doi:10.14311/ppt.2025.2.107
Plasma Physics and Technology **12**(2):107–111, 2025

STUDY OF CORRELATION BETWEEN VOLTAGE VARIATION AND SURFACE TEMPERATURE DURING ANODE MODE TRANSITIONS IN A MODEL VACUUM SWITCH

S. Gortschakow[a,*], N. Dorraki[a,b]

[a] *Leibniz Institute for Plasma Science and Technology, Felix-Hausdorff-Straße 2, 17489 Greifswald, Germany*
[b] *Siemens AG, Rohrdamm 88, 13629 Berlin, Germany*
[*] sergey.gortschakow@inp-greifswald.de

Abstract. The correlation between the voltage course and the anode surface temperature was studied by combined optical and electrical measurements. Performed analysis of the temporal evolution of electrical and optical signals reveals that in the case of constricted anode attachment a clear correlation between electrode surface temperature and arc voltage occurs. The results of the study provide new opportunities for qualification of electrode materials for switching applications.

Keywords: vacuum arc, optical diagnostics, optical emission spectroscopy, thermography.

1. Introduction

High-current operation of switching vacuum arcs is accompanied by pronounced electrode erosion. The erosion mechanisms for cathode and anode are different. As long as the arc remains diffuse, cathode erosion due to appearance of multiple small size cathode spots dominates. The anode remains passive, i.e. its surface temperature is below the melting point. An increase of the arc current above a certain current level leads to the arc constriction. Considering the anode-driven constriction, several high-current modes are distinguished: footpoint mode, anode spot (type 1 and type 2) and anode plume [1, 2]. In particular, the anode spot and anode plume modes cause intense material evaporation and surface degradation. Characterization of those modes is, therefore, in focus of intense research in the last decade [1–3].

The optical diagnostics by variety of methods has delivered a wide knowledge base about the arc plasma properties, surface temperature and anode modes transitions [2, 4]. The anode spot dynamics has a rapid nature with characteristic times of order of microseconds [5–7]. Therefore, the diagnostic equipment has to provide a high temporal resolution. In particular, the methods based on application of high-speed cameras are favoured for characterisation of mode transitions and surface temperature [2]. Conventional switching devices have however, no optical ports for diagnostics. The only signals which can be easily measured are the arc current and arc voltage. Detailed investigations of high-current anode modes [3, 5] reveal that the modes associated with constricted anode attachment are always accompanied by measurable voltage jumps and drops. Thus, formation of anode spot causes an increase of arc voltage by 2–20 V [5] , while appearance of anode plume leads to a voltage drop of the order of ten volts [6]. On the other hand, mode transition can also lead to the changes in surface temperature [7]. The lifetime of the electrode system in switching applications is mainly limited by accumulated thermal load of the electrode surface. The contact surface changes its morphology when it is loaded with a high current due to melting, evaporation and solidification processes. This can affect the arc properties, like e.g. arc voltage and arc current behaviour, arc dynamics, surface temperature dynamics and erosion rate. As the temperature variation seems to be linked to voltage changes, quantification of those correlations might open new opportunities in assessment of the surface status and lifetime prediction of switching devices. The correlation between the voltage variation and surface temperature was in the focus of current study.

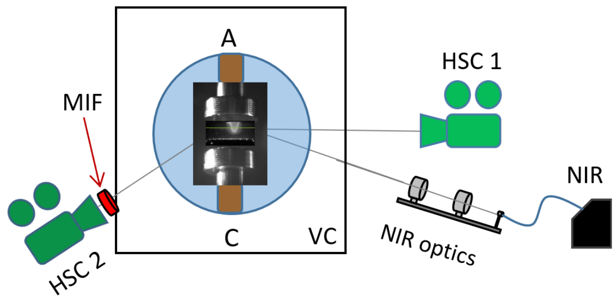

Figure 1. Schematic view of experimental setup. VC – vacuum chamber, A - anode, C – cathode, NIR – near-infrared spectrometer, MIF – narrow-band filter, HSC – high-speed camera.

2. Experimental setup

Experimental setup consists in general of a model circuit breaker, equipped with pumping system and drive for electrode movement, a power source, and diagnostic equipment. Detailed description of the setup is given elsewhere [2, 7]. Here only a brief description is presented. Schematic representation of the main part of experimental setup is shown in Fig. 1.

2.1. Model circuit breaker

The main part of the model circuit breaker is a vacuum chamber (VC in Fig. 1), which was evacuated by the pumping system below 10^{-6} mbar before every experiment. The chamber is equipped with four optical viewports allowing the use of various optical diagnostics. Cylindrical CuCr electrodes with 40% mass fraction of Chromium and a diameter of 30 mm were used. The upper fixed electrode was used as anode, the lower electrode was used as moveable grounded cathode. A pneumatic drive provided an average velocity of about 1.25 m/s. The arc ignition occurs by electrode separation during the current flow. A 50 Hz damped AC high-current generator based on capacitor bank provided the current in the range 100–7500 A.

2.2. Diagnostics

Synchronised electrical and optical measurements were applied. The arc current and voltage were measured by a Rogowski coil (PEM CWT 1500) and a voltage probe (Tektronix P6015A, bandwidth 75 MHz), correspondingly. A high-speed camera (Photron Nova S12, HSC 1 in Fig. 1) is used for the registration of general arc dynamics. Diagnostic methods based on optical emission spectroscopy are widely used for characterisation of the electrode surface [2, 8]. Temporal evolution of the anode surface temperature was determined from combined measurements by a high-speed camera (Photron Nova S6, HSC 2 in Fig. 1) equipped with a narrow band filter (MIF in Fig. 1, central wavelength 891 nm, FWHM 10 nm) and a compact NIR spectrometer (Hamamatsu C114GA, NIR in Fig. 1). The parameters of filter are chosen to minimize the contribution of plasma radiation during the measurements of anode surface temperature. The NIR spectrometer and camera HSC 2 are positioned at the same viewing angle to the anode surface. A focusing optical system (NIR optics in Fig. 1) images a region of about 3 mm^2 in the area where the anode spot was expected on the entrance slit of the NIR spectrometer. The NIR spectrometer provides a temporal resolution of 1.25 ms and exposure times of 100 µs, while the high-speed camera acquires the images with 22500 fps and an exposure time of 5 µs. The spectra recorded by the NIR spectrometer are processed by comparing the measured calibrated radiances to the black body emission according to Planck law [2, 4]. The correlation between arc intensity, recorded by high-speed camera, and surface temperature, measured by the NIR spectrometer, is used for determination of the anode surface temperature during the active phase. Further details of the method, like e. g. calibration routine, possible restrictions, handling in special case of intense arc radiation, can be found in [2, 4, 8].

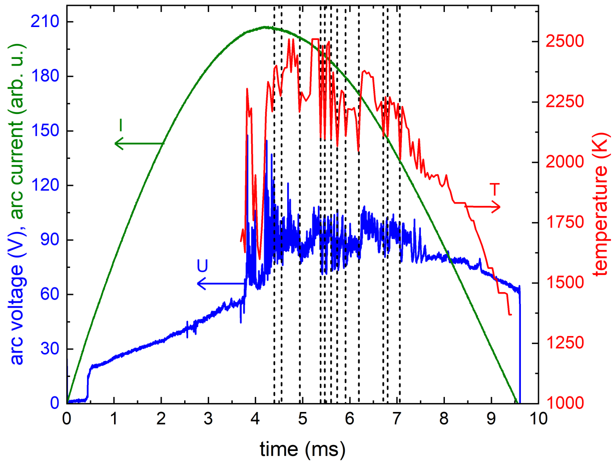

Figure 2. Example of evolution of arc voltage (U, blue line) and maximum anode surface temperature (T, red line) along with the shape of arc current (I, green line). Dashed lines mark the instants of reversible spot-to-plume transitions. Peak arc current 4 kA, arc duration 9 ms.

3. Results and discussion

The most relevant anode modes which lead to significant surface erosion are the anode spot and anode plume mode. Stable reproducible transition between those two modes were obtained in the current range 3–7.5 kA [7]. Figure 2 presents the typical evolution of arc current, arc voltage and maximum anode surface temperature in the case of pronounced anode activity. The arc ignition is accompanied by a voltage jump of about 15 V at $t = 0.5$ ms. After a certain time period of diffuse arc burning $(0.5 - 2.5\,\mathrm{ms})$, first voltage fluctuations of the order of few volts due to transition to the footpoint mode occur. Stable anode spot appears at $t = 3.8$ ms. Its formation is accompanied by significant voltage jump. Starting from this instant, several transitions between anode spot and anode plume modes occur. The first formation of anode plume takes place at the instant of about 4.5 ms. Each of plume formations causes a voltage drop up to 20 V. The consequent formation of the anode spot after extinguishing of an anode plume is accompanied by a voltage jump of the same order of magnitude.

Precise determination of the surface temperature requires fulfilment of two conditions - (i) clear view on the full anode surface and (ii) detectable undisturbed NIR signal from the anode surface before current zero. The first condition was always reached after the instant of about $t = 4$ ms. The temperature evaluation from NIR spectra was possible earliest at about 1 ms before current zero. In current experiments, the disturbing arc radiation at this instant was low enough. In presented example, the anode temperature prior to the

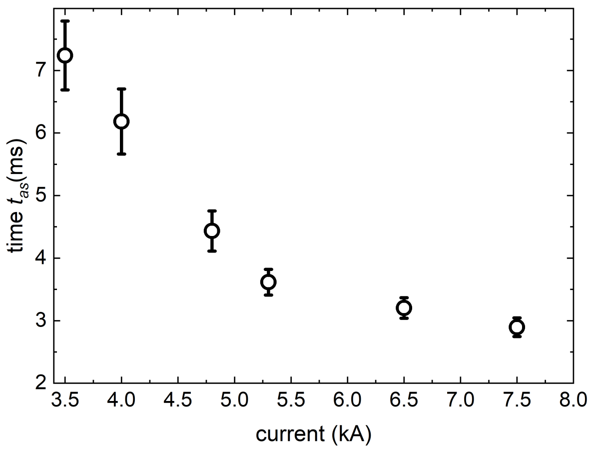

Figure 3. Time before the first anode spot occurrence t_{as} in dependency on maximum arc current.

spot formation was about 1700 K. After the formation of anode spot the temperature increases and can be as high as 2500 K. Starting from the instant of first spot appearance, each formation of anode plume causes the anode temperature drop, while each new spot formation is accompanied by a temperature rise. The instant of the stable anode spot appearance (t_{as}) is dependent on the current level. While the value of t_{as} for the lowest current limit was about 7.2 ms, much shorter time (less than 3 ms) was necessary at the highest current (Fig. 3). At lower currents, the time scatter was also larger. Formation of an anode spot depends on many factors. The main factor, however, seems to be a volume of melted material which can produce enough metal vapour. As long as the position of anode spot is not fixed, it is not possible to focus the heat flux on it. Stochastic movement of anode attachment reduces with increasing current. This leads to faster transition to an anode spot mode. In general, higher current provide more reversible spot-to-plume transitions [7].

An illustration of reversible spot-plume-spot transition is presented in Fig. 4. The temporal resolution of temperature measurements is restricted by parameters of the high-speed camera. Spot-to-plume transitions occur within few microseconds [7], while the HSC frame rate allowed for acquisition with temporal resolution of 50 µs. This fact complicates the analysis of the relation between the voltage changes and temperature variation. Nevertheless, it was possible to track the anode surface temperature changes in the spot and plume modes in the majority of considered cases. One of such successful evaluations is shown in Fig. 4. Upper row presents the arc images illustrating the anode spot mode (instants 5.33 and 5.42 ms) and anode plume mode (5.38 ms). The middle row presents the filtered images of the anode surface. It is clearly visible, that the anode spot provides much intense surface radiation comparing to anode plume. The surface temperature (lower row in Fig. 4 reaches about 2500 K in the spot mode. It decreases by about 400 K when the anode plume reaches its maximum length (instant 5.38 ms in Fig. 4. Immediately after the plume extinguishing, the anode temperature rises again, but remains slightly below the level before the spot-to-plume transition (ca 50 K). The difference between the temperatures before plume formation and after its extinguishing depends on the current phase. In the case when the current is growing, the surface temperature restores to the same level within 10 µs. In presented example, the current is decreasing. Therefore, the heat flux toward the anode is also decreasing. This lead to smaller surface temperature after spot reignition.

The anode plumes can have different spatial extension. Figure 5 shows several examples of anode plumes obtained within one experiment. Possible correlation between the plume length and temperature decrease as well as the voltage drop after plume formation was studied. Corresponding results are shown in Fig. 6 and7. In each series (denoted by numbers) the arc current was fixed. Following current levels have been tested: 3.5 kA (series 1), 4.0 kA (series 2), 4.2 kA (series 3), 4.8 kA (series 4), 5.2 kA (series 5).

Figure 6 presents the maximum plume length determined in dependency on surface temperature drop. Despite a strong scatter in the temperature range 50–250 K, in general„ larger plume length was obtained for higher temperature drop. Possible explanation is that the plume length is dependent on the amount of evaporated material. Larger plumes lead to more intense evaporation. On the other hand, evaporation is responsible for the electrode cooling due to the evaporation heat flux.. Therefore, higher evaporation leads to more heat loss and, hence, to stronger surface cooling.

Analysis of a dependency of plume length on voltage drop (Fig. 7) predict a tendency for longer plumes for larger voltage drop. Strong data scattering can be related to the stochastic character of plume formation process as well as to insufficient temporal resolution (necessary resolution for high-speed imaging should be below 1 µs) and uncertainties in determination of voltage values.

The temperature variation due to anode spot and plume formation is larger when the arc current is higher. Clear correlation between the value of voltage jump/drop and value of temperature rise/fall was obtained (Fig. 8). Larger voltage drop cause higher surface temperature fall.

As no external magnetic field for arc control was used, at higher currents the arc attachment was shifted to the lateral side of the electrodes (right inset in Fig. 9). At such conditions the mode reversibility was terminated and a significant voltage jump was observed. The voltage increase in the case of lateral attachment was by about factor of two higher

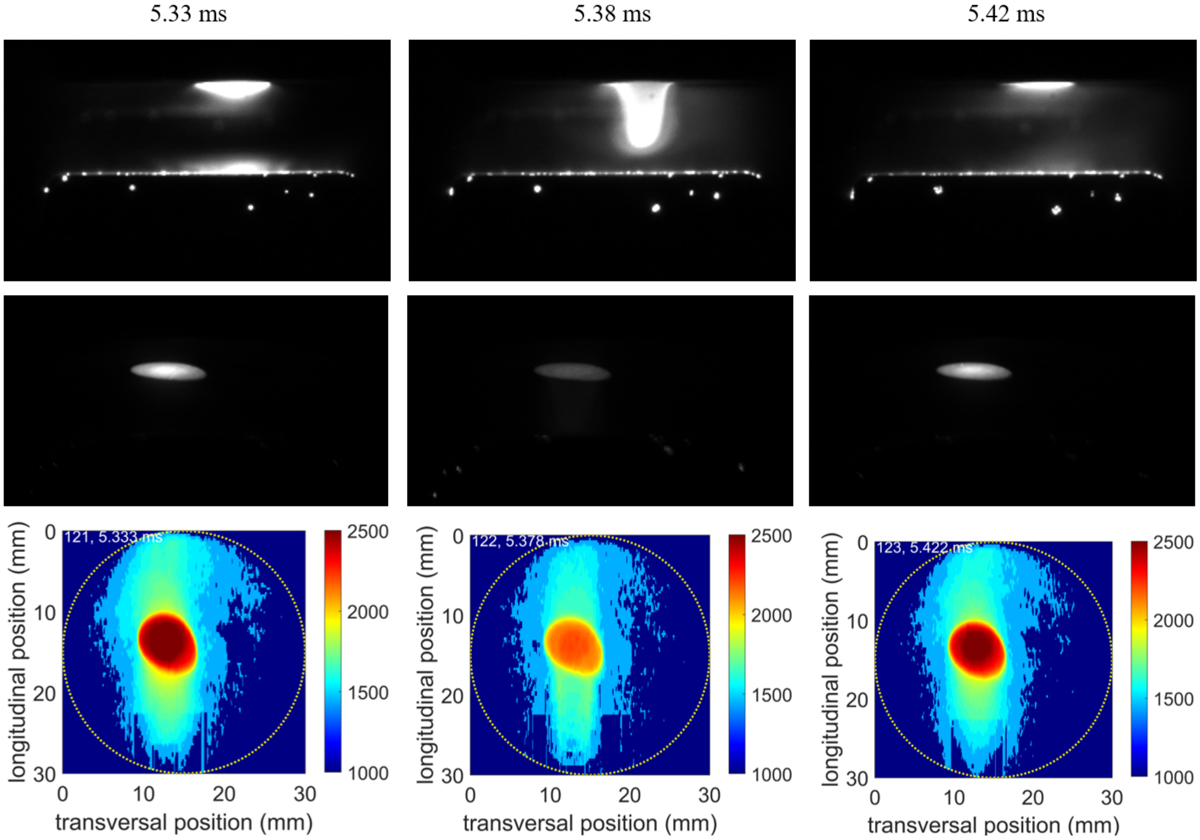

Figure 4. Illustration of reversible transition spot - plume - spot around the instant 5.4 ms. Upper row shows the arc image (anode on the top, cathode on the bottom), middle row – spectrally filtered image of the anode surface, lower row – reconstructed distribution of anode surface temperature (in Kelvin). Same experiential conditions as in Fig. 2.

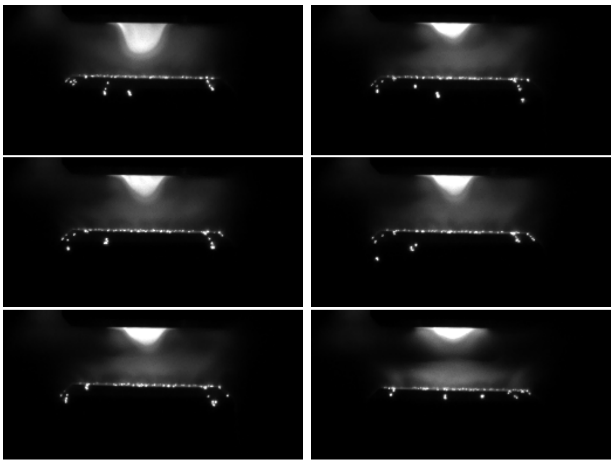

Figure 5. Examples of anode plumes observed within one shot. Acquisition instants 6.5, 6.61, 6.68, 6.76, 6.87 and 7.28 ms

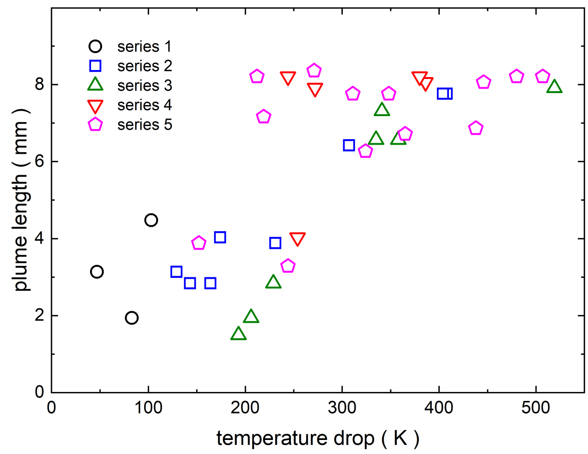

Figure 6. Dependency of maximum plume length on the temperature drop measured in different experimental series.

comparing to the cases when the arc was between the electrodes [7]. Thus, the lateral attachment can be potentially identified and excluded from analysis.

The dependency $T(U)$ shows a large scatter. In order to diminish it, an increase of temporal resolution of surface temperature measurements by about one order of magnitude is required. Nevertheless, the results of current study reveal that the analysis of voltage shape can be used for quantitative characterisation of surface temperature.

4. Conclusions

Combined electrical and optical diagnostics was applied to study the properties of high-current vacuum arcs in the case of multiple spot-to-plume transitions. The focus was put on analysis of the

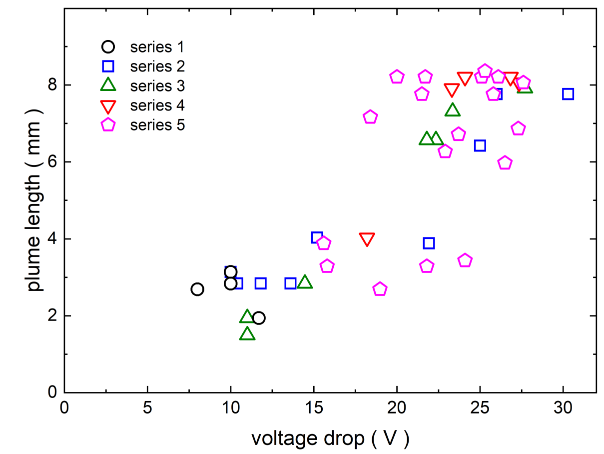

Figure 7. Dependency of maximum plume length on the voltage drop measured in different experimental series.

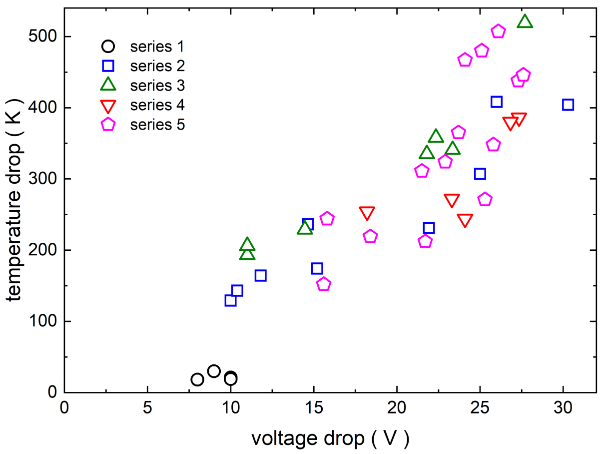

Figure 8. Dependency of temperature drop on the voltage drop $T(U)$ measured in different experimental series.

anode surface temperature during transitions between those two modes, as they lead to substantial electrode erosion. Obtained correlation between the arc voltage variations and anode surface temperature offer the opportunity for development of predictive method for choice of electrode material and optimization of electrode design for high-current operation regime based on analysis of temporal evolution of the arc voltage.

Acknowledgements

This research was funded by the Deutsche Forschungsgemeinschaft (DFG), project GO 3402/1-1.

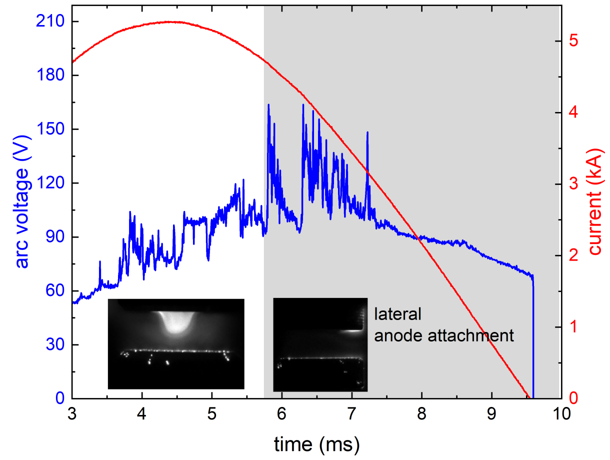

Figure 9. Temporal evolution of arc voltage and current in case of lateral anode attachment.

References

[1] H. C. Milner. Vacuum arcs. *IEEE Trans. Plasma Sci.*, 51:1585–1594, 2023. doi:10.1109/TPS.2023.3261779.

[2] S. Gortschakow. Diagnostic methods for switching vacuum arcs based on high-speed camera technique. *IEEE Trans. Plasma Sci.*, 52:4382–4389, 2024. doi:10.1109/TPS.2024.3353826.

[3] H. C. Milner. Anode modes in vacuum arcs: Update. *IEEE Trans. Plasma Sci.*, 45:2366–2374, 2017. doi:10.1109/TPS.2017.2708695.

[4] S. Gortschakow, S. Franke, R. Methling, et al. Advanced optical diagnostics for characterization of arc plasmas. *IEEE Trans. Plasma Sci.*, 49:2505–2515, 2021. doi:10.1109/TPS.2021.3096289.

[5] A. Khakpor, S. Franke, R. Methling, et al. Advanced optical diagnostics for characterization of arc plasmas. *IEEE Trans. Plasma Sci.*, 45:2505–2515, 2017. doi:10.1109/TPS.2021.3096289.

[6] A. Khakpor, R. Methling, D. Uhrlandt, et al. Time and space resolved spectroscopic investigation during anode plume formation in a high-current vacuum arc. *J. Phys. D: Appl. Phys.*, 50:185203, 2017. doi:10.1088/1361-6463/aa6494.

[7] N. Dorraki, R. Methling, and S. Gortschakow. Advanced temporal analysis of anode activity during mode transitions in high current vacuum arcs. *J. Phys. D: Appl. Phys.*, 58:075204, 2025. doi:10.1088/1361-6463/ad96c5.

[8] R. Methling, S. Franke, S. Gortschakow, et al. Anode surface temperature determination in high-current vacuum arcs by different methods. *IEEE Trans. Plasma Sci.*, 45:2099–2107, 2017. doi:10.1109/TPS.2017.2712562.