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Current and voltage distribution in the diffuse vacuum arc

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Introduction

Current interruption in vacuum arcs is strongly influenced by the arcing mode during the high current phase. Two modes are here of particular importance: the anode spot mode and the diffuse arc mode. It is thought that the anode spot is a product of phenomena that set in during the diffuse arc [1]. Therefore this last type of arc was subject of several experiments designed to obtain information about arc parameters in order to reveal some of these phenomena. Here the current distribution and the positive voltage-current relationship which is a feature of the diffuse vacuum arc will be discussed. It will be shown that the interaction between neutral and charged particles influences the diffuse arc decisively.

Experimental results

First some of the results obtained from an experimental study will be shown. In figure 1 the charged particle kinetic pressure build-up is shown for five arc parameters. The data are obtained by a combined method using laser interferometry, spectroscopy and Fabry-Perot interferometry. In figure 2 the current flow lines are shown for the same arcing parameters. The current flow is determined by diamagnetic loop measurements with the aid of the model described below. Comparison of figure 1 and 2 shows that the current constriction is correlated to the charged particle pressure drop: both are most pronounced at the lower applied axial magnetic field strengths. In figure 3 the neutral density and the electron density are shown as a function of radial position for one arc parameter. Contrary to the electron density the neutral density increases towards the arc periphery.

The most important conclusions that follow from these measurements are:

- the mean free-paths for momentum transfer collisions are less than the cha-

racteristic dimensions of the plasma ion-neutral friction has to be taken into account (due to the high neutral density and due to the large collisional cross-section)

- ion velocity is limited to subsonic velocities (direct experimental evidence exists for the azimuthal ion velocity and indirect evidence for the radial and axial ion velocity)

Arc model of the diffuse vacuum arc

Based on the experimental results the arc can be modelled according magnetohydrodynamic theory. This paper will focus on the momentum balances only. The following additional simplifications are used, which are supported by the experiments:

- the plasma is stationary
- the plasma is rotational symmetric
- the plasma is singly ionized
- no radial magnetic fields are present (This is correct only in first order. Radial magnetic fields can be substantial (25%) at the arc periphery)
- temperature gradients are small compared to pressure gradients
- the current is mainly carried by the electrons: $|w^i| \ll |w^e|$

The momentum balance equation then becomes for the ions:

$$\nabla p^i = enE - en\eta j - R_{io} \quad (1)$$

and for the electrons:

$$\nabla p^e = -enE + en\eta j + j \times B \quad (2)$$

The electron momentum balance resembles Ohms's law as derived by Boxmann [2, 3]. Here the kinetic pressure is taken into account but the Lorentz force caused by ion movement

Figure 1 Pressure distribution in the high current vacuum arc, 10 kA, for various axial magnetic field strengths. a = anode; c = cathode

1. at 8 mT peak pressure 9000 Pa
2. at 15 mT peak pressure 7900 Pa
3. at 25 mT peak pressure 7100 Pa
4. at 50 mT peak pressure 6100 Pa
5. at 100 mT peak pressure 4800 Pa

$\underline{w}^i \times \underline{B}$ is neglected due to the experimental fact $\underline{w}^i \ll \underline{w}^e$.

This last difference though is essential. In [2] the movement of the ions is dictated by the properties of the cathode spot only which are supposed to remain unaltered in the current range of 100 ampere to tens of kiloampere.

Figure 2 Current flow lines in the high current vacuum arc, 10 kA, for various axial magnetic field strengths. The numbers indicate the amount of current (kA) flowing inside the surface represented by the curve.

The ion movement interacts with the azimuthal magnetic field and hence influences the current distribution. Yet it is shown that the high ion velocities (60 eV) are unlikely [1].

In the model described in this paper the interaction between the ions and the electrons, the main carriers of the current, is through resistivity only (ηj_z in the electron-momentum balance).

For the moment we concentrate on the ion momentum balance as here the ion-neutral as well as the electron-ion interaction becomes visible.

The use of Maxwell's law for a stationary state $\nabla \times \underline{E} = 0$ and the use of the expression for

Figure 3 Radial density profile of the electrons and neutrals (copper) at 10 kA, 50 mT.

the electric field given by the ion momentum balance yield

$$\nabla \times \underline{E} = \nabla \times \left(\eta \underline{j} + \frac{1}{en} \nabla p^i + \frac{1}{en} \underline{R}_{io} \right) = 0 \quad (3)$$

which reduces to

$$\nabla \times \eta \underline{j} + \nabla \times \frac{1}{en} \underline{R}_{io} = 0 \quad (4)$$

since temperature gradients are neglected. We assume that the ion-neutral friction term can be described by a scalar field: $\underline{R}_{io} = \nabla \varphi$. In the special case of not moving neutrals the potential φ is identical to the neutral pressure p^0 . Hence equation can be further simplified to

$$\frac{\eta}{\mu_0} \nabla^2 \underline{B} = \frac{-1}{en^2} (\nabla n \times \nabla p^0) \quad (5)$$

Making use of $\mu_0 \underline{j} = \nabla \times \underline{B}$

This equation represents a source equation for magnetic fields provided the electron (or more specifically the ion) density gradient is not parallel to the neutral pressure gradient. In other words a pressure source generates magnetic fields.

In appendix A the nature of this source is demonstrated. For a rotationally symmetric vacuum arc plasma magnetic field generation is only in azimuthal direction. Apparently, gradients in the pressure affect through the azimuthal magnetic field the radial and axial current densities, and with these the current distribution in the arc.

In order to verify equation 5 for the plasma in the diffuse part of the high current vacuum arc, equation 5 is integrated over a vertical cross-section of the arc bounded by the anode, the cathode side of the diffuse plasma and arc axis as indicated in figure 4. The normal to this surface points in the azimuthal direction. The surface integral of equation 5 reads:

$$\iint_S (\nabla \times \underline{j}) \cdot d\underline{A} = \iint_S \frac{1}{en^2} (\nabla n \times \nabla p^0) \cdot d\underline{A} \quad (6)$$

(in which $\nabla \times \underline{B}$ is replaced by $\mu_0 \underline{j}$). Applying Stokes' theorem the left hand side of equation 6 can be written as a line integral along the boundaries of the surface. At the anode surface, an equipotential surface, the radial current density vanishes and hence the line integral. At the cathode side (beyond the cathode spots) the axial current density is homogenous, $\frac{\partial}{\partial z} j_z = 0$ and here also the radial current density vanishes. At the arc periphery there is no current flow, so equation 6 simplifies to:

$$\int_{R=0}^{\text{anode}} \eta j_z dz = \iint_S \frac{1}{en^2} (\nabla n \times \nabla p^0) \cdot d\underline{A} \quad (7)$$

cathode side plasma

Figure 4 Schematic picture of the vacuum arc showing the integration surface S.

Diamagnetic loop measurements [1] yield information about the axial current density and hence the left hand side of equation 7 can be evaluated. Spectroscopic and interferometric measurements [6] yield information about the neutral and electron density. The neutral temperature was not determined experimentally. It is shown in [1] that there exists in the vacuum arc an equilibrium between the kinetic pressures of the various particles, so the neutral pressure is closely related to the charged particle pressure: $(p^0 + p^i + p^e)(r) = \text{constant}$.

Hence the right hand side of equation 7 can be evaluated independently of the left hand side. In figure 5 the experimentally obtained values are shown as well as the theoretical prediction. This comparison is made for a 10 kA vacuum arc at axial magnetic field strengths between 8 and 100 mT. According to equation 7 the right hand side should be equal to the left hand side, which results in a straight line in figure 5.

The left hand side of equation 7 is also equal to the Ohmic voltage drop from the cathode surface layer to the anode, corrected for the anode voltage drop. For comparison, therefore, in table 1 the data of figure 5 are given as well as the measured arc voltage minus the cathode spot voltage drop (20 V). It is clear that at the arc axis the Ohmic voltage drop makes up the larger part of the arc voltage.

The close agreement between theory and experiment over a wide range definitely shows that the pressure source is responsible for the current constriction in high current vacuum arcs.

Figure 5 Comparison of theory and experiment in equation 8. Note the dimension of the scale is in volts and represents also the ohmic voltage drop at the arc axis.

Table 1: Magnitude of the terms of equation (7) and of the arc column voltage drop

Applied axial magnetic field (mT)	left hand side (7) (V)	right hand side (7) (V)	arc column voltage drop (V)
8	33	36	27
15	19	20	19
25	12	9.5	10
50	5	6	7
100	3	2	10

Discussion

The here presented theoretical and experimental results give a total picture of the interactions in the diffuse vacuum arc. Three attempts to model the arc which did contain elements of the here observed phenomena need to be mentioned.

Mitchell [4] stated that the increased voltage drop in the diffuse vacuum arc was due to electron-neutral collisions. This explanation was not generally accepted because of the dominance of coulomb collisions even at low ionization degrees.

Boxmann [5] measured the neutral and charged particle densities in the diffuse vacuum arc and found the neutral density to be three times the electron density; he did not connect any consequence from this observation. Boxmann preferred a magnetic constriction process due to an expected imbalance between kinetic and magnetic pressure. Essential in his assumption is a directed mass flow from cathode to anode [2]. In low current vacuum arcs this mass flow is associated with high ion velocity. In the high current vacuum arc, however, Mitchell already suggested that the ions are decelerated although not by the electric field set up by electron-neutral collisions, but [1] by direct ion neutral collisions. The ion velocity is subsonic and hence the basic driving mechanism for magnetic constriction as proposed by Boxmann is not present.

In an earlier publication the author proposed an axial charged particle pressure drop as the main mechanism for current constriction. The good correlation found in that paper between measurement and theory results from a proportional increase of the neutral pressure with the charged particle pressure [6].

The actual phenomena in the diffuse vacuum arc give equal credit to the three discussed theories:

- 1 a current constriction exists well before anode spot formation
- 2 the neutral pressure plays a dominant role as well as
- 3 the charged particle density gradient

Conclusion

The current constriction and the positive voltage current relationship in a diffuse vacuum arc are shown theoretically and experimentally to be caused by a pressure source, to which the charged particles and neutral particles contribute.

The current constriction is substantial already in the diffuse arc mode. Hence the current constriction influences anode spot formation decisively.

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Appendix A:

Microscopic description of the pressure source

Microscopically the pressure source can be understood as follows (see figure A1). When a density gradient of ions ∇n exists, the ions will try by expansion to smooth out this gradient, leading to a flow of ions with velocity w^i in direction of lower density. Ion flow is hindered by ion-neutral friction. When a neutral pressure gradient ∇p^o (perpendicular to ∇n) is present the flow of ions will not be uniform, which leads to an electric field E . This field generates a current carried by the electrons, which in turn gives rise to a magnetic field B .

In the special case of a rotationally symmetric vacuum arc plasma magnetic field generation is in azimuthal direction.

figure A1