Time and Spectra Resolved Investigation of Light Emitted by Cathode Spot at Vacuum Discharges[1]

S.A. Popov, R. Methling*, D. Uhrlandt*, and A.V. Batrakov

Institute of High-Current Electronics SB RAS, 2/3, Academichesky ave., Tomsk, 634055, Russia
**Leibniz-Institute for Plasma Science and Technology (INP), Greifswald, Germany*

Abstract – Cathode spots show a very dynamic behavior. Thanks to great improvements in experimental techniques, our knowledge on vacuum spots could be remarkably enlarged in the last one or two decades, e.g., by the application of fast intensified CCD cameras. Two-dimensional imaging techniques with high time resolution yield a wealth of information on the spot (sub-) structures, their dynamics and lifetimes. Ultra-high time resolution in the sub-ns range with long measuring intervals can be achieved in one-dimensional streak imaging. Here, we are interested in the optical emission of the cathode spots. Therefore, we combined a 0.5 m spectrograph with a streak camera enabling a time resolution in the nanosecond range. Limits concerning wavelength and time resolution as well as the emission intensity will be discussed. The investigations were carried out under UHV conditions using a liquid metal cathode of GaIn alloy. We present first results in which spectral lines of the atom and single as well as double charged ions of the cathode spot plasma could be observed simultaneously. At the beginning of the discharge, the emission spectra are dominated by ionic lines. With a delay in the range of hundreds of nanoseconds atomic lines appear. The intensity of atomic lines is much higher than that of the ionic ones and increases the brightness of the spot in this stage.

1. Experimental setup

The experimental setup is shown schematically in Fig. 1. After pumping down the vacuum apparatus by a turbo pump, UHV conditions are maintained by a vibration-free operating ion pump. Light from the cathode spot is focused by a quartz lens on the entrance slit of the spectrograph. At the output of the spectrograph, a 2D discharge gap image is formed where one dimension is associated with the spectrum and the other one with the projection of a narrow paraxial area of the discharge gap. This image is projected on the photocathode of the streak camera (Imacon 500 from Hadland) equipped with an UV-VIS photocathode with highest spectral sensitivity around 430 nm (S20 type). Finally, the luminescent screen image of the streak camera is recorded by a sensitive 16-bit CCD camera (Newton from Andor).

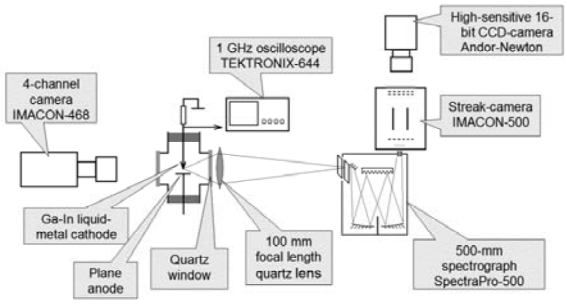

Fig. 1. Schematic diagram of the experimental setup

We apply two different modes. In “focus mode” the streak camera plainly works as an image converter tube transferring the two-dimensional image from the photocathode to the luminescent screen with neither distortion nor transformation. For “streak mode», a 100 μm wide slit is placed in front of the photocathode that restricts the discharge gap image along the discharge axis. As a result, the streak image is generated by the cathode spot light resolved in spectrum in one dimension and in time in another one. So, it was possible to register time-integrated emission spectra with one lateral dimension of the discharge gap in the “focus mode” or dynamics of emission lines of the cathode spot radiation with high time resolution in the “streak mode”. Besides, the gap can be observed with the use of the 4-channel framing camera (Imacon 468 from Hadland).

Sharp tip or needle cathodes covered with the liquid metal (LMC) have certain advantages concerning electrical and spatial reproducibility of arc operation and synchronization [2–4]. By applying a high positive voltage at the discharge gap the liquid metal surface at the cathode tip becomes unstable and a Taylor cone arises when the voltage exceeds some threshold value $|V_{th}|$ within 5.5 to 6 kV. Taylor cone formation is limited in time by extreme sharpening of its apex, strong enhancing of electric field, electrical breakdown of the gap, and ignition of a cathode spot.

Using the self-breakdown of the vacuum gap allows high repetition rates of $\nu \sim 1$ kHz. A trigger signal for data acquisition can be derived from the discharge current itself but with a certain delay. For example, streak imaging starts 150 ± 50 ns late. Improved triggering control is realized as follows:

[1] The work was supported by the Russian Foundation for Basic Research (Projects Nos. 06-02-17018 and 06-08-00684) and partly by the BalticNet – PlasmaTec Association.

A positive voltage a little bit higher than $|V_{th}|$ causes formation of a Taylor cone and low-current ion emission (limited by resistors to 10 to 100 μA). Now a high-voltage pulse of negative polarity is applied and the cone becomes an explosive-emission cathode of needle type when the pulse amplitude exceeds $|V_{th}|$ greatly. The circuit is closed by a triggered spark gap capable to switch for less than 10 ns with jitter less than 10 ns, which results in reproducible vacuum breakdown and cathode spot ignition. A delay generator is used to synchronize the data-acquisition equipment. The electrode distance was 1 or 2 mm.

2. Spectral range available for experimentation

The geometries of the spectrometer and the streak-camera photocathode (5 × 1.5 mm) restrict the spectral range available for registration within 70 nm. In a first step, the full-range spectrum of the gallium-indium cathode was recorded by taking a set of several 70 nm wide spectra. This enabled us to select the spectral range being most informative within the available spectral gate in a second step. For these measurements, the streak camera was set in the "focus mode". The discharge was operated in the self-breakdown mode with a low charging capacity yielding discharge times in the range of 100 ns.

The spectral range from 400 to 470 nm is the favored one for further detailed research because it contains intensive lines of neutral atoms (Ga I 403 and Ga I 417 nm) as well as single (Ga II 425 nm) and double charged ions (Ga III 438 nm) of the dominant cathode material Ga (85%). Furthermore, two atomic lines (In 410 nm and In I 451 nm) of the second (minor) cathode material In (15%) can be observed. Fortunately, the spectral sensitivity of the streak-camera photocathode is maximal, only weakly depends on light wavelength in this range, and could be neglected here.

3. Time-integrated and space-resolved spectra of the discharge gap

Figure 2 shows time-integrated and space-resolved spectra measured along the gap axis using the "focus mode". The spectrum in the upper panel is obtained from ultra short discharges of a few tens of nanoseconds in the self-breakdown mode at a repetition rate ν = 1 kHz. A similar data set for long discharges of microsecond duration at ν = 30 Hz is presented in the lower panel of Fig. 2. The left and right images in the spectra figures are different just in brightness to emphasize different aspects of the two-dimensional pattern. The highest brightness appears at the cathode spot position. Towards the anode, the intensity decreases. The middle panel displays typical waveforms of the discharge current for each case.

The image brightness profiles along 3-pixel-thick lines bordered with dashes in Fig. 2 are shown in Fig. 3.

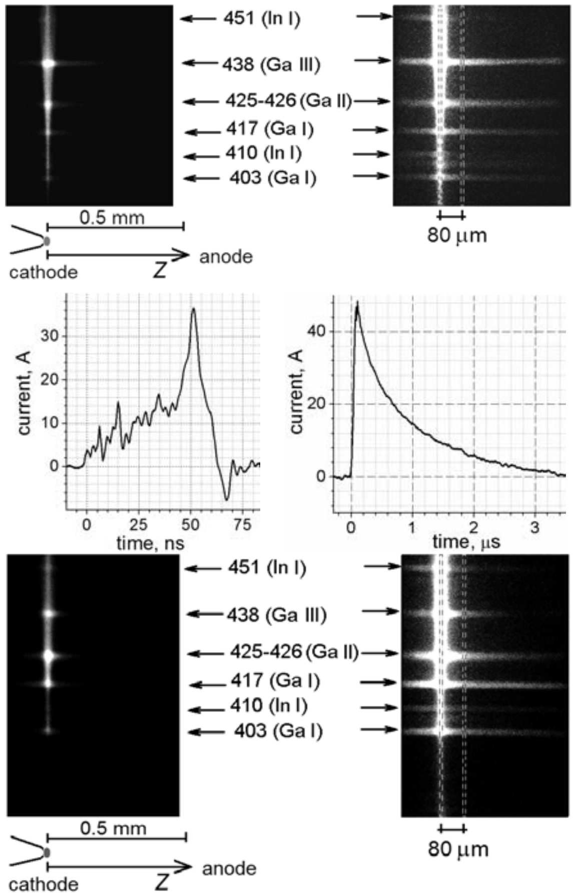

Fig. 2. Top: Two-dimensional spectra obtained in the self-breakdown mode with discharge times of a few 10 ns (cf. left current curve in the middle panel) at high repetition rate of ν = 1 kHz. Bottom: Same measurement for the prolonged discharge of a few μs (right current curve in the middle panel) with ν = 30 Hz

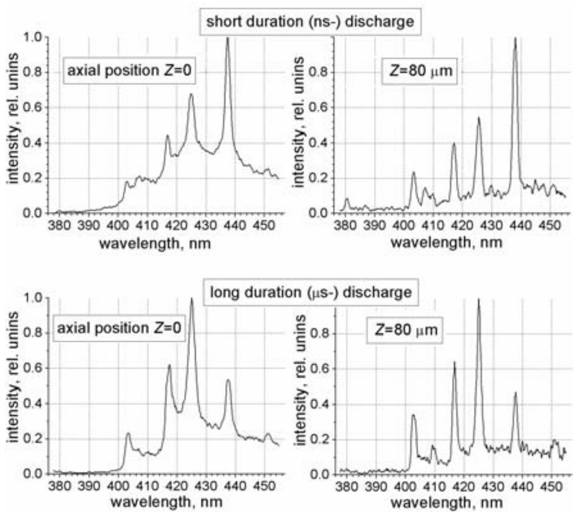

Fig. 3. Spectra at cathode spot position (left) and 80 μm away towards the anode (right) of the ultra short (ns-) discharges (upper panel) and of the long (μs-) discharges (lower panel). All image brightness profiles are obtained from Fig. 2

The left-hand line corresponds to the cathode spot location. The right-hand line corresponds to the position 80 μm far from the cathode spot towards the anode. The brightness profiles are normalized to unit after subtraction of a background level.

Figure 4 shows the behavior of the atomic line Ga I at 417 nm and the ionic line Ga II at 425 nm as obtained from Fig. 2 at various positions along the gap axis. Profiles are not normalized but the background level is subtracted there. Position at $z = 0$ corresponds to a maximum of light (cathode spot centre). Positive z corresponds to the anode direction. The intensity measured at negative z positions is probably caused by reflection at the cathode surface.

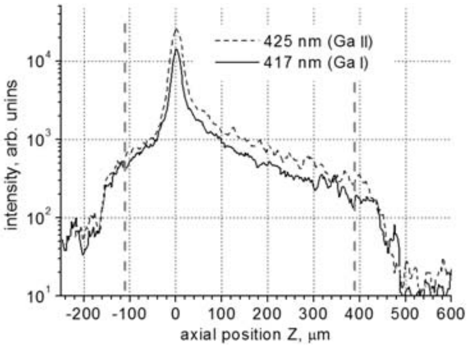

Fig. 4. Comparison of the spatial distributions along the gap axis of the atomic line Ga I at 417 nm and the ionic line Ga II at 425 nm obtained from Fig. 3. The upper diagram corresponds to the μs-discharges and the lower one to the ns-discharges

As evident from the data presented in Figs. 2–4, spectral characteristics of light from different regions of the discharge gap along the gap axis are different essentially in both intensity and behavior. The noticeable characteristics of spectra with regard to discharge regimes are as follows.

1) Presence of the continuous background in the spectral range under the experimentation is a characteristic of light coming from the cathode spot. The contribution of the continuous back-ground in light decreases essentially at distance of 80 to 100 μm. This characteristic is observed for both discharge modes. The nature of the continuous background could be associated with line broadening. Re-radiation in the luminescent screen could contribute in the background. The reason to think about alternatives for continuum in spectra is the fact that the continuous background becomes negligible far from lines as can be seen in Fig. 2. Data on spectrum dynamics presented in the next section confirm it also.

2) The difference in spectra of cathode spot light at different discharge modes (ns and μs time) consists in change in shares of plasma species of different charge states. In the ultra short discharge mode unlike the prolonged one, double-charged ions emit more light in line spectrum in comparison with the share of neutrals. That difference is caused most likely by higher mean charge state of heavy component in plasma at the beginning of discharge operation. The latter is proved by independent measurements of plasma composition.

3) There is the variation in rates of diminution of the line strength with distance from the cathode spot centre. Atomic and ionic lines fall in strength with distance at almost the same rate in the nanosecond mode of discharge operation. In the microsecond mode, the atomic lines fall in strength to a much lesser degree in comparison with the ionic lines. This is clearly seen in comparative analysis of Fig. 4.

4. Time-resolved spectra of the cathode spot

The streak camera was calibrated to ensure a synchronization of the streak images with the discharge current waveforms. Calibration was made with the use of a nanosecond semiconductor laser and a pulser generating nanosecond voltage pulses. Cables for signal transmission were adjusted in length to make optical and electrical paths at the set-up to be equivalent. Observation with the IMACON camera proves the cathode spot to be fixed at the cathode apex during first microsecond of discharge operation.

Figure 5 shows a typical streak pattern in the spectral range under recording taken at the pulse-initiated discharge. The cathode spot emits light mainly in a double-charged ion line at the beginning of spot burning, and no atomic lines are visible at that time. A single-charged ion line becomes intensive 100 ns later. Finally, atomics lines appear half microsecond later after discharge ignition. The scenario is reproducible from pulse to pulse.

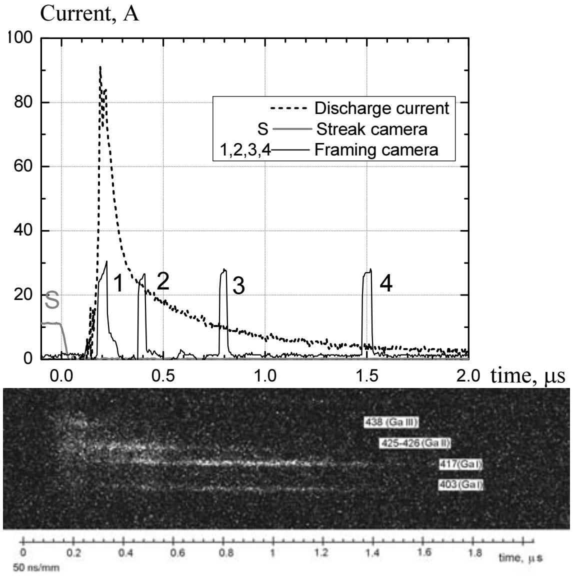

Fig. 5. Top: Waveforms of the discharge current and monitor pulses from the framing camera (streak camera starts at 0 ns). Bottom: Corresponding spectral streak pattern with timescale

The reproducibility of cathode spot ignition at the cathode apex allows one to record a streak image in the accumulation mode (Fig. 6). Nevertheless, each of the 20 discharges that are accumulated was checked for clear visibility of the cathode spot and proper discharge current waveform. This approach provides high quality streak images suitable for quantitative analysis.

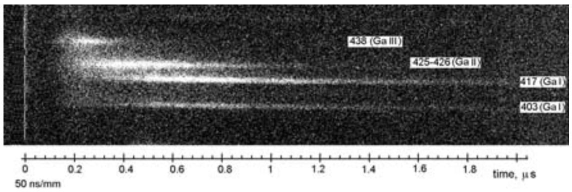

Fig. 6. Spectral streak pattern of 20 accumulated pulses with improved S/N ratio, measured under same conditions as in Fig. 5

Dynamics of line brightness is shown in Fig. 7. A plot for a line was obtained as a result of measurement along a 3-pixel-thick line corresponding to a centre line of a streak. The background level common for all the lines was subtracted.

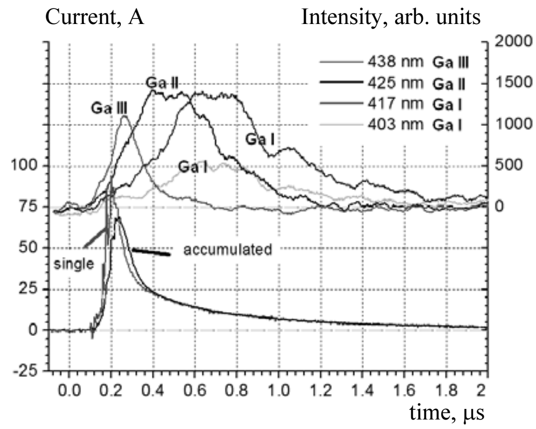

Fig. 7 Current waveforms in the figure are presented for a single pulse and average one

The Ga III 438 nm line gets maximum at the moment of 20 ns after discharge initiation, the Ga II 425 nm line at 200 ns, and the Ga I lines at 400 ns. Note that the data within the first 100 ns of the discharge operation is not enough exact since line broadening is high at that time. Delays in maximums of low-charge-state lines could be explained in terms of recombination radiation of plasma. Furthermore, a certain jitter has to be taken into consideration (cf. single vs. accumulated current waveform).

5. Summary

A new characteristic was found to differ between a spark and an arc discharge. A spark discharge is characterized mainly by emission from ionic lines. Immediately after ignition, the radiation is dominated by higher charges and wide line broadening. Step by step lower charged ions and atoms start to emit and increase their contribution to the emission whereas the share of the (multiple) charged ones decrease. Vacuum discharge with the high current rise rate bears the similar gradual decrease in the mean charge state from high states to low ones [5]. Steady arc discharge can be defined by the domination of atomic line radiation, mainly originating from the plasma cloud around the cathode spot. Continuous background in the spectra could be associated with light coming from the cathode spot. The further necessary step is an enhanced investigation of the line broadening.

References

[1] S.A. Popov and E.L. Pryadko, *Mass and energy analysis of plasma flow generated by cathode spot of low-current vacuum discharges*, this issue.
[2] L.M. Swanson and G.A. Schwind, J. Appl. Phys. **49**, pp. 5655–5662 (1978).
[3] A.V. Batrakov, S.A. Popov, and D.I. Proskurovsky, IEEE Trans. Plasma Sci. **25**, pp. 714–717 (1997).
[4] D.I. Proskurovsky, S.A. Popov, and A.V. Batrakov, IEEE Trans. Dielectr. Electr. Insul. **10**, pp. 604–609 (2003).
[5] G.Yu. Yushkov and A. Anders, Appl. Phys. Lett. **92**, pp. 041502–1-3 (2008).