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INVESTIGATION OF AN ABLATION-DOMINATED ARC IN A MODEL CHAMBER BY OPTICAL EMISSION SPECTROSCOPY

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Abstract. A switching arc in a model chamber is investigated by means of optical emission spectroscopy. Ignition wire is applied to initiate an arc of several kiloampere between tungsten−copper electrodes. Radiation emitted by the arc plasma is absorbed by a surrounding PTFE nozzle, leading to an ablation–dominated discharge. Video spectroscopy is carried out using an imaging spectrometer combined with a high–speed video camera. Carbon ion and fluorine atom line emission from the heating channel as well as copper, oxygen and nitrogen from ignition wire and ambient air are analyzed with focus on the low–current phases at the beginning of discharge and near current zero. Additionally, electrical parameters and total pressure are recorded while the general behavior of the discharge is observed by another video camera. Considering rotational symmetry of the arc the corresponding radial emission coefficients are determined. Finally, radial temperature profiles are calculated.

Keywords: ablation, switching arc, spectroscopy.

1. Introduction

High voltage circuit breakers are essential elements in modern power grids which ensure safe power flow [1]. In self–blast circuit breakers the pressure build–up in a heating volume, necessary for arc quenching, is attained by the ablation of material from the nozzle wall due to intense arc radiation. One focus of circuit breaker development is the substitution of the strong greenhouse gas sulfur hexafluoride by carbon dioxide. The current zero (CZ) crossing and the period immediately after current interruption are of high importance for the interruption performance of the circuit breaker. In these time intervals several physical effects occur, such as flow reversal in the heating channel, translation from an ablation–controlled to an axially blown arc, the extinction of the arc and a continued evaporation of nozzle material after current zero due to the preceding thermal stress. The deeper understanding of these effects, their transient behavior and their effects on the dielectric recovery of the gap between the contacts after current zero are key issues for further development of high voltage switchgear, either based SF_6 or alternative gases.

The complicated geometry of real circuit breakers usually does not offer direct optical access to the arc plasma. Thus, model chambers have to be applied to investigate the plasma parameters under more or less similar conditions, comprising solutions with movable pin and tulip electrodes [2] or with fixed electrodes ignited by explosion of thin wires [3] and with non–rotationally symmetric nozzles [4]. In this work two pin electrodes of fixed distance are placed in a long PTFE nozzle. A switching arc in a model chamber is investigated by means of optical emission spectroscopy (OES). In a first step, only the nozzle without the chamber is applied. Here, it is of special interest how far the arc is dominated by the PTFE ablation at low current phases, i.e. during the current increase when the discharge is initiated and when approaching CZ. Beside temperature distribution the influence of ignition wire and the surrounding gas (ambient air) are investigated.

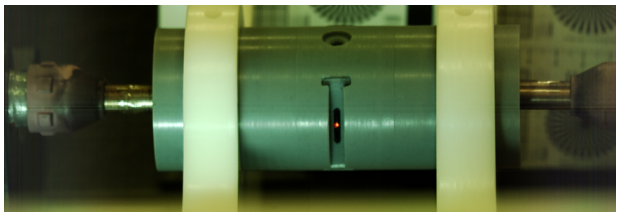

Figure 1. Experimental setup with PTFE nozzle. The observation window made of 2 mm thick quartz glass is positioned in the center of the PTFE nozzle. W–Cu electrodes at both sides are protected from exhaust plasma by ceramic caps.

2. Experimental

A photograph of the chamber setup is shown in Figure 1. The PTFE (polytetrafluoroethylene) nozzle has a length of 126 mm and an outer diameter of 50 mm. The inner diameter is 12 mm over a length of 30 mm along the main part of the arc, then increasing within the next 10 mm to a final diameter of 15 mm. Current flow from a high–current generator is started by a triggered spark gap. An about 0.2 mm thick copper ignition wire is applied to initiate an arc discharge between tungsten−copper electrodes of 40 mm distance and 10 mm diameter. Outside the chamber the ends

of the electrodes are protected from exhaust plasma by ceramic caps. The pressure inside the nozzle is measured by means of a piezo–resistive pressure sensor of type 6052C combined with a charge amplifier 5073 (Kistler). The connection port for the pressure sensor can be seen on top of Figure 1. Sinusoidal current waveform of about 100 Hz frequency is applied. The maximum pressure of about 8 bar is measured close to peak current of 11 kA at 4.6 ms.

The intense radiation emitted from the arc plasma is absorbed by the surface of a surrounding PTFE nozzle where it causes photo–ablation of the wall material [5]. Part of the ablated material is exhausted as vapor by axial flow, the other part enters the arc and is heated to plasma temperature by absorption of radiation coming from the arc interior, leading to a discharge that is dominated by the ablation [6]. Both arc plasma and vapor create an overpressure which causes an axial expansion flow towards the ends of the tube. To enable an optical investigation of the arc cross section, a vertical slit is inserted in the middle of the nozzle. Transparent windows made of 2 mm thick quartz plates in the chamber wall are applied to seal the nozzle. The windows transmission is measured before and after each shot. However, it turned out that deposition of ablated material is not critical as long as the windows are cleaned regularly and exchanged every few shots.

Using a combination of 0.5 m–imaging spectrometer and a high–speed video camera (Y4 series of Integrated Design Tools), time-dependent video spectroscopy is carried out. The red dot in Figure 1 marks the central observation position of the OES. The spatial resolution is 28 µm/pixel. The spectral resolution is 0.8 nm using a grating applied for overview spectra with 150 lines/mm and a slit width of 50 µm. The temporal resolution is given by the maximal number of frames per time. It depends mainly on the number of vertical lines of the video camera. For an observation of the complete slit of the nozzle as needed for determination of radial profiles, 600 vertical lines have to be used yielding a frame rate of 7500 fps (frames per second). The exposure time is 2 µs. Reducing the number of vertical lines of the video camera and skipping the spatial resolution, however, allows higher temporal resolution of 100 kfps which is equal to a period between the spectra of only 10 µs. The exposure time is chosen as high as possible (8 µs) in order to obtain highest sensitivity during low–current phases although overexposure occurs during high–current phases. A second high–speed video camera (Y6 series of Integrated Design Tools) is applied for the observation of the general behavior of the discharge.

Ionic as well as atomic line emission from the heating channel are analyzed. Considering rotational symmetry of the arc the corresponding radial emission coefficients are determined. Finally, radial temperature profiles are calculated with temporal resolution.

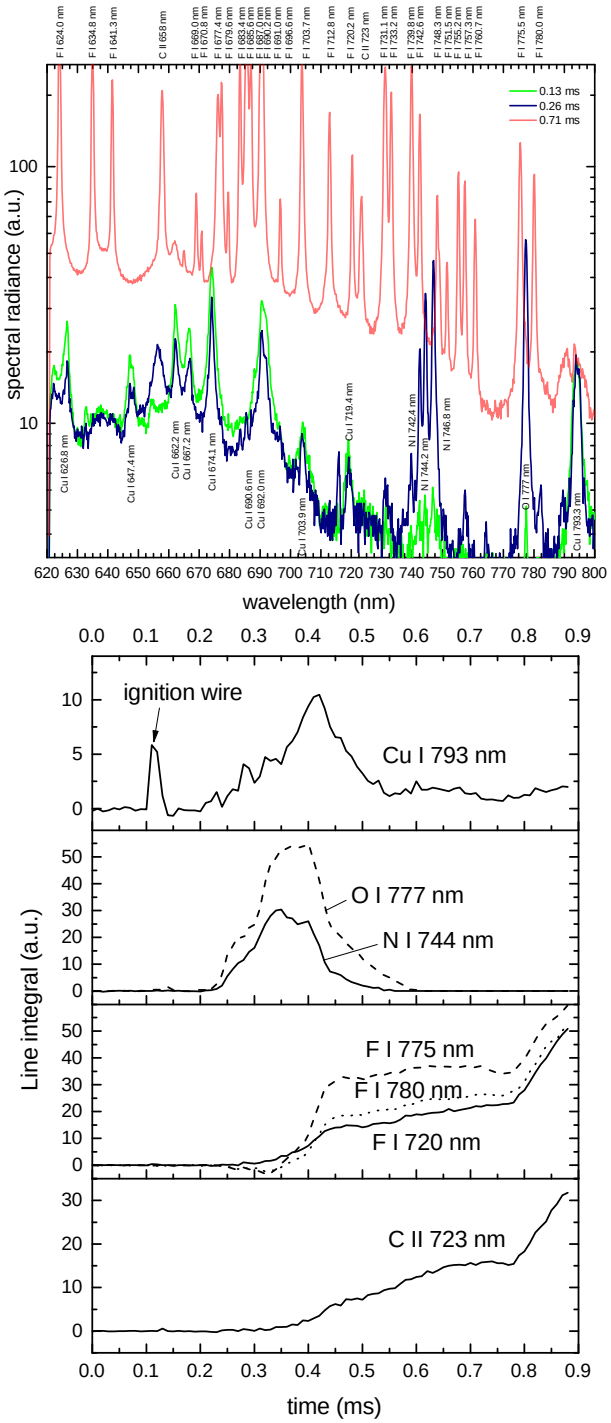

Figure 2. Spectrum variation during initialization. Top: Three spectra measured after 130, 260, and 710 µs are dominated by line emission of Cu I during wire explosion, N I and O I during heating up the arc column, and F I, C I, and C II from nozzle surface during ablation–dominated arc phase, respectively. Bottom: Temporal distribution of spectrally integrated line intensities of selected lines.

3. Results and discussion

Series of two-dimensional spectra containing spatial as well as spectral information are obtained by the video spectroscopy. In the following only the central position is regarded to analyze the temporal evolution

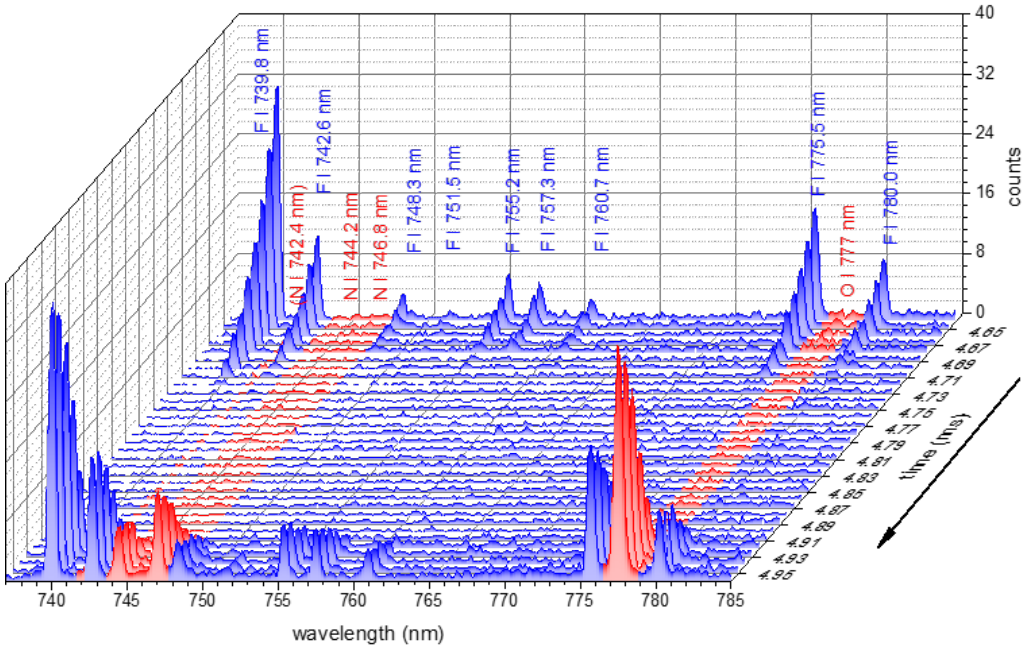

Figure 3. Temporal evolution of spectra around current zero showing influence of ambient air.

of the spectrum during the discharge with 100 kfps. An example of three spectra acquired during the initial phase of one shot is shown in the upper part of Figure 2. The major lines are labeled with PTFE material above and the rest inside the spectrum. For better distinction, logarithmic scaling of the spectral radiance is applied. In the lower part, the temporal distributions of spectrally integrated line intensities of selected lines are plotted.

The arc discharge is initialized by the explosion of a thin copper wire due to Joule heating. Thus, mainly corresponding lines of atomic Cu I radiation can be found in the spectra. The first spectrum with detectable Cu I radiation can be observed after 110 µs (with respect to the point of time when the current flow is started) at current of 1.1 kA. It is followed by a local maximum of Cu I line emission around 120 µs with slightly broadened lines and by weaker spectra at 130 and 140 µs. It should be noted that the intensity of both oxygen and nitrogen atomic lines around 777 and 745 nm, respectively, is very weak and keeps low for the next about 100 µs, cf. lower part of Figure 2. The arc discharge is dominated by the metal vapor of the exploding wire and the influence of ambient air surrounding the discharge plasma within the PTFE nozzle is low.

In the following time of current rise, the Cu line emission rises up again. Now the metal vapor can not originate from the ignition wire any more but is caused by erosion from the tungsten–copper electrodes. In parallel, the atomic line emission from the triplet O I at 777 nm and the three N I lines at 742.4 nm, 744.2 nm, and 746.8 nm increases considerably. That phase starts about 230 µs (100 µs after explosion) and lasts about 150 µs (current increases from 2 to 3 kA). The radiation energy from the arc discharge heats up the nozzle surface and wall material is evaporated. Hot plasma is blown out of the nozzle at both ends as can be observed in video images of the second camera. Thus, the plasma composition is changed, decreasing the amount of nitrogen and oxygen as well as copper. Additionally, a cooling of the arc occurs by increased amount of cold wall material. As a consequence the radiation from air components decreases. The emission from the oxygen line starts before and lasts longer than the ones of nitrogen lines in accordance with their lower energies of the upper levels (O I 10.7 eV, N I 12.0 eV).

Starting around 400 µs (about 3 kA), significant carbon and fluorine line emission can be observed in the spectra. After nearly stable intensity of some lines (F I 775 nm) and relative low increase of others between 400 and about 800 µs, the emission increases very fast. That delay of several hundred µs might result from the time needed to inject the wall material into the arc and to heat it up to temperatures necessary for intense line emission. The temporal evolution of the three F I lines shown here is quite comparable since they have rather similar upper line levels around 14.7 eV. The slower increase of the carbon ionic line C II at 723 nm might be due to the higher level of 18.0 eV.

During the ignition phase it takes more than half but less than one millisecond until the arc plasma is completely dominated by the material ablated from the nozzle wall and the influence of the surrounding gas can be neglected - at least in case of air under ambient conditions of one bar. In the following the influence of the air should be investigated around current zero (around 4.8 ms). Therefore, several successive spectra are plotted in Figure 3. Note that only a part of the spectral range is shown for better distinction of lines. The major lines of atomic fluorine

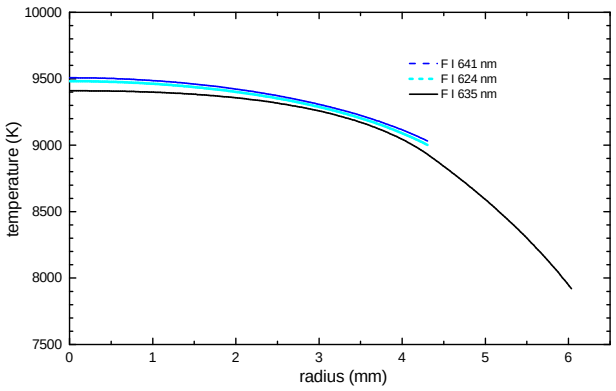

Figure 4. Radial temperature profile 0.4 ms before CZ obtained from three atomic fluorine lines.

as well as oxygen and nitrogen are labeled. Before CZ, only the fluorine lines are observed, cf. spectra between 4.65 ms and 4.71 ms. During a "dark" phase ranging from about 100 µs before until 100 µs after current zero, no emission can be detected due to the low energy input. Here, other spectral techniques are needed for investigation of the residual plasma, e.g. intensified cameras for emission spectroscopy or absorption measurements. However, in the following time starting about 100 µs after CZ (4.9 ms), the sensitivity of the applied video spectroscopy setup is capable to detect enough radiation for further analysis. Now the oxygen triplet O I at 777 nm as well as the three N I nitrogen lines around 744 nm are observed beside the fluorine lines, showing again an influence of ambient air. It was found that also in the second half wave the emission from air components can be detected for the following 500-600 µs.

For determination of radially resolved plasma temperatures, two-dimensional spectra with 600 vertical lines have to be applied. The temporal resolution is reduced to 7500 fps, i.e. increasing of the time between successive spectra to 133 µs. Thus, there remains just one "dark" spectrum at CZ (4.8 ms) for which no line but only noise is detected. The two spectra immediately before CZ, i.e. at 4.66 and 4.53 ms, show distinct emission from all fluorine atomic lines under investigation. Nevertheless, reliable temperature determination is still not possible due to limited line intensity. For the spectrum measured at 4.40 ms (0.4 ms before CZ), two-dimensional spectral fits are carried out. Assuming local thermodynamic equilibrium and rotational symmetry of the arc, Abel inversion of the fitted spectra is done delivering radially resolved emission coefficients. Finally, radial temperature profiles are determined as shown in Figure 4. Three F I lines are applied with quite similar results, including a rather flat temperature profile with a maximum 9500 K and a decrease by 500 K within more than 4 mm. Between radial position of 5 and 6 mm the temperature decreases rapidly to values around 8000 K.

4. Conclusions and outlook

A circuit breaker model is applied to investigate ablation–dominated arc with peak currents of about 11 kA. The radiation of the electrical arc is analyzed by optical emission spectroscopy for a spatially resolved determination of plasma temperature. The focus of our investigations is on the stepwise analysis of the physical properties and processes during the interruption process from the high–current–phase up to some milliseconds after current zero. One question is to which extent and up to which point of time before the arc extinction, the radiation emission of the arc leads to reliable results. Another question is how long the discharge plasma is dominated by ablated material and how far it is influenced by the surrounding ambient when the current is close to the CZ point of time.

In future, additionally to the emission spectroscopy that can also be carried out using more sensitive intensified CCD cameras. Furthermore, laser absorption shall be applied in order to determine the density of colder gas after CZ, such as resulting from the nozzle evaporation. Beside the optical investigations capacitive sensors will be used for measuring the spatially resolved distribution of the arc resistance over the complete time range. The experiments will be accompanied by simulations.

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