Technical Physics Letters, 2024, Vol. 50, No. 12

Radiation of a short high-current vacuum arc in the vacuum ultraviolet

© Yu.A. Barinov[1], K.K. Zabello[1], A.A. Logachev[1], I.N. Poluyanova[2], E.V. Sherstnev[1], S.M. Shkol'nik[1]

[1] Ioffe Institute, St. Petersburg, Russia
[2] Switchgear Design Bureau LTD, Sevastopol, Russia
E-mail: zabellok@mail.ioffe.ru

Received April 26, 2024
Revised August 5, 2024
Accepted October 30, 2024

In the vacuum ultraviolet, the radiation intensity of a high-current vacuum arc was measured in the spectral region of $100 \leqslant \lambda \leqslant 1100$ nm. The results obtained made it possible to analyze the dependence of the radiation power on the arc current in different wavelength ranges, including in the field of vacuum ultraviolet. The analysis showed that in a developed vacuum arc with anodic activity, there is a redistribution of radiation power in the studied spectral regions. The measurement results made it possible to calculate how much of the power released in the arc is transferred by radiation.

Keywords: vacuum arc, axial magnetic field, emission power.

DOI: 10.61011/TPL.2024.12.60370.6419k

In the energy balance of an arc, the contribution of radiation becomes more significant as the plasma density increases. However, it is difficult to introduce radiation into the description of the energy balance of an arc. One is forced to use approximate methods to handle this task. Research has been going on for decades. In contrast to gas arcs, the transfer of energy by radiation in vacuum arcs has remain virtually unstudied. Radiation is often neglected in mathematical modeling of vacuum arcs. Only a few approximate calculations where radiation was taken into account in the examination of the energy balance of an arc have been published [1–3]. However, both the calculation procedure and the obtained results were characterized very briefly in these papers. No experimental measurements of the radiation power of a high-current vacuum arc had been performed prior to our studies. Our first publications on this topic [4–6] were focused on the experiments with a vacuum arc at a current density up to $j \sim 3.5\,\mathrm{kA/cm^2}$. At the first stage of this research, we limited ourselves to examining the spectral region from „ordinary" ultraviolet to the near infrared range ($200 \leqslant \lambda \leqslant 1100$ nm). Arc radiation in gaps of 4 and 8 mm within the $200 \leqslant \lambda \leqslant 1100$ nm range, where the fraction of radiation power reached 25% of the total power released in the arc, was studied in [5,6]. It was found that the primary contribution to arc radiation is produced at $\lambda < 400$ nm. These results were used in [7] to estimate the pressure and temperature of a radiating arc based on the radiation power. Figure 1 shows the atomic and ion lines of copper (red) and chromium (black) within the 100−400 nm range. It was hypothesized that since a fairly large number of Cu and Cr ion lines are concentrated in the 100−200 nm region, a significant emission power could be added by vacuum ultraviolet (VUV) radiation. VUV measurements were carried out in the present study.

Vacuum arc radiation was examined within the $100 \leqslant \lambda \leqslant 1100$ nm range, which covers VUV radiation. The arc was ignited at the cathode center by an initiating discharge by switching off the current in an auxiliary circuit and was supplied by a rectangular current pulse with a duration of 9 ms. The arc was maintained in a 4 mm gap with a current ranging from 10 to 25 kA, which corresponds to an average current density in a developed discharge of $1.5 \leqslant j \leqslant 3.5\,\mathrm{kA/cm^2}$. Butt electrodes with a diameter of 30 mm were used. The electrode material was a CuCr30 copper–chromium composition.

The measurement procedure and the experimental setup were described in detail in [4]. The method for estimating the arc radiation power based on the intensity of radiation flux incident on a photodetector was based on the data reported in [8]. We present here only the key points and differences. Experiments were carried out in a continuous-evacuation vacuum chamber ($\sim 10^{-4}$ Pa). The arc was ignited at the cathode center and stabilized by a uniform axial magnetic field with an induction of ~ 10 mT/kA. The discharge was supplied by a current pulse with a duration of 10 ms. Three FDUK8-UVS photodiodes were used in the experiments. The diameter of the active region of these photodiodes is 3.5 mm. Their typical sensitivity within the $100 \leqslant \lambda \leqslant 800$ nm wavelength range is shown in Fig. 2, *a*. To record VUV, photodiodes were introduced into the vacuum chamber. Light filters were mounted in front of the photodiodes. These light filters were MgF_2, KU-1 quartz glass, and ZhS-10 colored glass (GOST 9411−91) plates. MgF_2, KU-1, and ZhS-10 glass filters cut off radiation with $\lambda \leqslant 100$ nm, $\lambda \leqslant 175$ nm, and $\lambda \leqslant 400$ nm, respectively. The transmission bands of these glasses are also shown in Fig. 2, *a*. The photodiode has a relatively flat spectral sensitivity characteristic within the 100−400 nm range, which allows us to separate narrow spectral regions of 100−175 and 175−400 nm by simple subtraction. Different diaphragms (0.5 mm in diameter for ZhS-10 glass and 0.3 mm in diameter for the other two

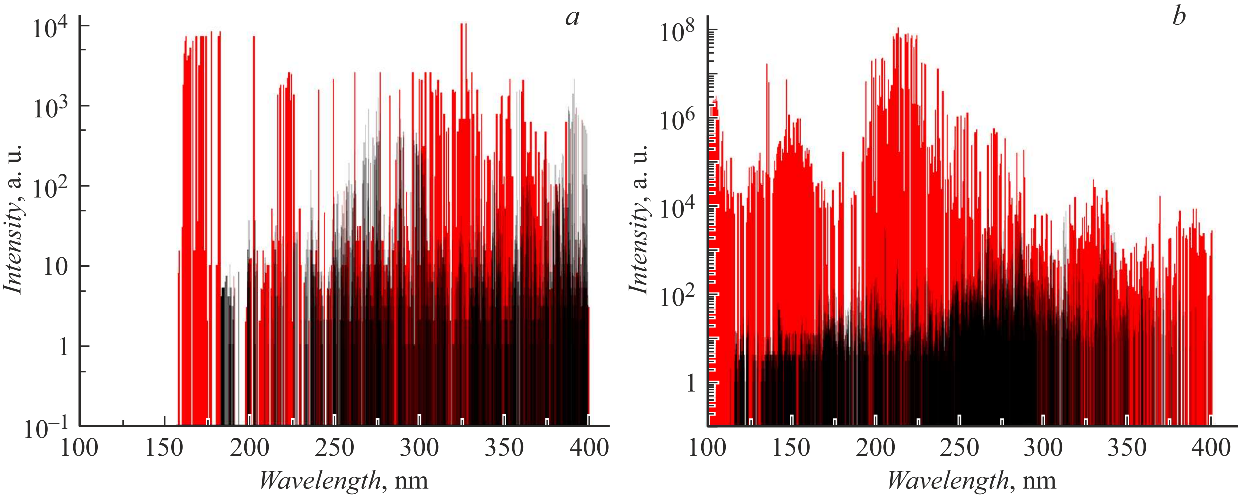

Figure 1. Atomic (a) and ion (b) lines of copper (red) and chromium (black) within the 100–400 nm range. A color version of the figure is provided in the online version of the paper.

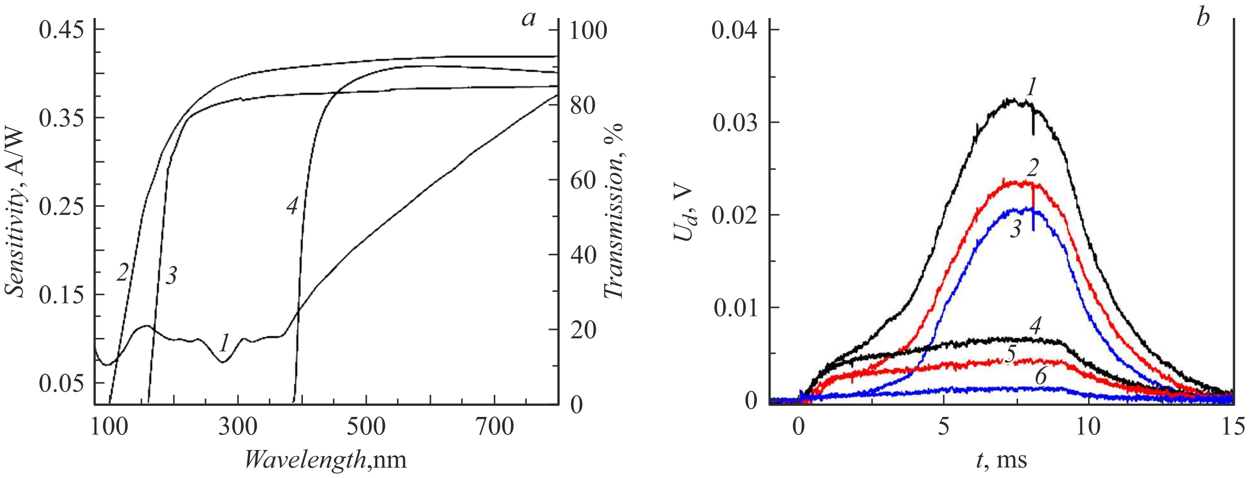

Figure 2. a — Spectral sensitivity of the diode (*1*) and transmission of MgF_2 (*2*), KU-1 (*3*), and ZhS-10 (*4*). b — Photodiode signal with different filters: *1* — MgF_2 filter, the current is 22 kA; *2* — KU-1 filter, 22 kA; *3* — ZhS-10 filter, 22 kA; *4* — MgF_2 filter, 16 kA; *5* — KU-1 filter, 16 kA; and *6* — ZhS-10 filter, 16 kA.

glasses) were used to limit the maximum signal recorded by the photodiode. The spectral characteristic of the photodiode sensitivity has no flat section at $\lambda > 400$ nm (Fig. 2, a). At the same time, the radiation intensity in this region remains low even though the photodiode sensitivity is high within this range. Therefore, an averaged sensitivity value was adopted in this region; in view of the above, such an approximation does not introduce any significant error.

A detailed report on the analysis of dependence of the diode signal shape within the spectral ranges of $\lambda > 175$ nm (glass KU-1) and $\lambda > 400$ nm (glass ZhS-10) was presented in [5]. Our estimates of the radiation power in the visible and ultraviolet spectral regions were also given there. In the present study, the $\lambda > 100$ nm VUV range (MgF_2 glass) was added, and the radiation power within this range was estimated. At relatively low currents (up to ~ 18 kA), prior to the onset of regimes with developed anodic activity and complete melting of the electrode surface, the waveforms of signals from all diodes have roughly the same shape (Fig. 2, b). This indicates that the radiation flux from the arc increases uniformly with increasing current throughout the entire observed spectrum. However, the waveforms of signals from the diodes change at $I_a > 18$ kA (Fig. 2, b). The radiation power in the VUV region ($\sim 100-175$ nm) also changes. During a 25 kA current pulse, the radiation power reaches its maximum of ~ 55 kW in just 4.5 ms and stops increasing (Fig. 3, a).

The obtained current dependences of radiation power in the VUV range ($\sim 100-175$ nm) at different moments of time are shown in Fig. 3, b. It is evident from this figure that the maximum radiation power achieved at the end of a pulse increases with current, ceasing to grow only at limiting currents when the anodic activity becomes strong

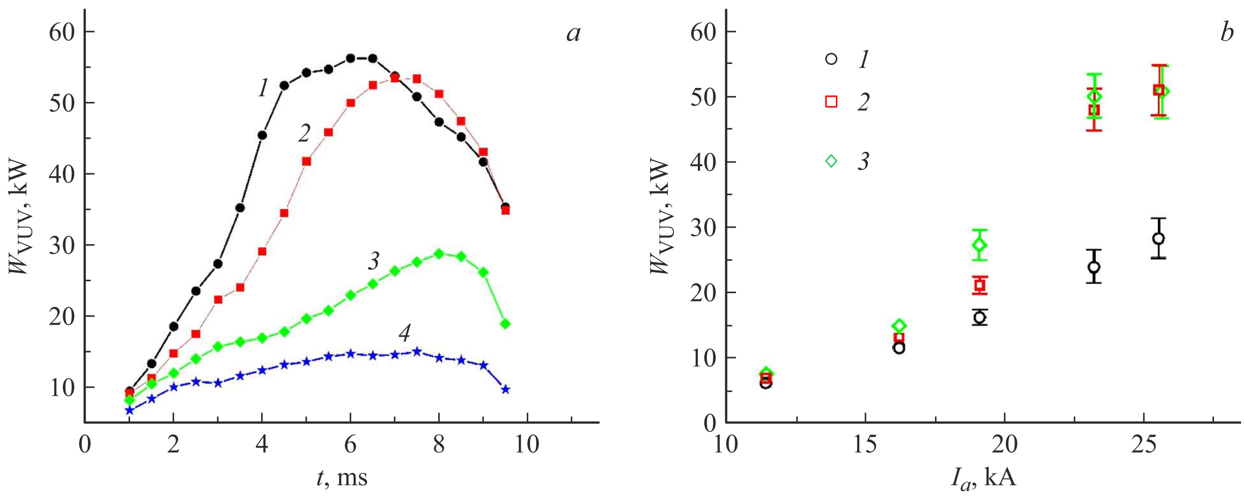

Figure 3. a — Time dependences of the radiation power in the vacuum ultraviolet region for current values $I_a = 25$ (*1*), 22 (*2*), 19 (*3*), and 16 kA (*4*). b — Dependences of the radiation power in the vacuum ultraviolet region on the arc current at chosen time points $t = 3.5$ (*1*), 5.5 (*2*), and 7.5 ms (*3*).

($I_a > 20$ kA). Moreover, at a current of ~ 22.5 kA, the radiation power does not exceed the one at a higher current (~ 25 kA), although it still reaches its maximum at the end of a current pulse (7.5 ms). It is instructive to compare the current dependences of radiation power in the VUV range obtained in the present work with the dependences for the „ordinary" ultraviolet region (175–400 nm).presented in [6]. In the „ordinary" ultraviolet region, the maximum radiation power achieved at the end of a pulse grows exponentially with current as the anodic activity intensifies, and its growth rate decreases only at the limiting current when the anodic activity becomes catastrophically strong (the anode starts breaking down, and intense spattering of droplets is observed); i.e., the „ordinary" ultraviolet region differs from the vacuum one in that the radiation power in it continues to grow with current throughout the entire examined range of currents. Presumably, this redistribution of radiation power between the regions of vacuum and „ordinary" ultraviolet is associated with the fact that radiation of atomic lines starts to dominate within the 175–400 nm range with an increase in the concentration of metal vapors forming in the gap as a result of boiling on the surface of electrodes. In the ~ 100–175 nm region, such a line density is observed neither for an atom nor for an ion.

The estimate of radiation power W_{UV} within the 100–400 nm range obtained in the present study revealed that $W_{UV} \sim 300$ kW at the end of a pulse with a current of 25 kA, while $W_a \sim 900$ kW is released in a discharge; i.e., at high current densities at the end of a pulse, the radiation power reaches $\sim 30\%$ of the power released in the discharge. It was found that a redistribution of radiation power with an increase in current is observed in the studied spectral regions in a developed vacuum arc with anodic activity. Radiation power W_{VUV} within the 100–175 nm range reaches a level of ~ 55 kW in regimes with developed anodic activity and ceases to grow further.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] E. Schade, D.L. Shmelev, IEEE Trans. Plasma Sci., **31** (5), 890 (2003). DOI: 10.1109/TPS.2003.818436

[2] L. Wang, S. Jia, Y. Liu, B. Chen, D. Yang, Z. Shi, J. Appl. Phys., **107** (11), 13306 (2010). DOI: 10.1063/1.3386568

[3] N. Wenzel, S. Kosse, A. Lawall, R. Renz, W. Hartmann, in *2012 25th Int. Symp. on discharges and electrical insulation in vacuum (ISDEIV)* (IEEE, 2012), p. 321–324. DOI: 10.1109/DEIV.2012.6412518

[4] Yu.A. Barinov, K.K. Zabello, A.A. Logachev, I.N. Poluyanova, E.V. Sherstnev, S.M. Shkol'nik, Tech. Phys. Lett., **47** (2), 118 (2021). DOI: 10.1134/S1063785021020024.

[5] Y.A. Barinov, K.K. Zabello, A.A. Logachev, I.N. Poluyanova, E.V. Sherstnev, A.A. Bogdanov, S.M. Shkol'nik, IEEE Trans. Plasma Sci., **50** (9), 2729 (2022). DOI: 10.1109/TPS.2022.3175577

[6] Yu.A. Barinov, K.K. Zabello, A.A. Logachev, I.N. Poluyanova, S.M. Shkol'nik, in *Proc. of the 30th Int. Symp. on discharges and electrical insulation in vacuum (ISDEIV)* (Okinawa, Japan, 2023), p. 235–237.

[7] V.F. Lapshin, Plasma Phys. Rep., **49**, 1429 (2023). DOI: 10.51368/1996-0948-2023-3-10-17

[8] V.F. Lapshin, Prikl. Fiz., No. 5, 25 (2022) (in Russian). DOI: 10.51368/1996-0948-2022-5-25-31

Translated by D.Safin