the column reached the region where the optical axes of the probe beam and of the monochromator receiver optical system intersected.

The position of the plasma column was observed with a spectroscopic photoelectric tracking system, in which the coordinate pickups were two LI-602 dissectors. The angle

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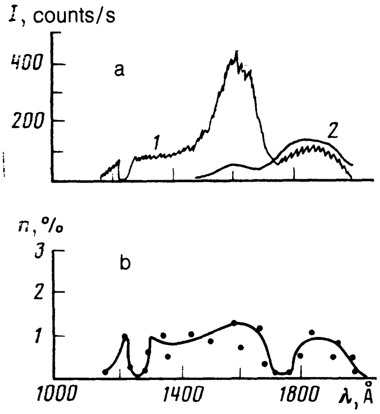

FIG. 1. Spectra of discharges in deuterium. a) Measurements with a counter without spatial and temporal resolution: 1—microwave plasma-column spectrum; 2—dc-arc spectrum. b) Streamer spectrum measured by coincidences with a standard counter (the ordinates represent percentages of the spectrograph counts). Deuterium pressure in microwave installation 1.3 atm; column power 10 kW.

between optical axes of the dissectors was 90° (or 60° in the larger installation). The electronic image of the plasma column from the dissector photocathodes was scanned with a sawtooth voltage at 10 kHz.[21] After the reduction of the dissector signals by the electronic system, it was possible to determine the instant at which the column reached a prescribed point. At the same time, the dimensions and shape of the transverse column were measured, as well as its displacement velocity. In most measurements the laser pulse was synchronized with the instant at which the column center (the maximum emittance of the column along the two coordinates) landed in the chosen observation point. The accuracy was ± 0.5 mm.

The transverse dimension of the plasma region from which the scattered signal was observed was determined by the diameter of the laser beam near the focus, while the longitudinal dimension (along the laser beam) was determined by the aperture of the receiving optical system. The minimum diameter of the observation region in the experiments was 0.5 mm, and the minimum longitudinal diameter was also 0.5 mm. The filament center passed through this region infrequently, approximately one every 3–5 minutes.

In the scattering experiments we used a ruby laser actively Q-switched by a Pockels cell. The laser generated pulses of 30 ns duration, with energy ≈ 1 J and beam divergence $5\cdot 10^{-3}$ rad. An additional laser amplifier with output pulse energy up to 6 J was used in some individual experiments.

The focused laser beam entered the cavity though a glass window and a system of diaphragms, and was extracted through a Brewster-angle window with a conical optical trap. The spectrum of the scattered radiation was observed at 90° with an SDL-1 monochromator feeding an FÉU-79 photomultiplier. The measurements were performed on the blue wing of the scattering spectrum; the monochromator wavelength was varied point by point with a spectral resolution 2–10 Å. About one hundred laser pulses were used in each measurement run.

Particular attention was paid to suppression of parasitic scattering of the laser radiation from the elements of the optical channel, and the gas in the setup was carefully made dust-free prior to the experiments. As a result, the parasitic scattering in experiments with 2 mm spatial resolution was $5\cdot 10^{-3}$ of the Rayleigh scattering in N_2 under normal conditions, so that it was possible to record also the central part of the spectrum of the scattering from the plasma. When, however, an optical system of shorter focal length was used in the laser optical channel and the spatial resolution was improved to 0.5 mm, the parasitic scattering level increased drastically and the scattering spectrum could be reliably recorded only at a distance ~ 10 Å from the laser line.

Another major difficulty in the observation of the scattering spectrum was that at wavelengths close to 7000 Å, where the measurements were made, the radiation from the plasma column was appreciable. The measurements have shown that the spectral intensity of this radiation is comparable with that of the radiation scattered from a plasma with $n_e = 10^{14}$ cm^{-3} and $T_e = 1$ eV at a distance 10 Å from the wavelength of a laser of pulse energy 1 J. The procedure for measuring the scattered radiation was therefore the following. The gain of the receiving photomultiplier was strobed twice by a 60-ns pulse, first in synchronism with the laser pulse, and then again at 100 μs after the pulse.[22] The useful signal was the difference between these two signals, with account taken of the measured statistical properties of the particular photomultiplier used.[23] This also suppressed considerably the plasma luminance and furthermore practically eliminated the dark noise of the photomultiplier. In such a method, of course, plasma luminance fluctuations of duration on the order of 100 μm are not recorded. However, direct measurements of the column luminance with resolution up to 10 ns revealed no noticeable fluctuations. The photomultiplier load was a calibrated capacitor, the voltage across which was proportional (with allowance for the statistical properties of the photomultiplier) to the number of the photoelectrons in the strobing pulse.[24] This moreover made it possible to store scattering signals in a recording oscilloscope operating at relatively low frequency.

Each set of measurements of the scattering from the plasma was preceded and followed by an absolute amplitude calibration of the diagnostic system. It is known[20] the absolute amplitude calibration makes it possible to determine from the scattering spectra not only the electron temperature but also the local electron density. We have calibrated the diagnostic system against the spontaneous Raman scattering (SRS) from the rotational levels of H_2 (or D_2). The lines of this scattering are shifted by up to several hundred angstrom from the exciting line, so that, in contrast to calibration with Rayleigh scattering, there is no need for complete elimination of the parasitic scattering. The cross sections for this scattering in H_2 and D_2 were measured beforehand with high precision.[25] Calibration against SRS was convenient also because it permitted straightforward monitoring of the parameters of the diagnostic setup in the course of the plasma experiments, since the plasma of the same gas was investigated.

The scattering experiments were performed at various pressures and powers. The measurement procedure permitted, in principle, observations of radiation scattered by electrons of energy up to 100 eV. However, only the scattering spectrum corresponding to $T_e = 0.7$–0.9 eV could be reli-

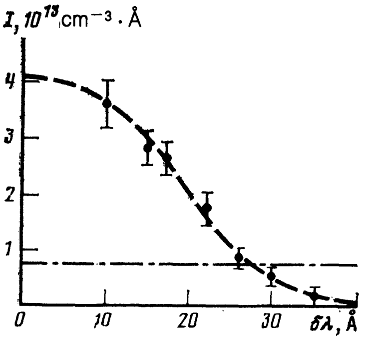

FIG. 2. Spectrum of laser-beam scattering by a plasma column. Deuterium pressure 2 atm, power in column 9 kW. Dash-dot line—averaged background of intrinsic column radiation.

ably recorded in all the experiments. Figure 2 shows one of the recorded spectra.

The electron density determined from the scattering spectra (up to $4\cdot10^{15}$ cm^{-3} agreed to within 20% with the results obtained by submillimeter interferometry[33] and from the Stark broadening of hydrogen lines in the optical band.[1]

Laser scattering has thus permitted measurement of the local electron density and density in the plasma column. These experiments, however, yielded only the low-temperature component of the plasma, without reliable information on the higher-energy electrons responsible for the observed radiation. The succeeding efforts were therefore aimed at developing new diagnostic techniques for the VUV and shorter-wavelength regions of the spectrum, with allowance for the specific features of the plasma column.

2. INVESTIGATION OF VUV RADIATION OF A PLASMA COLUMN BY PROPORTIONAL COORDINATE COUNTERS

We have already mentioned that in contrast to traditional arc,[26] hf,[27] and microwave[28] discharges, a plasma column in a microwave cavity becomes localized far from the walls. With the circulating gas continuously cleaned, this permitted the plasma to be investigated at a record plasma purity (minimum impurity content 10^{-5}%) or at carefully monitored impurity content. This was of particular importance for spectrocopy in the VUV and USX spectral bands.

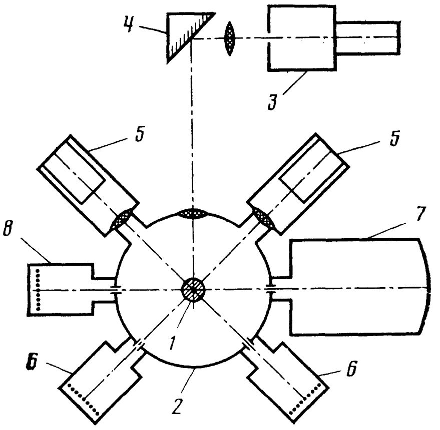

FIG. 3. Schematic diagram of experiments on the spectra of a plasma column in the wavelength range 1000–8000 Å: 1—plasma column; 2—cavity; 3—visible-band spectrograph; 4—image stabilizer; 5—dissectors; 6—multiwire coordinate counters; 7—vacuum monochromator; 8—standard coordinate multiwire counter.

A schematic of the diagnostic system used for the spectroscopy of the plasma column in the VUV and in visible bands is shown in Fig. 3. A spectrograph with stabilized display (see Ref. 1, p. 1814 of Russian original) was used to record (to within 20 ms) the distribution of the radiation intensity over the column diameter at wavelengths 4000–8000 Å. The distribution of the integrated brightness in the visible band over the diameter of the column was recorded (to within 10 μs) by the stereoscopic two-dissector system described above. In the VUV region (1000–3500 Å) we used for the analogous measurements a stereoscopic system consisting of two pinhole cameras and multiwire coordinate counters.[12] It was possible to blow through the counters various gases or gas mixtures, and to record radiation due to the photoeffect in the volume of the gas and to the photoeffect from the surface of the counter cathode. The pinhole cameras served as additional spectral filters for the VUV radiation, and for this purpose a different gas or gas-mixture system was made to flow through them. The coordinate counters operated in the proportional regime and the necessary radiation level was set in the experiments by varying the diameter of the pinhole and (or) by placing an absorber in the gas blown through the pinhole camera. The coordinate resolution of the counters, referred to the center of the cavity, was 0.3 mm at a temporal resolution 0.1 μs. The signals from each of the counter wires were picked off by a scanning electron beam and stored in recording oscilloscopes. The use of gas filters in conjunction with filters made of LiF, MgF_2, sapphire, and quartz, together with the multiwire counters, permitted spectral analysis of the radiation, with a spectral resolution 10–100 Å, in the range 1050–2000 Å (Refs. 29 and 30).

Measurements with the proportional coordinate counters have shown that the VUV radiation of the plasma column takes the form of flashes coming, against a weak continuous background, from thin filaments in the column. The flashes lasted from 1 to 5 μs, were irregularly spaced, and varied greatly in intensity (by up to three orders of magnitude) from flash to flash. In purified H_2 and D_2 with about 10^{-5}% impurity content the strongest flashes had frequencies from a fraction of a hertz to several times ten hertz, and weaker ones had frequencies reaching hundreds of hertz and increasing as the power in the column increased. In impure H_2 and D_2 (impurity density about 10^{-2} %), however, the flash frequency was higher by almost an order of magnitude.

A typical distribution, obtained with coordinate counters in the range 1050–2000 Å for the VUV radiation brightness in one flash, along two mutually perpendicular diameters of the column, and the analogous distribution of the visible radiation along the column diameter, obtained from the dissectors at the same instant, is shown in Fig. 4. It can be seen that the VUV radiation is emitted only from a region substantialy smaller than the visible column diameter. While the column seemed to be quite uniform in azimuth in visible light, the formation that emitted the VUV flash had two very different dimensions in two mutually perpendicular directions.

To determine the longitudinal dimensions of this formation, the multiwire counters were rotated through 90°. The measurements showed that this formation can extend

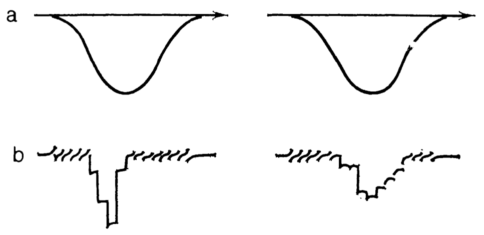

FIG. 4. Typical measured distribution of visible and VUV radiation over mutually perpendicular diameters of the column. Large plasma installation; deuterium pressure 1.3 atm; power in column 15 kW. a) Signals from dissectors. b) Simultaneously recorded signals from 15-wire counters.

over the entire visible length of the column. In the succeeding experiments the multiwire counters were also replaced by two-dimensional matrices[31] consisting of miniature end-window counters of 2 mm diameter. They yielded, albeit with lower spatial resolution, an instantaneous two-dimensional picture of the column VUV radiation (Fig. 5). The results revealed the following. First, VUV is emitted from a filamentary region that is in general azimuthally asymmetric, stretches along the column axis, but is not necessarily a straight line. Second, such a filament is the trail of a "head" a fraction of a millimeter long, whose emission is a maximum in the VUV band and which moves along the column at a velocity up to 10^6 cm/s. The VUV emission of the trail (streamer) of the head attenuates by an order of magnitude over several microseconds.

Note that the shape of the streamer and its temporal characteristics and emisison spectra could be measured only if the VUV flashes were strong enough with at least 10^3 photons entering the counter per microsecond. From calculations with allowance for the reception solid angles, the counter efficiency, and the absorption measured in the diagnostic system, it follows that a recorded flash containing 10^3 photons corresponds to 10^{15} VUV photons emitted from the column in a spectral interval 100 Å. In all the subsequent measurements and investigations, only the most intense VUV flashes were taken into account.

Measurements with averaging over several hundred flashes have shown that when the power in the column is increased from 5 to 40 kW the average transverse dimension of the streamer increases from fractions of a millimeter to several millimeters, and at high power can constitute up to 20% of the visible diameter of the column.

Note that the signals from the microwave loops placed in the cavity decrease pulse by pulse (by up to 10%) in synchronism with the VUV flashes; this indicates that additional energy is drawn from the cavity microwave field when the streamer is produced.

The flashes in the VUV band were investigated at high spectral resolution (to 0.3 Å) to estimate the effective electron temperature in the streamer. A DFS vacuum monochromator was used and the photons were recorded with a proportional counter in the 1050–2000 Å band, as well as with a coordinate counter located at the opposite window of the cavity (see Fig. 3). A system of diaphragms of up to 0.3 mm diameter aligned the optical axes of the reference coordinate counter and of the spectrograph accurate to 0.5 mm. The monochromator signal output was measured at the instant when a streamer appeared on the observation axis, using coincidences of the signals from the central wires of the coordinate counter with those from the counter in the spectrograph. This permitted reliable registration of the streamer pulsed radiation against the background of the continuous (in time) molecular radiation from the plasma column (the latter is discussed in more detail in Ref. 4).

Typical measurement results are shown in Fig. 1(b). The emission spectrum reconstructed from these measurements, with allowance for the instrumental error of the detection system, is approximated fairly accurately by a slightly inclined straight line. The spectrum is a sum of recombination radiation, bremsstrahlung, and the H^- continuum radiation. Judging from the slope of the spectrum, with allowance for the measurement errors, the electrons in the streamer can be assumed to have a temperature 3–5 eV. According to well-known calculations, however see, e.g., Ref. 32), the plasma in the fast head of a small streamer should be far from equilibrium so that its degree of ionization and the form of the distribution function remain open questions, while its temperature can be defined only very vaguely. It is apparently more correct to speak of the electrons as having not a temperature but some energy, say average, maximal, etc.

It was noted in spectral measurements in visible light, using the coincidences of the photomultiplier signals with the signals from a multiwire counter, that the wings of the Balmer lines broaden at the boundary. This broadening amounted to about 20% and was reliably observed only when the discharge power exceeded 30 kW and the gas pressure exceeded 3 atm. The maximum intensity of the last resolved line of the Balmer spectrum increased only by 10–30%, and a typical transverse streamer dimension was about 10% of the visible column diameter. It can therefore be concluded that the electron density in the streamer should exceed the average density in the column by at least a factor of ten.

The foregoing data pertained to a plasma column in a pure gas. The gas mixtures used in the measurements were deuterium or hydrogen to which several percent of He or Ne were added. Measurements with coordinate VUV counters have shown that the presence of the impurity has no noticeable influence on the properties and dimensions of the resulting streamers, and the spectra differed little from those obtained in pure hydrogen or deuterium. There, if the typical streamer-electron energy estimated from the continuum data is correct, one can expect the radiation to contain, besides a continuous spectrum, also lines of ionized impurity atoms. In the earlier measurement with poor spatial and

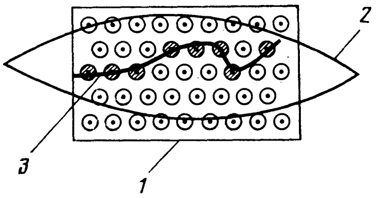

FIG. 5. Diagram and typical results of measurement with a two-dimensional matrix of end-face counters: 1—matrix; 2—projection of visible image of the plasma column on the matrix; 3—matrix counters that record high intensity VUV flashes (shaded).

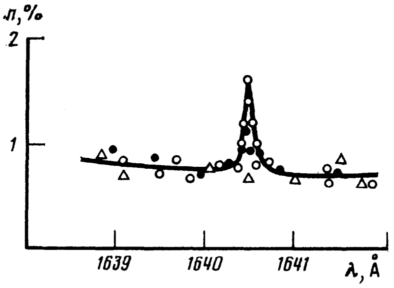

FIG. 6. Results of measurements of He II line by coincidence with a standard coordinate counter. Gas pressure in the plasma installation 1.5 atm, power in discharge 9 kW, spectral resolution 0.3 Å: ○ — D_2 + 0.5% He; ● H_2 + 0.5% He; Δ — D_2.

temporal resolution, these mixtures revealed (Refs. 1 and 11) no impurity atom or ion lines with a higher ionization potential than that of hydrogen (either in the VUV or in visible light). This property of the plasma column sets it apart from all similar plasmas. This can be explained only by assuming that, disregarding the flashes, the electron distribution function in energy cuts off abruptly at an energy close to the first excitation potential of the hydrogen atom. Note, incidentally, that a similar fall of the distribution function, albeit smaller, is revealed also by investigations of glow discharge (see, e.g., Ref. 33), and attests to a low degree of gas ionization in a stationary column.

The inert-gas ion lines were observed by coincidence of the signals from the counter placed in the DFS-29 spectrograph with those from the reference coordinate VUV counter. Since the spectrograph has low transmission 10^{-2}–10^{-3}) in the 1050–2000 Å band, the measurements were made also in the coincidence regime—a signal from the counter at the spectrograph output was recorded only when a strong VUV flash appeared. We measured the number of time coincidences of the signals from the counter in the DFS-29 per 100 pulses of the reference coordinate counter that recorded these high-power flashes.

Figure 6 shows the results of the measurements of the profile of the 1640 Å He II line (approximate excitation energy 40 eV in a D_2 + 0.5% He mixture at a spectral resolution 0.3 Å. It follows from the results that the streamer indeed contains electrons with energy of at least 40 eV. The spectral interval in which the measurements were made was 1050–2000 Å, and contained only the 1640 Å He II line (the 1215 Å He II line merged with the L_α line). The brightness of the He II line decreased rapidly with the power input to the discharge, and also with the helium concentration. If it is assumed that the line profile is a convolution of a Gaussian instrumental profile of half-width Δ_0 and a Doppler profile of half-width Δ_D, the total linewidth is $\Delta = (\Delta_a^2 + \Delta_D^2)^{1/2}$. The measurement results permit (under the above asuumptions) an estimate of the He-ion temperature in the streamer ($T_i \approx 1$ eV). The measurements have also shown that when a high-power VUV flash appeared the He II line emission preceded the continuous streamer emission by approximately 0.5 μs. The He I lines can in principle appear even earlier, but we did not succeed in observing them in visible light, where photomultiplier recording was used. The He I lines have apparently a rather low intensity and cannot be separated in global measurements from the strong H^- continuum background.[1,4]

Ne II lines, but no Ne III lines, were observed in D_2 + Ne mixtures in the 1050–2000 Å band.

3. MEASUREMENT OF ULTRASOFT X RAYS

The further investigations of the column discharge were based on the results of the VUV-radiation measurements. It is quite natural to assume that VUV flashes can be accompanied, even at relatively low average streamer-electron energies, by ultrasoft x rays with photon energy higher than 100 eV, to which the hydrogen shell of the discharge becomes transparent. There could be no hope that this radiation would have appreciable intensity, since in earlier experiments the x rays from a plasma column could not be separated from the background.[1] In our experiments, however, the sensitivity to USX could be substantially increased by synchronizing them with the VUV pulses, which were reliably produced by the processes in the discharge plasma.

Since the spectral measurements in the USX region entail well-known difficulties that were further aggravated in our experiments by the expected low intensity of the recorded radiation, the USX spectrum was measured with a specially developed x-ray counter that recorded gas-photoionization events along the propagation path of a collimated USX photon beam.[16] The construction of the multiwire counter used for this purpose is shown in Fig. 7. The radiation enters the counter through diaphragms in a direction parallel to the cathode and perpendicular to the anode wires, and the measured signals from each wire are recorded simultaneously. If the USX intensity is low enough, each photoionization event can be regarded as produced by a single photon, so that the distribution of the number of counts among the wires duplicates the spectral variation of the radiation, since the photoionization cross section, and hence the USX photon mean free path in the gas, depends substantially on the energy of this photon.

Indeed, the counting rate N_i for the ith counter wire is given by

$$N_i = \int_0^\infty I(E_\nu)\left[1 - \exp\{-\alpha(E_\nu)\Delta_i\}\right] \exp\{-\alpha(E_\nu) x_{i-1}\} dE_\nu,$$

where $I(E_\nu)$ is the spectrum of the radiation entering the counter, $\alpha(E_\nu)$ is the absorption coefficient in the counter volume, Δ_i is the distance between the wires, and x_i is the distance from the entrance window to the ith wire. Solution of this integral equation yields the spectrum (see Refs. 34, 35, and 9).

To decrease the absorption of the radiation in the cold-gas layer, a differentially evacuated intermediate chamber was placed between the exit flange of the cavity and the x-ray counter. The pressure in the chamber was maintained at about 0.1 atm (the pressure in the counter was equal to that in the cavity, i.e., 1–2 atm). It wa also possible to introduce into the intermediate chamber impurity gases that served as filters for the radiation. When necessary, it was possible to place ahead of the counter various filters, viz., LiF, MgF_2, and also a specially developed set of collodion films approximately 1000 Å thick coated with about 200 Å of aluminum. Such filters suppress effectively long-wave radiation

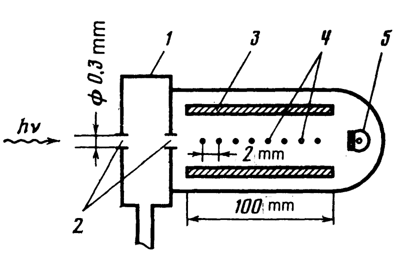

FIG. 7. Schematic diagram of multiwire x-ray counter for the measurement of the USX spectrum: 1—differentially evacuated intermediate chamber; 2—throttling inlets; 3—planar cathodes, 4—node wires; 5—standard VUV counter with LiF window.

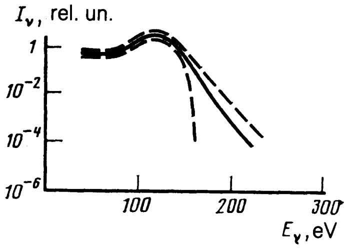

FIG. 8. Recovered spectrum of USX from a microwave plasma column; (power in column 20 kW, pressure of purified deuterium 1.3 atm). Dashed—range of error; $\Sigma \bar{N}_i = 10^3$.

($\lambda > 1000$ Å), but are anomalously transparent to USX.[36] A standard VUV counter with an LiF window was placed directly behind the x-ray filter and recorded the radiation in the 1050–1550 Å band (see Fig. 6).

The transparency of the plasma column to USX in the surrounding gas was measured with a low-voltage electron gap with an intermediate chamber placed on the resonator window opposite to that of the counter.[10,37] The gun produced x rays of energy 120–600 eV, sufficient for reliable measurements of the gas transmission coefficient. This corroborated the reliability of the USR recording, and made it also possible to estimate the absolute intensity of the radiation from the plasma column.

We dwell now in greater detail on the procedure used to measure the dependence of the counting rate on the serial number of the wire in the x-ray counter. Note that this counter was open, and while the entering radiation from the plasma was well collimated, the intensity of the individual VUV flashes was high enough to permit even insignificant scattering from the diaphragms to affect the measurement results. Scattered radiation of wavelength less than 1000 Å can produce in the counter, in principle, both bulk and surface photoeffects, whereas radiation of wavelength longer than 1000 Å can produce in practice only a surface photoeffect. Preliminary measurements have shown that, in the geometry used in these experiments, primary electrons are produced by bulk ionization only near the x-ray counter anode, and an avalanche is produced 1 μs after the ionization act. Electrons knocked out of the cathode, on the other hand, produce on the anode an avalanche after about 5 μs, in view of the longer drift path. On the other hand, owing to the small size of the standard VUV counter, the avalanche is produced in it also within 1 μs after the primary ionization event. Thus, if the plasma emission contains photons of a wavelength longer than 1000 Å, the x-ray-counter signals due to volume ionization can be quite reliably separated by time coincidence with the VUV-counter signals. The USX from the plasma was therefore estimated quantitatively from the average number N_i of counts from the x-ray counter, shifted relative to the start of the pulse from the standard VUV counter by a time shorter than 5 μs. In each measurement run we recorded 100 VUV pulses. For example, when the power in the plasma column was increased from 10 to 25 kW, the number $\Sigma \bar{N}_i$ increased from 5 to 10. Estimates show that at random coincidence of the pulses in an interval shorter than 5 μs the value of $\Sigma \bar{N}_i$ would be approximately 10^{-3}, i.e., three orders of magnitude lower. It was thus established quite reliably that the plasma emission contains photons that produce a bulk photoeffect in the x-ray counter. The absolute counting rate of these photons was approximately one in several minutes.

In principle, a volume photoeffect can be produced in an x-ray counter either by photoionization of the deuterium itself or by photoionization of impurity molecules having a low ionization potential, which are inevitably present even in highly purified deuterium. Experiments have shown that, owing to absorption by the deuterium filling the resonator, only radiation of energy $E_\nu < 10$ eV or $E_\nu > 100$ eV can penetrate into an x-ray counter at 1 atm pressure. To check whether the bulk photoeffect is produced by radiation with $E_\nu < 10$ eV, LiF or MgF_2 filters, which are transparent only to $E_\nu < 10$ eV, were placed ahead of the USX counter. The VUV counting rate remained practically unchanged, but the number $\Sigma \bar{N}_i$ of the coincidences dropped to zero. As another check, helium (up to 0.2 atm), which is transparent to VUV radiation of energy $E_\nu < 25$ eV was fed into the intermediate chamber ahead of the x-ray counter. The VUV counting rate remained unchanged, but the number of coincidences likewise dropped practically to zero. It was thus reliably established that the bulk photoeffect was produced in the x-ray counter by radiation of energy $E_\nu > 25$ eV.

The plasma emission spectrum (Fig. 8) was recovered from measurements of $\bar{N}_i$ by a procedure described in Ref. 9. It can be seen that the microwave spectrum of a plasma column in purified deuterium falls off steeply at a characteristic energy $E_\nu \approx 100$ eV. Since no emission lines from any impurity were observed in this case in the visible and VUV regions of the spectrum, it can be assumed that the USX has a continuous spectrum. On the other hand, the column emission spectrum in nonpurified hydrogen revealed also harder photons with energies up to 300 eV, which could be intepreted as emission of a group of hydrogen lines, all the more since the carbon lines were observed in this case in the VUV and the visible spectra.

In another experiment, the aluminum-coated collodion filters were placed in front of the entry aperture of the x-ray counter; this produced a tenfold decrease of the VUV counting rate, whereas the number $\Sigma \bar{N}_i$ of the coincidences increased to 80–100. It should be noted here that since the VUV radiation is strongly attenuated by the film, the VUV counter could record in these experiments only the strongest VUV flashes from the plasma. Since the measured x-ray counter efficiency at 1 atm pressure was about 10%, it followed from comparison with the experimental results without the filter that each powerful radiation flash caused about ten USX photons to enter simultaneously into the detector. The spectrum determined from the values measured in this experiment agreed fairly well with the spectrum recorded by an open counter.

The absolute brightness of the streamer x rays was estimated from the known efficiency of the x-ray counter and from measurements of the absorption of the x-ray gun radiation in the path from the plasma column to the counter (see above). In well-purified hydrogen and deuterium (impurity concentration $10^{-5}\%$) the average transmittance of radiation of energy $E_\nu \approx 300$ eV increased upon ignition of the plasma column from 10^{-2} to 0.3, i.e., by 30–50 times. This was due to the decreased gas density in the resonator on heating. The average absolute intensity of the USX from the streamer amounted to $7 \cdot 10^5$ photons per pulse in all directions.

When the plasma column was ignited in nonpurified gas, the USX transmittance increased to only double the value for the cold gas. Measurements in nonpurified gas (about 10% impurity concentration) by the method of Ref. 19 have shown an appreciable (approximately tenfold) increase of the USX absorption at the center of the cavity, with the diameter of the strong-absorption region approximately equal to the visible column diameter. The absolute intensity of the USX emitted from the streamer, however, was substantially higher in nonpurified gas than in purified gas and reached 10^8 photons per count.

To verify whether the streamer heat contains a noticeable group of electrons with preferred velocity directions, measurements were made to estimate the degree of polarization of the plasma USX. The idea underlying these measurements was that if sufficiently hard radiation (with $E_\nu > 300$ eV) produces photoionization, the velocity vector of the produced photoelectron is on the average parallel to the polarization of the ionizing radiation. In low-density gas (pressure lower than 0.1 atm) such an electron produces an ion track that should have approximately the same direction as the polarization vector. The track length and dimension were measured with the multiwire counter described in Ref. 18. This counter was placed in a chamber in which the pressure was maintained by differential evacuation in the range 0.1–0.001 atm. Placed behind the multiwire x-ray counter was a coordinate VUV photon counter with an LiF window. A system of diaphragms guided a collimated beam of 0.3 mm diameter to both counters. The only photoelectron tracks measured were those which appeared simultaneously with the pulses from the VUV counter. The tracks were 2–10 mm long. It could be concluded from the measurement that, to within 20%, the plasma radiation is not polarized. To check on this procedure, the same counter was used for polarization measurements of the x-ray-gun bremsstrahlung which is known[16] to have observable partial polarization.

CONCLUSION

The experiments have shown that a fine-scale instability is produced in a stationary microwave plasma, in the form of rapidly moving short-lived filaments that emit VUV radiation USX. The emission of USX from a plasma column of energy up to 300 eV was noted by P. L. Kapitza.[3] Unfortunately, in view of the large error with which the USX spectrum is determined, no unequivocal conclusions can be drawn concerning the electron distribution function; it can only be stated that the maximum electron energy in a streamer head is hundreds of eV, and one can hardly speak of an electron temperature in view of the obvious departure of the pulsed plasma from equilibrium in the head.

An instability-development mechanism that leads to formation of a streamer filament and to additional absorption of electromagnetic energy from the cavity was suggested in Ref. 14. This instability should develop most intensively in high-Q cavities, where the stored magnetic energy is higher. This was distinctly observed in experiment: although the appearance of streamers in plasma columns could be recorded in a wide range of experimental conditions, the brightest VUV flashes, USX, and highly ionized ion lines were observed only in the N-550 installation with a large-volume cavity. Neither USX nor ion lines were recorded with the N-220 installation, whose cavity Q was smaller by almost an order of magnitude. The slit-coupled installation,[5] whose Q was smaller by several more times, (although the power input to the discharge was a maximum, up to 100 kW), the intensity of the VUV from the filaments was extremely low, and the average streamer-head electron energy estimated from the measurements was less than 1.2 eV.

A similar instability was independently predicted and calculated in Refs. 38–40, where it was shown that the energy of the electrons in the filaments can reach tens of eV. This instability was experimentally observed also in Refs. 41 and 42.

Thus, in a microwave plasma column having an averge electron temperature $T_e \approx 1$ eV and a density $n_e \sim 10^{14}$ cm^3, the development of a fine-scale instability produces within a time on the order of a microsecond groups of fast electrons of energy up to 300 eV. The energy distribution of the remaining electrons in the stationary column, however, is cut off near the first excitation potential of the gas. These properties make the microwave plasma column an extraordinary physical object whose investigation turned out to be very difficult and lasted many years.

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