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Study of the Spectral Composition of Optical Radiation during Electrical Explosion of a Tungsten Wire

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Abstract—In this paper, we present the results of the study of the spectral composition and temporal dynamics of optical emission during electrical explosion of a tungsten wire. It is found that the second emission peak ∼1 ms long appears at wire diameters exceeding 100 μm. At the same wire diameters, an intense continuous Plank spectrum is observed in the red region of the optical spectrum. During electrical explosion of wires less than 100 μm in diameter, the second intensity peak is absent, and the survey spectrum contains only atomic spectral lines. The assumption about the correlation of these two effects is made.

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Introduction. The electrical explosion of metal wires is one of the actively developing directions in modern physics of low-temperature plasma [1]. The electrical explosion allows the study of not only the plasma behavior in a strong magnetic field, the high-current processes in conductors, and extreme states of matter at high pressures and temperatures, but also is used in technologies for producing nanopowders of metals and refractory non-metal compounds. Therefore, the study of the gas phase in experiments on the electrical explosion of conductors (hereafter, EEC) in vacuum is of great importance for theoretical and experimental plasma physics.

The EEC optical emission spectrum is an important characteristic of the process. Since the major objective of most experiments on the high-current electrical explosion is soft X-ray and neutron production, much researchers' attention is paid to the study of emission spectra in the region of soft X-rays and ultraviolet [2–4]. Nevertheless, the study of the optical spectral region in low-current ($I \sim 1$ kA) EECs makes it possible to judge the initial stage of high-current ($I \sim 1$ MA) EECs.

Registration of tungsten atomic lines during electrical explosion of a single wire is a difficult problem. The difficulty is that tungsten has a large number (∼5000) of lines with almost identical intensities in the visible region.

1. Experimental setup description

Experiments on electrical explosion of a tungsten wire were performed using a "GELIOS" setup. The equivalent electrotechnical schematic diagram of the setup is shown in Fig. 1. The setup consists of four IMN 100-0.1 capacitors with capacitance $C = 0.1$ μF and an inductance of 150 nH connected in parallel. To reduce the total inductance, the bus of capacitors is made of sheet copper 1 mm thick. Charging was performed by an AII-70 power supply unit through a rectifier and a charging resistor to the voltage $U = 35 - 40$ kV. The capacitor bank was closed using a three-electrode low-inductance controlled air discharger. The discharger was connected to the explosion chamber by eight parallel radio-frequency cables ($\rho = 50$ Ω, $L = 200$ nH/m) two meters long each.

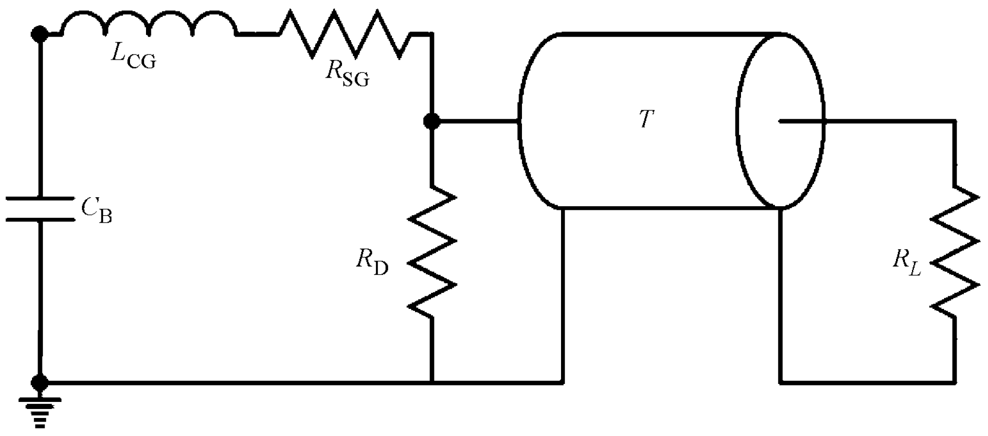

Fig. 1. Calculated schematic diagram of the discharge circuit of the setup: L_{CG} is the total inductance of capacitors and discharger (spark gap), R_{SG} is discharger spark resistance, T are connecting cables shown as the equivalent line length, R_L is the load resistance, R_D is the divider resistance.

Explosion chambers made of KV-3 drawn quartz (inner diameter is 55 mm, height is 110 mm, and wall thickness is 2–3 mm) were used in the experiment. The chamber was vacuum pumped to a pressure of $\sim 10^{-4}$ Pa using an oil-free Varian SH-110 scroll vacuum pump (limit is 5 Pa) and a 01AB-450-003 turbomolecular pump (limit is $4 \cdot 10^{-5}$ Pa). The electrode–wire contact was provided by a grip seal. Both tungsten and stainless steel electrodes were used in experiments. The use of the stainless steel electrodes promoted a decrease in electron emission from the electrode surface, which improved the result reproducibility. Tungsten wires of various cross sections (10, 50, 70, 130, and 200 μm) from 24 to 40 mm long were used as loads.

2. Description of diagnostic techniques

Study of the survey emission spectrum. To determine the spectral characteristics of light emission, two optical spectrometers, i.e., UM-2 and STE-1, were used. The spectrometers differ in spectral resolution. The Abbe prism is used as a dispersing element in the former, which does not allow high spectral resolution, but provides sufficient optical efficiency.

Its another advantage is the fact that the entire visible spectral region fits into a length of ~30 mm, which allowed the use an image converter as a light amplifier and an RF-3 film (35 mm wide) as a recording element. An EP-19 image converter was rigidly is attached to the UM-2 monochromator instead of an output slit so that a semitransparent photocathode is in the focal plane of the monochromator objective. The film was placed into a special ebonite holder tightly pressed to a planar fiber-optic screen of the image converter. After developing, the film was scanned using an Epson Perfection 2480 scanner with a resolution of 4800 dpi and analyzed in the Photoshop CS 5.5 environment. Spectral lines were calibrated using hydrogen (DVS-25) and mercury–helium (DRGS-12) lamps by sequential overlapping of the spectra through different slits of the Hartmann diaphragm. The required exposure time was controlled by the duration of the pulse applied to image converter electrodes. The light flux was attenuated using neutral filters with various attenuation factors.

The high optical efficiency of the spectrometer and additional amplification of the image converter made it possible to measure the survey spectrum of the optical radiation pulse during electrical explosion of a tungsten wire.

High-resolution study of separate spectral regions. To register separate portions of the spectrum with high resolution, the STE-1 optical spectrometer with a diffraction grating as a dispersing element was used. However, the STE-1 sensitivity was significantly worse than that of the prism spectrometer; therefore, it was possible to measure spectra only at large light fluxes. A Toshiba TCD 1304DG CCD array was used as a photographic recording element. The measured spectral range was limited by the geometrical size of the CCD array (29 mm). The output unit design made it possible to displace the CCD array with respect to the studied spectrum along vertical and horizontal axes, which allowed the study of spectral regions of interest in all working ranges of STE-1 wavelengths. An electronic unit [5] sent the data from the CCD array to a computer through an USB port.

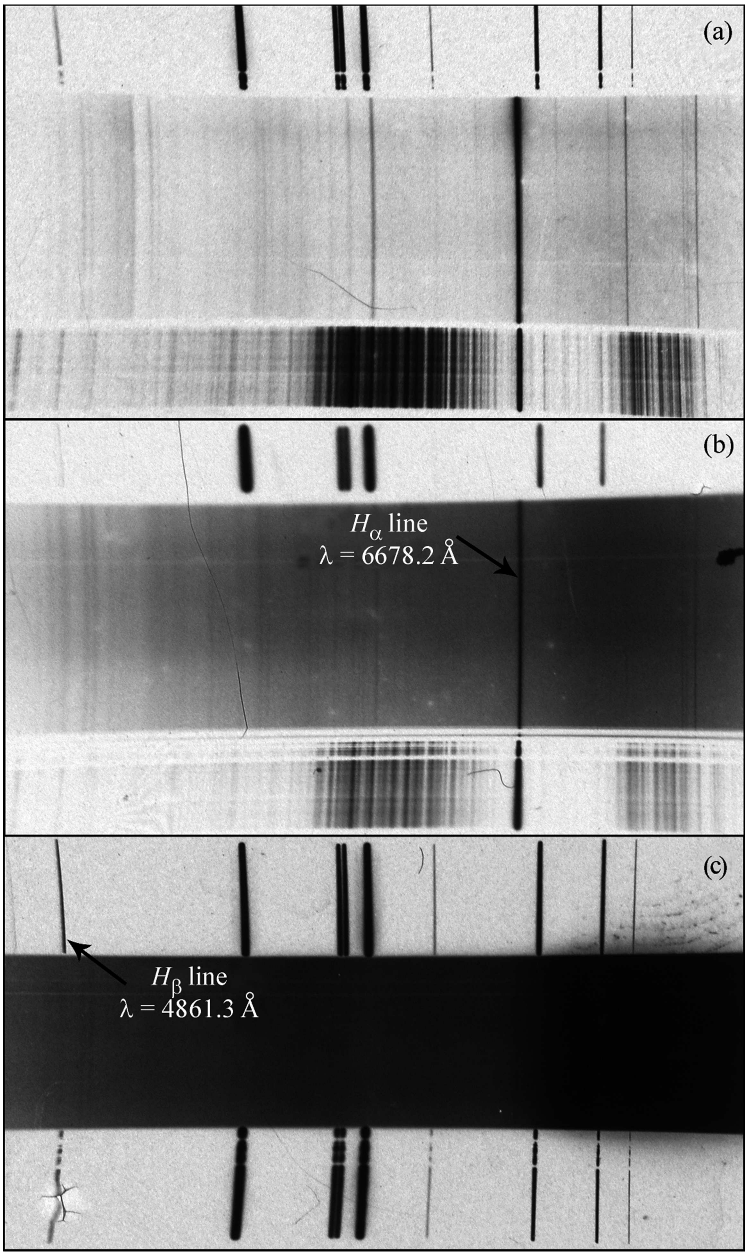

Fig. 2. Survey spectra of electrical explosions of tungsten wires (a) 10, (b) 70, and (c) 200 μm in diameter.

Radiation intensity measurements. The time behavior of the integral (over the wavelength) light intensity was measured using an FD-263-01 silicon photodiode with amplifier. The detector was characterized by the linear dependence of the output voltage on the radiation intensity. The photodiode spectral sensitivity range was 400–1100 nm. The temporal transient response of the detector was of the order of 100 ns. The signal from this device was sent to a Tektronix TDS-2024B digital oscilloscope via an RK-50 cable. The oscilloscope was placed in a shielded diagnostic box. To reduce the effect of electromagnetic radiation from the discharger and wire, the photodiode was placed in a grounded thick-walled metal casing. The sensor was supplied from a “Krona” battery. The optimum level of the photodiode output signal was preliminarily adjusted using neutral light filters.

3. Results and discussion

The high sensitivity of the technique using the UM-2 prism spectrometer and image converter made it possible to measure survey spectra of the visible region for each electrical explosion of a tungsten wire in vacuum.

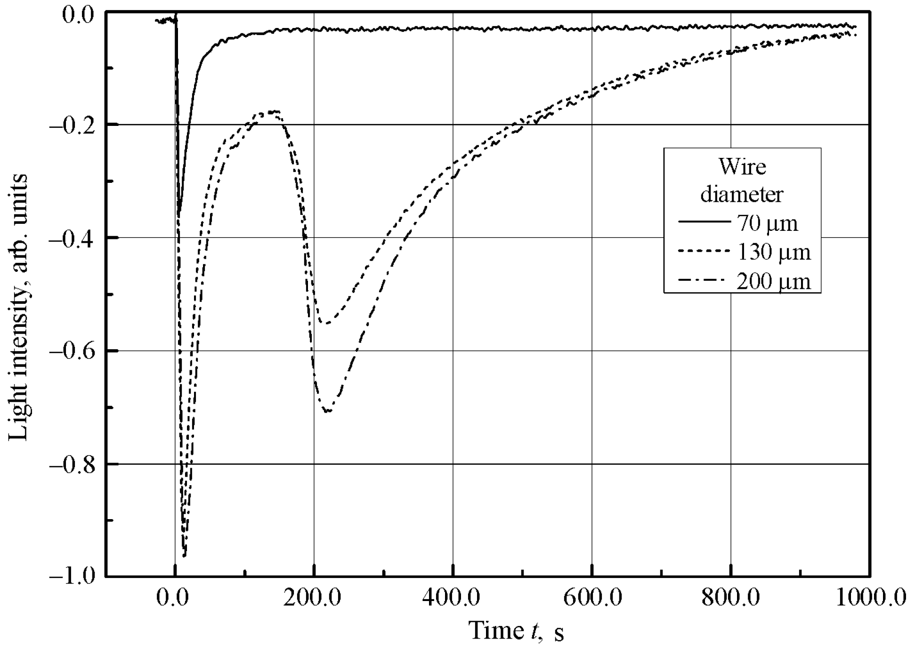

Fig. 3. Time dependence of the integral light intensity for wires of various diameters.

Figure 2 shows the survey spectra obtained at electrical explosions of tungsten wires of various diameters (10, 70, and 200 μm). The studied emission spectrum is placed in the central region of each panel. The bottom and top parts of each panel show the calibration spectra of mercury—helium and hydrogen lamps, used to identify separate lines of the spectrum under study. The most pronounced in this spectrum are the atomic hydrogen line H_α ($\lambda_{H_\alpha} = 6563$ Å), and two lines in the red region which cannot be identified by the used diagnostics due to low resolution of the UM-2 spectrometer.

As a rule, the survey spectrum represented a combination of the discrete and continuous spectra. However, at small wire diameters (10 μm), the "Plank" component was almost absent (Fig. 2(a)); at large diameters (200 μm), its intensity was so significant that nothing can be said about the discrete component in the red region of the optical spectral region (Fig. 2(c)). As seen in Fig. 2(b), the intensities of the discrete and continuous spectral components are almost identical at intermediate diameters (70 μm).

Simultaneously with spectral measurements using the semiconductor photodiode, the temporal behavior of the integral light intensity was studied. It was found that the radiation intensity is two-humped at wire diameters larger than 100 μm. The intensity maximum of the second peak is at $\sim$200 μs from the EEC beginning. By this time, the capacitor bank is almost completely discharged; therefore, the observed light behavior seems to be rather unexpected. At diameters smaller than 100 μm, the second intensity peak does not appear. The photodetector signals reduced to the unified scale are shown in Fig. 3.

A comparison of the results presented in Figs. 2 and 3 allows the assumption that the first and second intensity maxima are caused by the discrete and continuous components of the optical spectrum, respectively.

For more accurate identification of spectral lines of optical radiation, the STE-1 spectrometer was used, combined with the CCD array which was a recording element. The high resolution of this technique allowed us to recognize a significant number of tungsten lines. The spectral fragment in the range of [5842, 5860] Å is shown in Fig. 4. Several lines were also unambiguously identified, which were also observed in survey spectra, but their identification was complicated by low resolution of the UM-2 spectrometer. They are: the yellow sodium doublet ($\lambda_{\mathrm{Na}} = 5889/5895$ Å), the atomic oxygen line ($\lambda_{\mathrm{O}} = 7771/7774/7775$ Å), and the carbon ion line ($\lambda_{\mathrm{C+}} = 7231/7236$ Å).

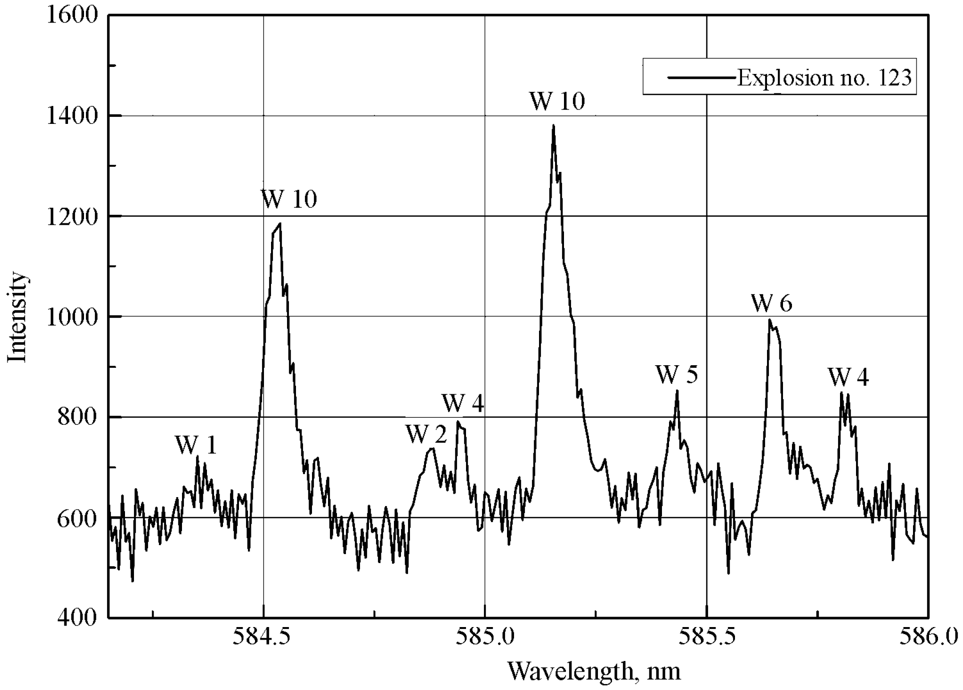

Fig. 4. Fragment of the high-resolution line spectrum of tungsten.

Conclusions. This study detected the appearance of the second maximum in the integral light intensity during electrical explosion of tungsten wires larger than 100 μm in diameter. Presumably, the appearance of the second peak is associated with the continuous spectral component.

Using a high-resolution spectrometer, a significant number of tungsten atomic lines were detected. To our knowledge, the tungsten spectrum measured during EEC was not previously presented in the scientific literature.

The technique also allowed identification of all optical lines in the survey spectrum.

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REFERENCES

1. W. G. Chace and H. K. Moore, *Exploding Wires* (Plenum, New York, 1959).
2. G. V. Ivanenkov, S. A. Pikuz, T. A. Shelkovenko, et al., Preprint FIAN № 9 (Moscow, FIAN, 2004) [in Russian].
3. Yu. G. Kalinin et al., Fiz. Plazmy **32**, 714 (2006) [Plasma Phys. Rep. **32**, 656 (2006)].
4. S. S. Anan’ev et al., Fiz. Plazmy **36**(6), 1 (2010) [Plasma Phys. Rep. **36**, 601 (2010)].
5. *Photoelectronic Cartridges for Emission Spectrographs. Multichannel Optical Spectrum Recorders, 2012*; http://www.ooo-mors.ru/catal1.htm.