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Publication Date
2005-07-15

Peer reviewed

LBNL-58310

Submitted to the
Journal of Physics D: Applied Physics

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July 15, 2005

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This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Material and time dependence of the voltage noise generated by cathodic vacuum arcs

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Abstract

The high frequency fluctuations of the burning voltage of cathodic vacuum arcs have been investigated in order to extract information on cathode processes. Eight cathode materials (W, Ta, Hf, Ti, Ni, Au, Sn, Bi) were selected covering a wide range of cohesive energy. The voltage noise was recorded using both a broad-band voltage divider and an attenuator connected to a fast oscilloscope (limits 1 GHz analog and 5 GS/s digital). Fast Fourier transform revealed a power spectrum that is linear in log-log presentation, with a slope of $1/f^2$, where f is the frequency (brown noise). The amplitude of the spectral power of the voltage noise was found to scale with the cohesive energy, in agreement with earlier measurements at lower resolution. These basic results do not depend on the time after arc initiation. However, lower arc current in the beginning of the pulse shows greater voltage noise, suggesting an inverse relation between the noise amplitude and number of emission sites (cathode spot fragments).

1. Introduction

It is known that cathodic arcs have fractal properties such as random walk of spot ignition [1, 2], self-similarity in visual appearance and optical emission [3], and power laws in macroparticle size distribution [4]. Recently it has been argued that considerations of fractal spot properties are essential for an adequate modeling of cathodic arc spots in space and time. For example, the long-standing dispute about the "true" current density can be resolved and various, somewhat conflicting models (explosive model [5-7] and layer model [8, 9]) can be re-evaluated from a different prospective. The fractal approach has stimulated preliminary research into the noise of the cathodic arc burning voltage [10]. The burning voltage was identified as a physical parameter suitable to study the random behavior of the ignition of emission sites (fragments of cathode spots). The arc voltage is a free parameter that adjusts itself such as to satisfy the momentary energy needs of the arc discharge. In comparison, the arc current is relatively smooth because it is determined by the circuit impedance which is typically dominated by either a stabilizing ohmic resistor or inductive load.

Because different materials require different amounts of energy to be "liberated" from the solid and transferred into the plasma phase, the cohesive energy of the cathode is a suitable parameter to scale such phase transition. Indeed, the burning voltage was experimentally found to be proportional to the material's cohesive energy (cohesive energy rule [11]). Not coincidentally, materials of higher cohesive energy show also higher ion charges states and ion energies [11-13].

Electron emission and plasma production occur by fast, non-stationary processes at cathode spots [14, 15]. Investigations with increasingly sophisticated diagnostic equipment revealed ever smaller structures and faster processes [15-20], which is precisely a characteristic of fractals [21]. Voltage measurements can be made with very good time resolution, and data analysis by fast Fourier transform (FFT) is easily accomplished with digital data acquisition and processing. Preliminary analysis [10] indicated that the spectral power of the arc noise drops as $1/f^2$, where f is the frequency. Such behavior is generally called brown noise [21] in association to Brownian motion (one should recall that the well-investigated random walk is the discrete approximation to Brownian motion [4]). The preliminary analysis [10] considered a number of cathode materials and found that not only the arc burning voltage but also the noise approximately scales with the cohesive energy of the cathode material.

In this contribution, we attempt to improve the measuring technique and data handling with the goal to address a number of questions that were left unanswered by the preliminary investigations. These questions are related to improving the confidence in the data, to the origin of peaks seen in some Fourier spectra at certain frequencies between 30-300 MHz, to the interpretation of material dependences, and to exploring the evolution of arc noise after arc triggering.

2. Experimental setup

The fluctuating character of the cathodic arc was investigated by recording the burning voltage with high band width, and analyzing the time-dependent data by fast Fourier transform (FFT). To preserve the frequency characteristics of the voltage noise as it is generated by cathode processes, a coaxial plasma source was used, consisting of a rod of 6.25 mm diameter (center cathode) surrounded by a coaxial, grounded cylinder (anode). The setup is very similar to what was previously used [10].

The pulsed arcs were initiated by self-triggering, i.e. the arc started when the arc supply voltage was switched on and thereby applied to the electrodes [22] (One should stress that the open-circuit supply voltage is ~ 300 V and it must not be confused with the arc burning voltage; the latter is directly measured between anode and cathode and typically 20 V). The principle of self-triggering is based on the formation of a hot spot at the interface of a metallized ceramic tube and the cathode [23]. A wide range of arc cathode materials was selected, including W, Ta, Hf, Ti, Ni, Au, Sn, and Bi (this order reflects decreasing cohesive energy).

The arc was fed by a large, 0.33 F capacitor bank charged up to 315 V and switched with a high-voltage, high-current transistor. In all experiments, the arc pulse duration was 1 ms, see Fig. 1, at a repetition rate of 1 pulse per second. The arc current was determined by the charging voltage and the circuit's impedance; the latter was dominated by an ohmic resistor of 1 **Ω**. As mentioned before, because the arc impedance is much smaller than 1 **Ω**, the arc current was relatively smooth even when the arc impedance fluctuated.

Single-pulse voltage data were collected, always picking the 5th pulse after running 4 pulses for cathode surface conditioning. The beginning of data acquisition was delayed by 20, 30, 50, 100, and 150 µs after arc initiation. Most data in this study were collected with 150 µs delay after arc initiation, as it is indicated in Fig. 1. This delay was chosen because it is known that arc plasma parameters have almost "settled" to steady-state values representative of DC arcs. No process gas was added; the experiments were preformed in oil-free, cryogenically pumped vacuum at a base pressure of about 10^{-4} Pa.

The arc burning voltage was monitored directly at the vacuum feedthrough, using two measuring setups simultaneously. One was a broadband 100:1 voltage divider (Tektronix P5100, nominal maximum frequency 250 MHz), the other was a high-power, 50 Ω, 30 dB attenuator (Aeroflex/Weinchel, nominal maximum frequency 2.5 GHz) in series with two additional attenuators (HP 8491A with 10 dB, and HP 8491B with 3 dB, both with a nominal maximum frequency of 18 GHz). For simplicity, we call these setups "divider" and "attenuator" in the remainder of this paper. Both divider and attenuator were connected to a digital storage oscilloscope (Tektronix TDS 684B, nominal maximum frequency 1 GHz analog, 5 GS/s digital, corresponding to 200 ps per data point). Voltage data were captured in sample mode, with 15000 points measured during a total acquisition time of 3 µs, using the maximum acquisition rate of 5 Gs/s. Fig. 2 shows an example of raw data measured with attenuator and divider for Bi and W cathodes, at 150 µs into the pulse. The similarity between the voltage patterns obtained by divider and attenuator is evident, and so was the strong material dependence of the fluctuations. Because the arc current has a finite rise time, current was also monitored (high current Pearson coil, model 301X, 3 dB at 2 MHz, sensitivity 0.01 V/A). The arc current was measured to be up to 225 A. It depended slightly on the plasma impedance, which was different for different cathode materials. The captured data of the arc burning voltage and the current were recorded in the scope's memory and then exported to a computer for further analysis.

3. Data treatment

Each single-pulse data acquisition was repeated 16 times at constant measuring conditions. The data set of each pulse included (i) the burning voltage acquired with the divider (ii) the same voltage but measured with the attenuator, and (iii) the arc current. Noise analysis was limited to voltage data and done as follows. In order to deal only with the fluctuating part of the voltage, the average voltage was calculated for each data acquisition and subtracted from the measured raw data. The spectral power was calculated by FFT of each of the 16 reduced data sets. The FFT results were averaged and additionally 10-point smoothing was applied to better visualize the result (Fig. 3). Because averaging was done *after* the FFT analysis, no information on fluctuations was lost. Bismuth and tungsten were selected as the extreme examples for showing relatively weak and strong fluctuations, respectively.

The same analysis method was also used on 16 measurements of the zero line (i.e., data collected without arc burning), and exactly the same procedure was applied. The resulting base line curves are inserted in Fig. 3.

4. Results

The initial experiments involved measurements at 150 µs after arc ignition, i.e. at a time when the plasma approaches a steady-state regime (that does not mean that cathode processes are stationary). The eight cathode materials were selected such as to cover a wide range of cohesive energies, enabling a study of the material dependence of the voltage noise. The result of data analysis is shown in Fig. 4. For clarity, only the smoothed curves are shown. Each of the materials show spectral power curves that are approximately linear in log-log presentation. Their slope is about the same, namely $1/f^2$, until the curves reaches a frequency of about 100 MHz. Here, the low cohesive energy materials reach the spectral power curve of the zero line, indicating that no information on arc noise is anymore available because the circuit noise is equal to or larger than the arc voltage noise. One can evaluate and compare the spectral power for the various materials by looking at appropriate lower frequencies. It is found that the spectral power of voltage noise power increases with increasing cohesive energy of the cathode material, confirming the result obtained earlier with lower bandwidth [10].

So far, analysis was done for data sampled at 150 µs after arc initiation. Measurements at different times could give insight in the development of voltage noise and the underlying cathode processes. Therefore, data were collected at earlier times into the pulse and analyzed with the same procedure as described above. The result is shown in Fig. 5 for W, Ni, and Bi cathodes. While the general character and spectral power distribution is maintained for each cathode, one can clearly discern a vertical shift toward smaller spectral power as time elapses. However, as will be further discussed, time is not the only variable: the arc current has not yet reached its nominal, steady-state value, and therefore data sampled early into the pulse are data obtained at low current.

To further quantify time and material dependences of the noise power, the frequencies of 30, 60, and 100 MHz were arbitrarily picked, and the FFT power levels determined. The choice of several frequencies was to cover a larger frequency range in the investigation. Conclusions that are based on observations at several frequencies are more reliable. The results for different cathode materials are presented in Fig. 6.

As was previously observed for a fixed time after arc ignition, materials of higher cohesive energy material showed greater noise of the burning voltage, as quantified by its spectral power distribution. Now, this statement was found to be generally true over the entire frequency range studied and independent of the time after arc ignition.

From Fig. 6 one can further see that all the materials studied showed a decrease in voltage noise within the first 30-50 μs of the arc pulse. Later in the arc pulse, the low cohesive energy materials showed a further reduction in arc noise, whereas high cohesive energy materials tended to have constant or even increasing noise.

In order to better interpret these data, additional information on arc parameters is needed. Fig. 7 shows the evolution of the burning voltage (attenuator data but without FFT), and Fig. 8 shows the corresponding arc current for the 8 different materials. Materials of greater voltage represent a higher impedance to the circuit, and therefore the current is correspondingly smaller. However, because the arc impedance is small compared to the 1 Ω series resistor, the differences in arc current remained small (within a range of 12 A).

5. Discussion

The main motivation for this study was to gain better knowledge on cathode processes by looking for information that can be derived from the noise behavior of vacuum arc quantities. Because the burning voltage is a fast responding quantity directly associated with plasma production and arc impedance, it was selected for this and earlier studies [10].

Compared to the earlier measurements, an attempt was made to increase the spectral resolution by utilizing circuits of greater analog bandwidth and high digital sampling rate. One approach was to not only use a high-frequency voltage divider probe but an attenuator, as commonly used in radio-frequency technology. The two systems, voltage divider probe and attenuator, gave approximately the same result, as indicated by Figs. 2 and 3. No clear advantage or disadvantage could be identified for using one or the other. However, the main part of the presented results were attenuator data, motivated by the nominally higher spectral resolution.

A main point of this investigation was to improve the data handling by focusing on the fluctuating component of the voltage, thereby identifying characteristic features in the noise power spectrum, should such features be present. Several conclusions can be derived from the measurements.

First, the voltage noise scales with cohesive energy of the cathode material, confirming earlier measurements of less resolution. This finding is another manifestation of the cohesive energy rule [10, 11]. For materials of high cohesive energy, it is energetically more difficult to make the phase transitions to form plasma. This leads to the suggestion that these materials have fewer simultaneously active spots or spot fragments, which is related to the relative "difficulty" to ignite new emission sites. Fewer active emission sites result in greater voltage noise.

Second, for the physically relevant frequency interval, the noise power spectra are linear in log-log presentation with a slope of about $1/f^2$, confirming the fractal character of cathode processes and the relation to Brownian motion [4]. The relevant frequency interval is limited at the low frequency end by insufficient data, dictated by the limited number of data stored in the oscilloscope's memory. At high frequency, measurements are limited by the noise of the measuring circuit itself, that is, when the power spectrum of voltage noise approaches the power spectrum of the voltage taken without arc (zero line), as can be seen in Figs. 3-5.

Third, the general character of the voltage noise and its material-dependent amplitude do not strongly depend on the time after arc initiation. This is an *a-posteriori* justification for having arbitrarily selected a fixed time for many of the data acquisitions, namely 150 μs after arc ignition. It is an indication that our study of pulsed arcs is applicable to long-pulse arcs and even DC arcs. This is not surprising because it is known that DC arcs are based on non-stationary, fast cathode processes, regardless of arc duration.

Fourth, looking closer to the time-dependence observed at the beginning of the arc pulse, one realizes that the initial decrease in voltage noise (Fig. 6) coincides with the rise in current (Fig. 8). For the first 50 μs, as the current is rising, the number of plasma-producing emission sites (spot fragments) is increasing. If the cathode surface state is not greatly altered, the number of emission sites can be assumed to be proportional to the arc current (this applies to noble metals like gold but the situation may be more complicated for easily oxidized metals). Analysis of the results for Au (Fig. 6) shows that the arc current increased by 22% when going from 20 to 30 μs into the pulse, whereas the spectral noise power decreased by 34, 43, and 32% at 30, 60, and 100 MHz, respectively. The difference between current changes and noise changes are even larger when going from 30 to 50 μs. One can therefore conclude that the noise depends stronger on arc current than one would expect by simple superposition of independent noise generators. A preliminary interpretation is that the ignition of new emission sites is facilitated by the existence of plasma generated from already active sites, and hence the noise-generating ignition events cannot be considered independent. Furthermore, the character of an emission site (current per fragment, duration of emission, etc.) may dependent on its environment such plasma density distribution given by the number of neighboring emission sites and their capability to produce plasma. The latter is greatly affected by the cohesive energy of the cathode material, which relates back to the first point in this discussion.

Fifth, there seem to be competing cathode processes as the arc burns for longer times. Depending on the cohesive energy of the cathode material, voltage noise tends to decrease for materials of low cohesive energy, and to increase for materials of high cohesive energy. No certain interpretation can be given at this time. However, we may suggest the following hypothesis. As the arc discharge burns, the global temperature of the cathode and especially the surface temperature increase. Materials of low cohesive energy tend to have low melting and boiling point, and therefore the surface conditions are more favorable for phase transitions to liquid, gas, and ultimately plasma to occur. In other words, as the cathode surface is heated, the formation of emission sites on materials of low cohesive energy is promoted, which would lead to less noise in the arc voltage.

The situation is different for materials of high cohesive energy because the increase in cathode temperature is relatively small compared to their melting and boiling temperature. However, for those materials, another effect can be of greater importance, namely the cleaning of the surface from water, oxides, and other contaminants. It is known that arc spots transition from type 1 (contaminated cathodes) to type 2 (clean metal cathodes) [14, 24] as the cathode is cleaned by ion bombardment from the plasma. The current per spot of type 1 is generally about 1 A or less while the current for type 2 is typically 10 A or more. So, as the arc burns and the cathode area surrounding the currently active spots is bombardment by ions, the arc creates conditions for type 2 spots, which are less numerous and thus the noise is increasing. This is consistent with previous observations of influence on surface contamination on the amplitude of arc voltage fluctuations [25].

Finally, we need to address the peaks that are observed at high frequencies for materials of high cohesive energy. Unfortunately, we are still not in a position to determine conclusively whether these peaks are associated with elementary spot processes, such as individual micro-explosions or "ectons" [5, 26], or just an artifact caused by resonances in the measuring circuit. We can say that the absence of such peaks in materials of low cohesive energy indicates that there are many emission sites and that the time between ignition events is shorter than the inverse upper frequency of our observations (i.e., shorter than 10 ns for Bi, see Fig. 3). For materials of high cohesive energy, such as W and Ta, it is possible that the peaks arc caused by elementary processes with time constants of a few nanoseconds. However, the two different measuring circuits (divider versus attenuator) indicate different peak positions (Fig. 3). Therefore we suspect that we deal —at least in part— with resonances in the measuring circuit. This interpretation is also supported by looking at the small peaks found in the zero line (Fig. 4). One can clearly see that there are harmonics of the lowest frequency seen at 2.6 x 10^7 Hz. Further research is planned to find evidence of elementary processes, should such evidence exist in the noise.

6. Summary and conclusions

Summarizing this study, we have investigated the high frequency fluctuations of the burning voltage to extract information on fast cathode processes. FFT analysis presented evidence for a spectral power of the arc noise that drops as $1/f^2$ (brown noise), and scales with cohesive energy of the cathode material, consistent with previous measurements. This material dependence does not depend on time after arc initiation. However, all materials studied showed a decrease in voltage noise within the first 30-50 μs, which suggests that the noise is due to an increase in arc current and hence the number of cathode spot fragments. After 50 μs, the noise continued to decrease for low and cohesive energy materials, whereas it increased for materials of high cohesive energy. A possible explanation is given through effects of surface contamination as well as promotion of emission site formation when the cohesive energy is low. From the above presented results we can also conclude that the time between ignition events (formation of spot fragments) is less than 10 ns.

Acknowledgements

The authors thank Derun Li and Robert MacGill, both Berkeley, for discussions and technical support. This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Figure Captions

Fig. 1 Burning voltage (measured with voltage divider) and arc current (measured with Pearson coil) during the 1 ms arc pulse (Ni cathode). Most data of this paper were collected at 150 μs into the pulse, as indicated in graph.

Fig. 2 Comparison between raw data as measured simultaneously with (a) attenuator, and (b) divider, 150 us into the pulse, for Bi and W cathodes.

Fig. 3 Power spectrum of voltage fluctuations, measured by (a) attenuator and (b) divider. Each curve was obtained by averaging of 16 individually determined FFT power spectra. The average FFTs are in grey, and the 10-pointed smoothed curves are in black.

Fig. 4 Spectral power obtained by FFT of the fluctuating component of the arc voltage, as a function of frequency, for eight different cathode materials and no-arc data (acquisition with attenuator, curves smoothed using 10-point average).

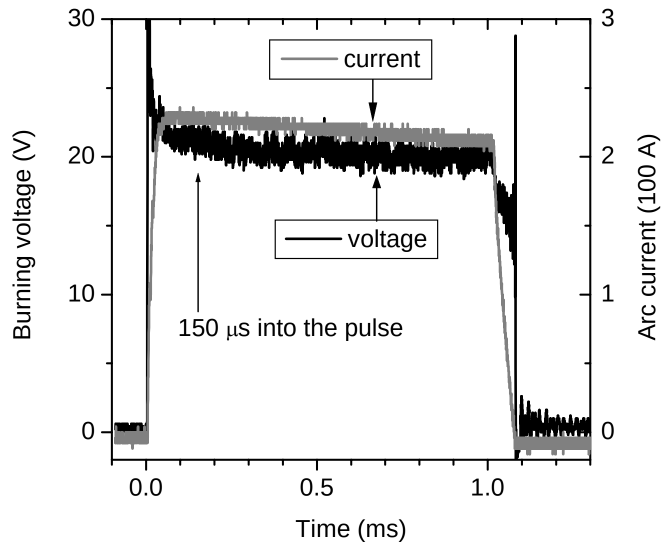
Fig. 5 Example of spectral power of the arc burning voltage for W, Ni, and Bi cathodes, with the time after arc initiation as a parameter (attenuator data).

Fig. 6 Time dependence of spectral power at (a) 30 MHz, (b) 60 MHz, and (c) 100 MHz, analyzed for eight cathode materials (attenuator data).

Fig. 7 Burning voltage at different time into the pulse (attenuator data).

Fig. 8 Arc current at different time into the pulse.

Figures



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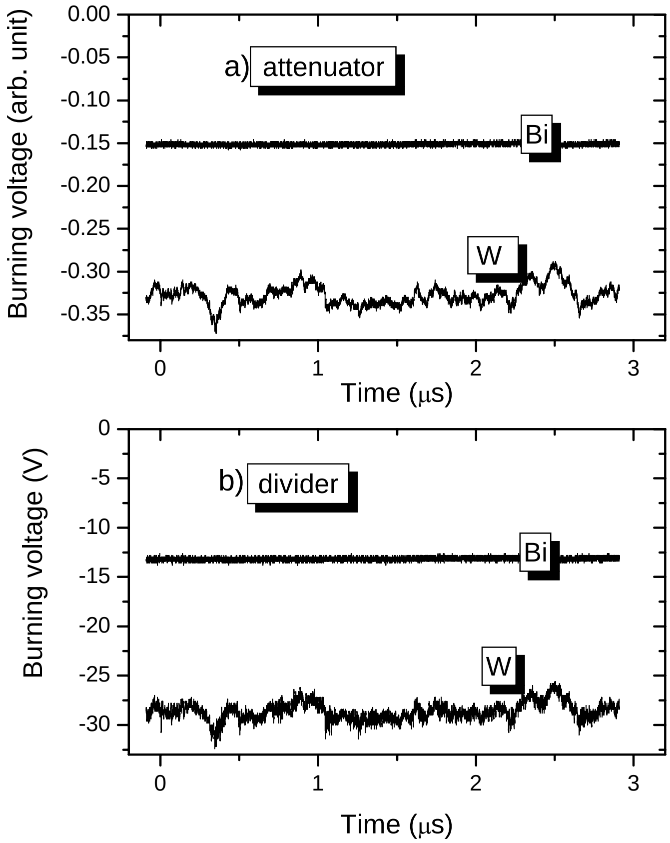

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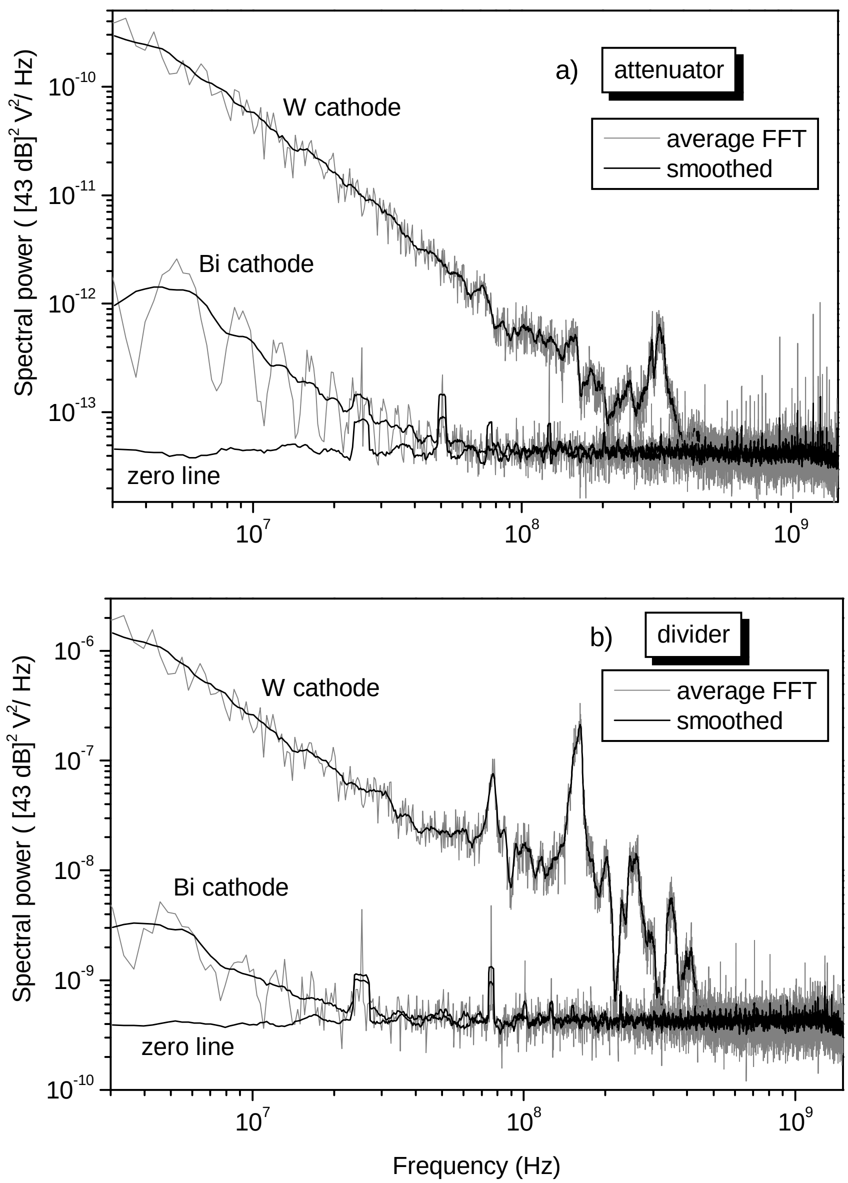

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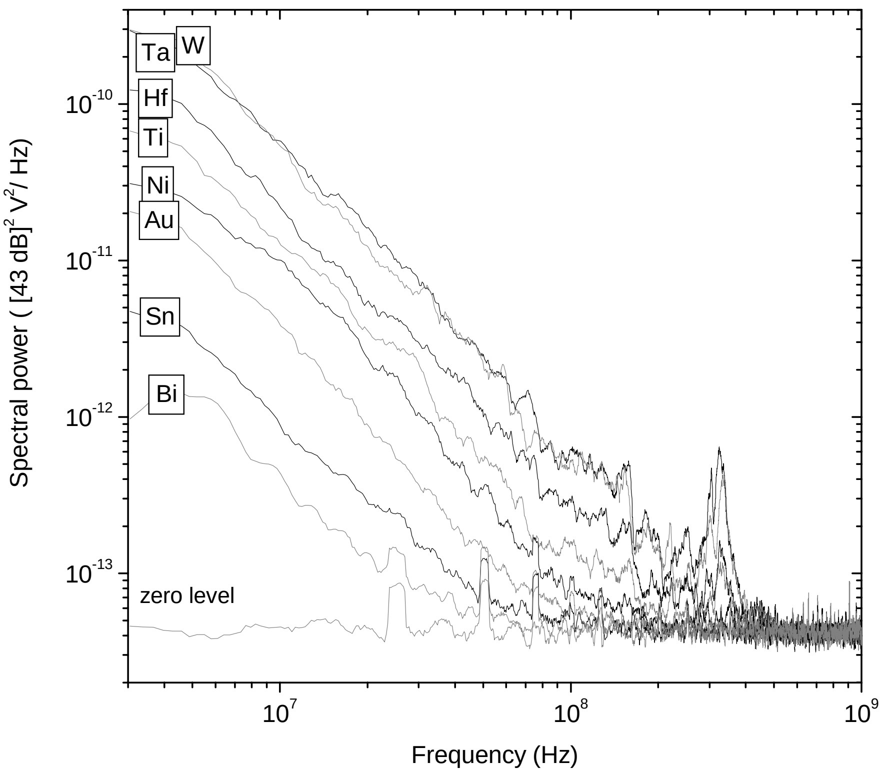

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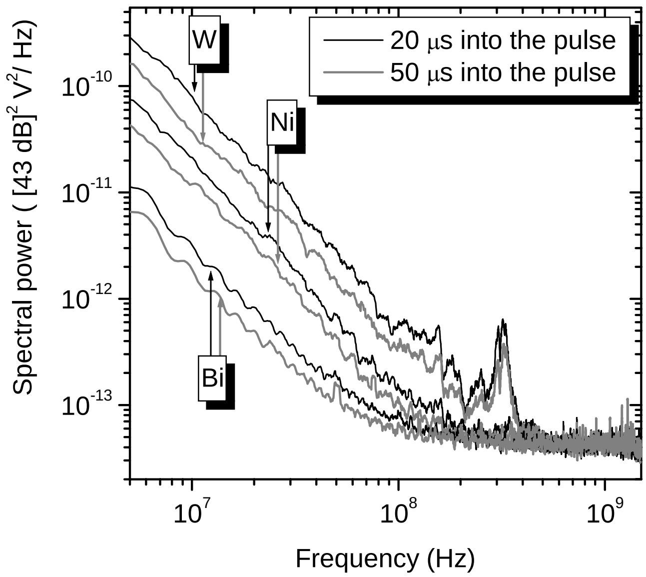
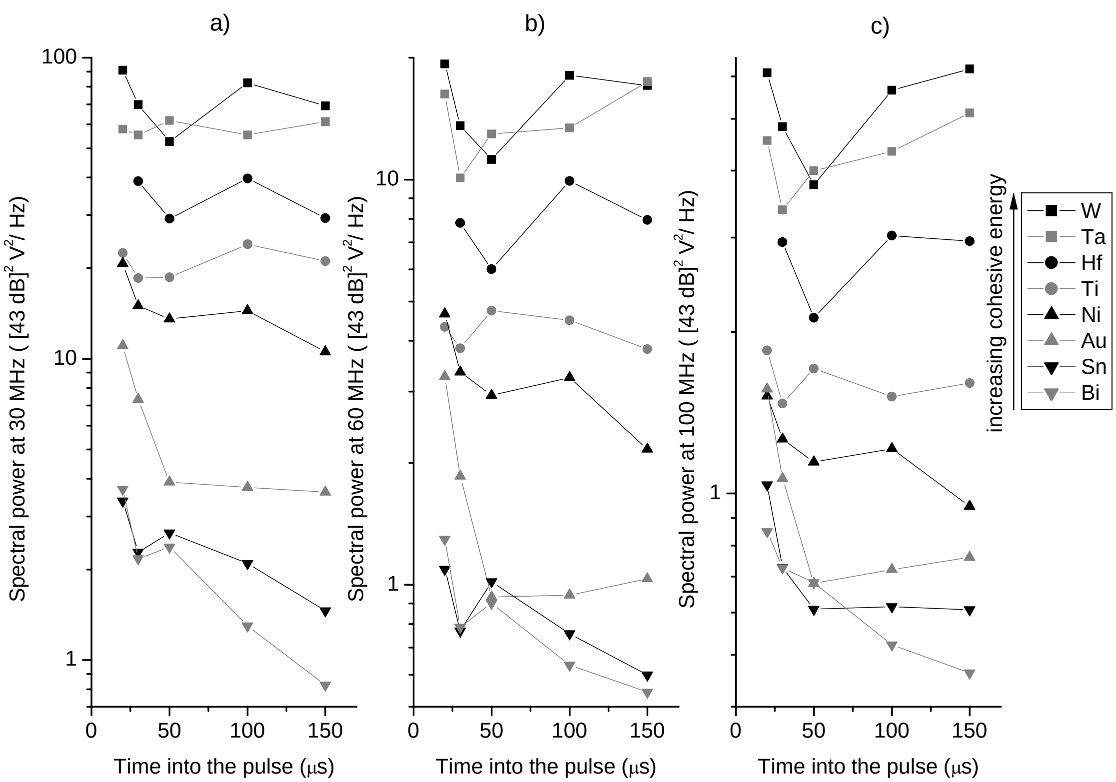


Fig. 5 Example of spectral power of the arc burning voltage for W, Ni, and Bi cathodes, with the time after arc initiation as a parameter (attenuator data).



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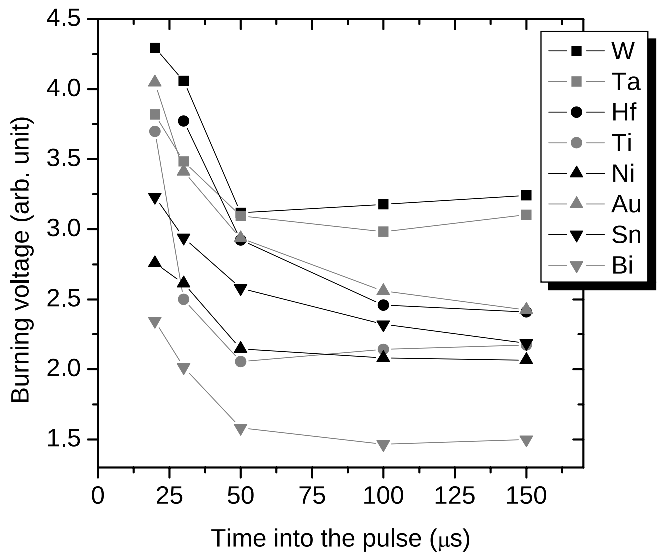

Fig. 7 Burning voltage at different time into the pulse (attenuator data).

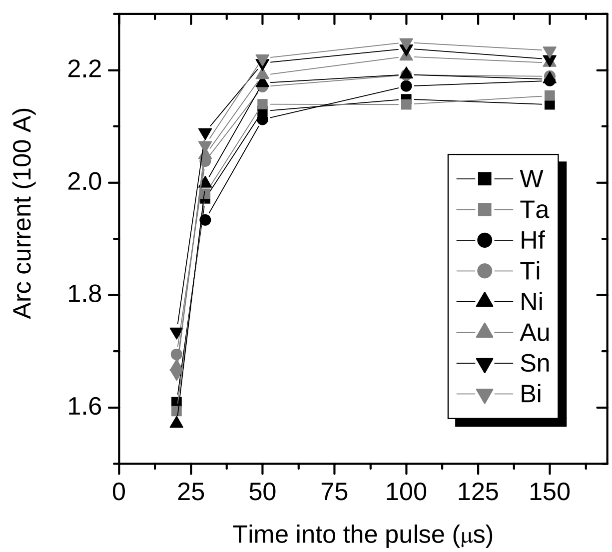

Fig. 8 Arc current at different time into the pulse.