J. Phys. D: Appl. Phys. **31** (1998) 584–587. Printed in the UK PII: S0022-3727(98)87183-0

‘Triggerless’ triggering of vacuum arcs

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Received 26 August 1997, in final form 12 December 1997

Abstract. Vacuum arcs can be initiated without external means of power enhancement at the cathode surface (by using a high-voltage trigger, laser triggering, and so on). Arc initiation by simply applying the relatively low voltage of the arc power supply is possible if the cathode–anode-separating insulator is coated with a conducting layer and the current at the layer–cathode interface is concentrated at one or a few contact points. The local power density at these contact points can exceed 10^{16} W m^{-3} which is sufficient for plasma production and thus arc initiation. This ‘triggerless’ principle has been tested successfully with a large number of cathode materials. One extended test was performed with titanium and more than 10^6 pulsed vacuum arc initiations have been obtained.

1. Introduction

A vacuum arc (or ‘cathodic arc’) is a low-voltage, high-current discharge between metal electrodes in vacuum, characterized by an interelectrode metal plasma which is generated at cathode spots. The term ‘metal’ refers here to all solid conductive materials, including alloys, carbon and doped semiconductors. Vacuum arcs are widely used in high-voltage, high-current switches as well as for thin film deposition and ion implantation. Basic properties and applications of vacuum arcs have been covered in a recently published book [1].

Special means are usually required to initiate a vacuum arc, such as high-voltage breakdown, mechanical motion and trigger plasma injection. An overview is given in table 1. All triggering mechanisms have in common that they produce an initial plasma at one of the electrodes. The arc is established when the initial plasma bridges between the cathode and the anode thus allowing a high current to flow at a relatively low voltage (often as low as 20 V). The arc is maintained when the supply circuit is capable of delivering a current greater than the ‘chopping’ current, a material-dependent critical minimum current which is associated with the minimum metal plasma production.

For completeness, low-voltage or ‘triggerless’ vacuum arc initiation is already included in table 1; this paper deals with this simple but little known approach. In the next section we describe its general principle, followed by the results of a number of experiments performed.

2. The concept of low-voltage or ‘triggerless’ vacuum arc initiation

The advantages and disadvantages of trigger schemes are listed in table 1; the most frequently used approach is high-voltage surface flashover, presumably because it is relatively easy to achieve. The number of maintenance-free triggering events, of order 10^5, is sufficient for most applications. It has been empirically found that the reliability of surface flashover is improved if the surface of the insulator is slightly conductive; this is naturally the case after some arc operation since metal plasma and macroparticles (droplets) are deposited onto the insulator surface. The resistance of a virgin insulator can be too high for breakdown and it is known that contaminating the insulator with a graphite pencil mark overcomes this problem. Erosion of material from and deposition onto the insulator surface is a delicate balance. After prolonged operation, typically some 10^5 pulses, the trigger tends to fail due to either excessive deposition of cathode material on the insulator surface or destruction of the insulator by erosion.

It is interesting to consider more closely the effect of graphite contamination. The interface between the cathode and the insulator becomes the location with the highest resistance and therefore the highest electric field strength. For instance, if the applied voltage is 10 kV, the field strength can reach the critical $\simeq 10^8$ V m^{-1} (for the onset of electron field emission) if there is a gap between the insulator and the cathode which is smaller than 1 mm (assuming a field enhancement factor of $\beta \approx 10$). The same field strength can be obtained with a much smaller voltage (say 500 V) when the gap is smaller (5–50 μm).

0022-3727/98/050584+04$19.50 © 1998 IOP Publishing Ltd

Table 1. An overview of vacuum arc triggering (note that the references are suggestions for further reading in the literature, but completeness is by no means claimed).

Triggering mechanisms	Advantages	Disadvantages	References
High-voltage vacuum breakdown	No contamination of metal plasma	Requires a high voltage; breakdown voltage changes with electrode conditioning	[2–4]
Fuse wire explosion	No contamination of metal plasma	Not usable for repetitive mode operation	[5]
Contact separation	Reliable, simple, repeatable	Low repetition rate; contacts may weld	[6]
Mechanical triggering	Reliable, relatively simple (depending on actuator mechanisms)	Low repetition rate; contacts may weld and wear; limited number of triggering events (less than 10^4); large jitter	[7]
High-voltage surface discharge	High repetition rates, reliable typically up to 10^5 pulses, low jitter	Needs high-voltage pulser; fails when approaching 10^6 pulses; plasma contamination by erosion of insulator	[8–14]
Plasma injection triggering	Moderate to high repetition rates, small jitter	Needs high voltage pulser; works only with sufficiently strong triggering discharge	[11, 15, 16]
Gas injection triggering	No trigger supply	Needs sufficiently high pressure in the discharge vicinity; metal plasma contamination by gas species; very large jitter	[11]
$\boldsymbol{E} \times \boldsymbol{B}$ gas discharge triggering	Reliable for more than 10^6 pulses, small jitter, gas load negligible for most applications	Requires special electrodes, magnetic coil arrangement and additional power supplies for gas discharge and magnetic field	[17]
Laser plasma triggering	Reliable, trigger location controllable, very small jitter	Expensive; needs sustainable optical access to cathode (problems of window coating); minimum power density 10^{11} W m^{-2}	[18–21]
Low-voltage or ‘triggerless’ vacuum arc initiation	Reliable for 10^6 pulses, simple, high repetition rate possible, works without high voltage	Needs arc switch and moderate ‘booster’ voltage; may fail for low-melting-point and easily oxidizing cathode materials	This work

This can be easily done using the arrangement shown in figure 1. A conductive surface layer (such as graphite) is used on the surface of the insulator separating the cathode and the anode. This layer brings the anode’s potential very close to that of the cathode. No trigger electrode is present. In the course of our experiments we discovered that this conductive-layer principle works more reliably when the layer actually connects the anode and the cathode. There is no gap in this case and the resistance between the anode and the cathode can have low values (such as a few ohms). The mechanism of plasma production is no longer based on field emission across a small gap but on explosive destruction of the layer–cathode interface caused by Joule heating (see the estimate below).

Note that figure 1 shows an example; other schemes have been tested in which the thyristor (SCR) was replaced by a high-current transistor switch. Also, the arc-feeding capacitor can be replaced by a pulse-forming network, or the arc could be fed by a high-current supply such as an arc welder.

As indicated in the inset of figure 1, the current flow between the thin insulator coating and the cathode takes place at only one or a few contact points. The current density at the ith contact point is correspondingly high,

$$j_i = I_i/A_i \tag{1}$$

where I_i is the initial current through the ith contact point having the initial cross section A_i. The initial cathode and anode resistance is given by

$$R_0 = R_{coat} + \left(\sum_i (1/R_i)\right)^{-1} \tag{2}$$

where R_{coat} is the resistance of the coating (without a cathode–trigger junction) and

$$R_i = \int [\rho(T(l'))/A_i(l')]\,\mathrm{d}l' \tag{3}$$

is the resistance of the ith contact of the cathode–trigger interface, ρ is the temperature-dependent specific resistivity of the contact material, $A_i(l')$ is the cross section of the ith contact and $\mathrm{d}l'$ is an infinitesimal section of the contact length. Joule heating of the infinitesimal contact section is given by

$$\mathrm{d}P_i = I_i\,\mathrm{d}U_i = I_i^2\,\mathrm{d}R_i = I_i^2 \frac{\rho}{A_i}\,\mathrm{d}l. \tag{4}$$

In the simplest case, only one contact point is present. Let us assume that its shape is cylindrical with length l and cross section $A_1 = \pi r_1^2$. For $l \approx 10$ μm and $r_1 \approx 5$ μm we obtain $A_1 = 78$ μm^2 and $R_1 = 6.9$ mΩ for tungsten at room

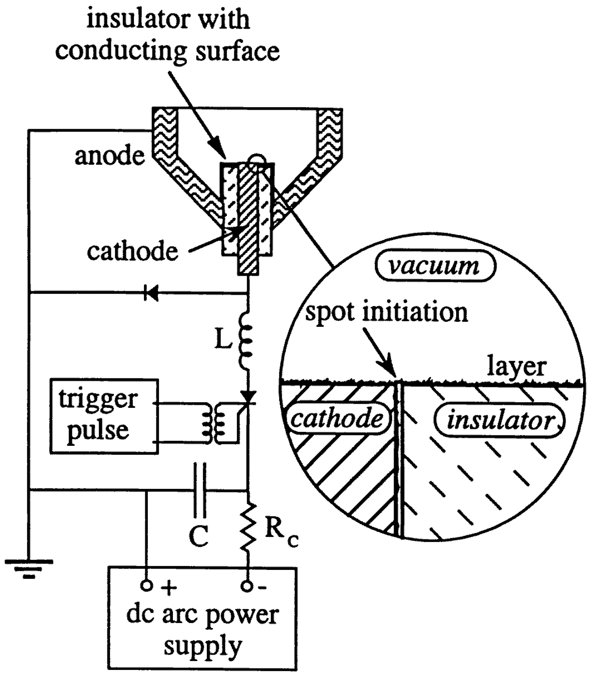

Figure 1. One possible scheme for a 'triggerless' vacuum arc; the inset shows an enlarged view of the cathode–insulator–vacuum triple junction; R_c is the charging resistance and L is the current-limiting inductance.

temperature (for the temperature-dependent resistivities of selected metals see [22]). Let us assume that the initial current is about 10 A (limited by the circuit or R_{coat}). The initial current density would be $j_1 \approx 1.3 \times 10^{11}$ A m^{-2} and the Joule heating power 0.7 W; this power is concentrated in a small volume of only 780 μm^3 and the volume power density is about 9×10^{14} W m^{-3}. Joule heating increases the temperature of the contact material and its specific resistivity. For most metals, the increase in resistivity is as great as one order of magnitude if the temperature rises by 1000 K [22] and is even greater at higher temperatures when taking phase transitions into account (solid/liquid and metal/dielectric). Thus, from equation (4), the power density increases also by an order of magnitude or more, reaching 10^{16} W m^{-3}, a value known to cause explosive formation of plasma. We can conclude that it should be possible to form a metal plasma with a relatively low voltage (for instance, 500 V) based on the concentration of power in a microscopic volume. Unlike other vacuum arc discharge schemes, switching of a separate trigger pulse is avoided but switching of the arc is required.

3. Tests of 'triggerless' vacuum arc initiation

Various experiments have been carried out to test the low-voltage or 'triggerless' principle. For most of the experiments, a high-current power supply was combined with a second supply which boosts the voltage to ensure reliable triggering. This is shown in figure 2 for a pulsed system. In another system, a 200 V, 150 A DC power supply was 'upgraded' by the addition of a 600 V ignition voltage. In yet another set of experiments, we use a thyristor-switched, pulsed high-current arc ($I_{max} = 5$ kA), similar to that described in [23].

It has been found in all experiments that arc initiation is possible when the resistance between the cathode and the anode (with a conducting layer on the insulator) is in the range 1 Ω to 10 kΩ. This extremely wide range makes it possible to tolerate large changes in the surface coating and its resistance. Tests of the principle have been performed with the following cathode materials: Li, C, Mg, Al, Ti, V, Cr, Fe, Co, Ni, Cu, Zn, Y, Zr, Nb, Mo, Pd, Ag, Cd, Nd, Ba, Hf, Ta, W, Pt, Au, Pb, brass and stainless steel. Figures 1 and 2 show schematically our preferred insulator

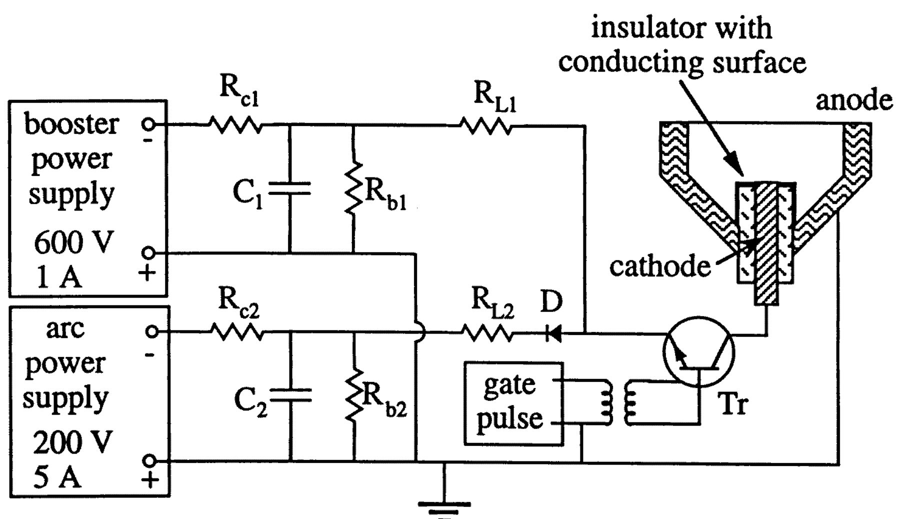

Figure 2. A simplified schematic diagram of the arc supply with a 'booster' voltage used for most tests of our 'triggerless' pulsed vacuum arcs; R_b is the bleed resistance for safety, R_{L1} = 2 Ω and R_{L2} = 0.5 Ω are current-limiting resistors, C_1 = 20 μF, C_2 = 10 mF, D is a high-voltage, high-current diode preventing backfeeding of 600 V into the 200 V supply and Tr is a 200 A/1000 V transistor switch.

geometry which has the advantage that a large portion of the coated insulator is not in the line of sight of the cathode spots and that erosion of the insulator coating as well as deposition of cathode material is minimized.

In most experiments, the conducting layer was made from graphite. Routine tests using Rutherford backscattering (RBS) with 1.8 MeV H^+ and 2.0 MeV He^+ have shown that the carbon contamination of thin films deposited on test samples is as small as the RBS detection limit. However, carbon contamination may be a concern for some applications; therefore, we use the cathode material itself for the conductive layer in selected experiments with Ti, Al and Cu. In these experiments it was found that it is possible to operate with an anode–cathode resistance as low as 1–5 Ω.

The firing rate, defined as the ratio of the number of arcs actually initiated to the number of attempts, was 100% for most cathode materials tested as long as the anode–cathode resistance remained small (less than 1 kΩ). Low-melting-point materials (such as Pb) have a large droplet erosion rate and the droplets tend to produce a conducting film on the insulator, thus shorting the anode and the cathode. In our work, triggering stopped after about 500 pulses when the resistance between the anode and the cathode became less than 1 Ω. At the other extreme, triggering failed if the conducting layer has been eroded, leading to a very high resistance ($>$100 kΩ). This was a particular problem with easily oxidizing materials such as barium, for which the erosion was of a chemical nature; that is, the barium at the insulator/barium-cathode interface oxidized even when the residual gas pressure was as low as 10^{-6} Torr. With the exception of very-low-melting-point materials (Pb) and easily oxidized materials (Li, Mg, Ba), we have always obtained a number of arc pulses sufficient for applications of pulsed plasma deposition and metal plasma immersion ion implantation [24]. This number was usually in the 10^5 range. We did not carry out a systematic study of the maximum numbers of pulses possible because the focus of our work was to obtain thin films and surfaces with new properties. However, one test with a titanium cathode was successfully extended to 10^6 arc pulses, demonstrating the capabilities of the 'triggerless' arc initiation method. The arc parameters in this test were 200 A, 5 ms and 2 pulses per second, with a 'booster voltage' of 600 V. 'Triggerless' arc triggering has become the standard method of arc initiation in our pulsed vacuum arc plasma sources.

Acknowledgments

We acknowledge fruitful discussions with E Oks and G Yushkov, Tomsk. We are indebted to T McVeigh and M Rickard for electronics support. This work was supported by the USA Department of Energy, Division of Advanced Energy Projects, under contract DE-AC03-76SF00098.

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