

## Dependence of radiation power on the length of a high-current vacuum arc in the vacuum ultraviolet region

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The radiation power of a high-current vacuum arc 8 mm long was measured in the vacuum ultraviolet region and the results were compared with measurements in a short arc (4 mm). With increasing arc length, the increase in radiation power in the vacuum ultraviolet region ( $100 \leq \lambda \leq 175$  nm) is less pronounced than in the 175–400 nm range. This confirms the view that the main increase in radiation power in an arc with developed anodic activity occurs due to the emission of atomic lines. The proportion of total energy transferred by radiation increases with arc lengthening and reaches a maximum of 30%.

**Keywords:** vacuum arc, radiation power, low-temperature plasma, electromagnetic radiation, electric arc.

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The role of radiation in the energy balance of vacuum arc discharges remains understudied. This is attributable to the fact that the plasma density in vacuum arcs is not that high at moderate currents. Therefore, the role of radiation was considered insignificant. In studies into the energy balance, radiation is neglected also for the reason that radiation calculations are very complex. Only a few research groups have performed approximate calculations that allow one to estimate the role of radiation in the energy balance of a vacuum arc [1–3]. Prior to the start of the present research project, no results of experimental measurements of the radiation power of vacuum arcs in the vacuum ultraviolet (VUV) region have been reported.

In earlier studies, we have measured the radiation power of a short (4 mm) high-current vacuum arc in the VUV region [4–6]. The examined arc was stabilized by a uniform axial magnetic field (AMF) and bridged the gap between butt electrodes made of a copper-chromium composition (CuCr30) with a diameter of 30 mm. It was found that the radiation power in the VUV region starts to increase rapidly at high current densities when anodic activity (intense evaporation of the anode) is triggered. At current  $I > 20$  kA (average current density  $j \geq 2.9$  kA/cm<sup>2</sup>), the radiation power reaches a level of  $\sim 50$  kW. With an increase in current to 25 kA (current density  $j \geq 3.6$  kA/cm<sup>2</sup>) and a corresponding significant intensification of anodic activity, the radiation power in the VUV region increases only slightly. The dependence of the maximum radiation power in the VUV region on the arc current was traced in [4] through to current  $I = 25$  kA ( $j \sim 3.5$  kA/cm<sup>2</sup>) at which anodic activity is manifested profoundly. During a 25 kA current pulse, the radiation power reaches its maximum of  $\sim 55$  kW in just 4.5 ms and stops increasing afterward. An assumption was also put forward that the redistribution of radiation power between the regions of vacuum and „ordinary“ ultraviolet is associated with the fact

that radiation of atomic lines within the 175–400 nm range starts to dominate with an increase in the concentration of metal vapors forming in the gap as a result of boiling on the surface of electrodes. The estimate of radiation power within the range of 100–400 nm obtained in [4] at current  $I = 25$  kA at the end of the pulse is as high as  $\sim 300$  kW. The instantaneous electrical power released in the discharge is  $\sim 900$  kW. This implies that the radiation power (including the VUV region) in discharges with a high current density, where anodic activity is well developed, may amount to almost 30% of the total power released in the discharge.

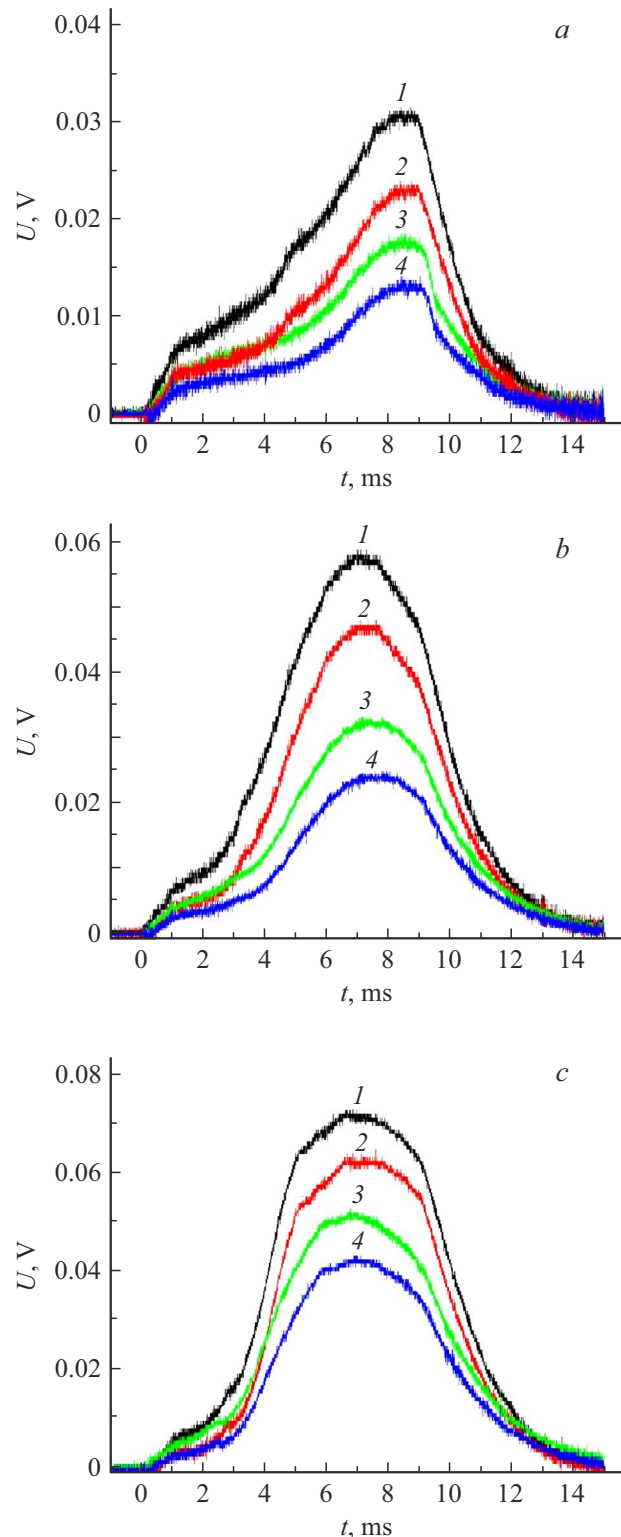
It is of research interest to measure radiation from a longer arc (8 mm) and compare the results. Such measurements were carried out in the present study. The task was to determine how the radiation power changes with an increase in interelectrode gap width (i. e., extension of the arc). On the one hand, a twofold increase in arc length is expected to translate into a significant increase in radiation power (in the VUV region). On the other hand, if our assumption is correct and the major share of radiation power is associated with metal vapor, the total radiation power should increase only slightly. To clarify this issue, radiation power measurements were carried out under conditions similar to those described above, but with a doubled interelectrode gap. Only the radiation power in the vacuum ultraviolet region is considered in the present study.

The experimental setup was characterized in detail in [4]. Its key parameters are listed below. Experiments were carried out in a continuous-evacuation vacuum chamber ( $\sim 10^{-4}$  Pa). The arc was ignited deliberately at the cathode center and stabilized by a uniform AMF with an induction of  $\sim 10$  mT/kA. The AMF was produced by external coils (Helmholtz pair), and its induction was chosen so as to ensure a virtually uniform current distribution on the end

surface of electrodes. Electrodes based on the CuCr30 composition with a diameter of 30 mm were used. They were positioned vertically at distance  $h = 8$  mm from each other. The arc was fed by a current pulse with a duration of  $\sim 10$  ms. Arc radiation was recorded by three FDUK8-UVS photodiodes produced by AO Tekhnoeksan. The photosensitive element of these diodes had diameter  $d = 3.5$  mm. The diodes were mounted inside the vacuum chamber at distance  $L = 990$  mm from its axis opposite the middle of the interelectrode gap. Light filters were placed in front of the photodiodes to account for the type of their spectral sensitivity within the  $100 \leq \lambda \leq 1100$  nm range. The light filters were made from crystalline  $\text{MgF}_2$ , quartz KU1, and colored glass ZhS-10 (GOST 9411–91). A crystal of  $\text{MgF}_2$  transmits radiation with wavelength  $\lambda \geq 100$  nm, quartz KU1 transmits radiation with  $\lambda \geq 175$  nm, and glass ZhS-10 transmits radiation with  $\lambda \geq 400$  nm. Radiation measurements in each mode were performed simultaneously. The transmittance of these filters and the spectral sensitivity of the diodes were presented in [4]. The method for estimating the arc radiation power based on the intensity of radiation flux incident on a photodetector was detailed in [7] and relies on the data reported in [8].

The results of experiments with arc length  $h = 8$  mm are qualitatively similar to those obtained with a short arc ( $h = 4$  mm). Figure 1 shows the examples of measurements with photodiodes through  $\text{MgF}_2$  and KU1 filters at different currents with developed anodic activity in comparison with measurements performed at an arc length of 4 mm. The chosen current magnitudes are characteristic values at which qualitative changes (see below) caused by anodic activity start to manifest themselves in the discharge. At relatively weak currents ( $I_a \sim 10$  kA), anodic activity is not observed. Arcing voltage  $U_a$  remains virtually unchanged after the completion of arc development. The shape of oscilloscope records of photodiode voltage  $U_d$  matches the shape of the oscilloscope record of current. When the current amplitude increases to 14–15 kA, traces of anodic activity appear on the electrodes. At currents greater than 18 kA, the shape of oscilloscope records of the photodiode voltage changes significantly (Fig. 1, *a*): within 3–4 ms, the signal starts to grow noticeably and reaches its maximum 7–7.5 ms after. Following that, it decreases due to a reduction in current. As the current amplitude increases further, anodic activity becomes more pronounced. Melt traces also appears on the cathode. The maximum photodiode signal value grows very fast and is reached earlier. At a current exceeding 22 kA, the rate of growth of the photodiodes signal is such that the maximum signal is observed just 3.5–4 ms after the onset of the current pulse.

The time dependences of radiation power in the VUV region derived from the presented oscilloscope records for different currents in arcs of various lengths are shown in Fig. 2. It is evident that at maximum currents (22–25 kA), the maximum radiation power in the VUV region is achieved as quickly as possible and ceases to depend on



**Figure 1.** Signals from the photodiodes with different filters. 1 —  $h = 8$  mm,  $\text{MgF}_2$  filter; 2 —  $h = 8$  mm, KU-1 filter; 3 —  $h = 4$  mm,  $\text{MgF}_2$  filter; 4 —  $h = 4$  mm, KU-1 filter.  $I = 18.5$  (a), 22.5 (b), and 25 kA (c).

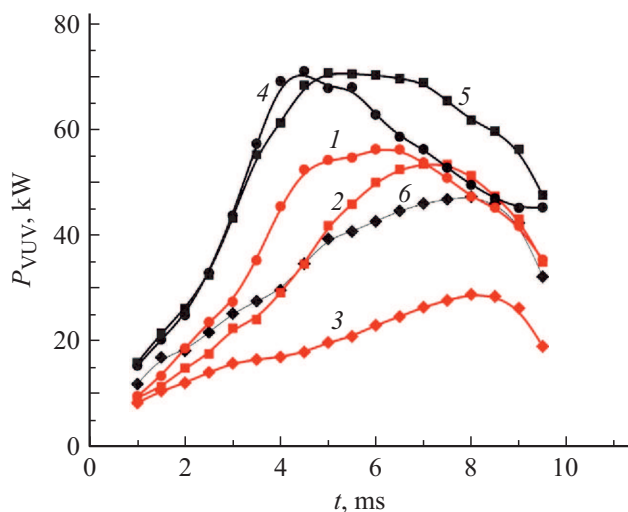
current. At 25 kA, the radiation power in the VUV region, having reached its maximum, starts decreasing.

The obtained dependences of radiation power in the VUV region on current at different moments in time in arcs of different lengths are compared in Fig. 3. It can be seen that the maximum radiation power achieved in a pulse grows exponentially with current in both short and long arcs as the anodic activity develops. It is also evident that the maximum radiation power in the VUV region in a long arc (with its length increased by a factor of 2) exceeds slightly the power emitted by a short arc. This differs significantly from the increase in radiation power in the „ordinary“ ultraviolet region [6]. It was concluded then that the maximum radiation power in a long arc is almost 2 times greater than the power emitted by a short arc; i.e., the power emitted per unit arc length remains unchanged, and the total power increases proportionally to the arc length. As the current increases and the arc evolves during a pulse, the radiation power in the VUV region varies in a completely different manner. This difference is apparently attributable to the fact that both electrodes are completely melted at currents greater than 22 kA and radiation in the gap is dominated by atomic line emission of the evaporated electrode material. It should be noted that the resonance lines of copper (324.7 and 327.4 nm) and chromium (357.9 nm) atoms lie precisely in the „ordinary“ ultraviolet region, while ionic lines of copper are dominant in the VUV region.

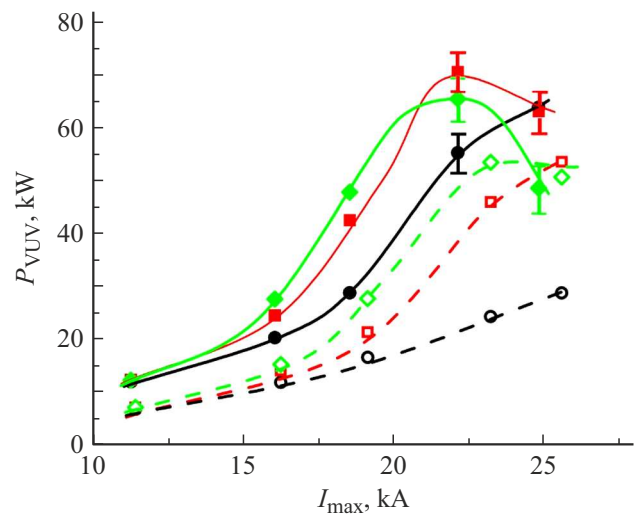
When the arc was extended, the fraction of power transferred by radiation increased to 400 kW at a current of 25 kA, which is  $\sim 30\%$  of the total power released in the arc (1200 kW).

### Conflict of interest

The authors declare that they have no conflict of interest.



**Figure 2.** Time dependences of the radiation power in the VUV region for different currents and intervals.  $h = 4$  (1–3) and 8 mm (4–6).  $I = 25$  (1, 4), 22.5 (2, 5) and 18.5 kA (3, 6).



**Figure 3.** Dependences of radiation power in the VUV region on arc current at chosen points in time. Open symbols (dashed curve) —  $h = 4$  mm; filled symbols (solid curve) —  $h = 8$  mm.  $t = 3.5$  (circles), 5.5 (squares), and 7.5 ms (diamonds). Vertical bars represent the scatter of experimental data.

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