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EMISSION PERFORMANCE OF A SLIT TYPE CAESIUM FIELD ION SOURCE

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ABSTRACT - Results are reported of a study of the emission performance of a slit type liquid caesium field ion source which originally was developed by the European Space Research and Technology Centre as an ion thruster for electric space propulsion. The emission site distribution and the ion beam divergence are examined as a function of the wetting properties at the emitter slit edge.

1 - INTRODUCTION

When the surface of a liquid metal exposed to vacuum is subjected to a high electric field resulting from suitable voltages applied to an emitting electrode geometry, it is distorted into a cone or a series of cones which protrude more and more from the surface with increasing field strength. When the field reaches values of some $10^5$ Vm$^{-1}$, according to the polarity of the field generating voltage field emission or field ionization occurs from the apex region of these cones. Because the radius of curvature at the apex of such a cone is of the order of $10^{-7}$ m or less, applied voltages of some $10^5$ V are sufficient to obtain the required high electric fields with macroscopic interelectrode distances of about $10^{-5}$ m. Electron and ion beams can be created from liquid metal wetted needles or from capillaries into which the liquid metal is allowed to flow; electron emission as well as ion emission from caesium-wetted tungsten needles and stainless steel capillaries has been demonstrated successfully /1/.

One of the most advanced field ion sources is the slit emitter originally developed at the European Space Agency (ESA) as an ion thruster for electric space propulsion with liquid caesium as propellant /2/. In this case, the capillary is elongated to a slit of some $10^{-3}$ m length with nearly rectangular cross section, allowing therefore the occurrence of a series of equally spaced emitting cones. This type of ion source represents an ultimate development in precision mechanics, demonstrated by actual numerical values of about $10^{-4}$ m for both the emitter slit width $w$ and the round-off radius $r_e$ of the emitter slit edge (Fig. 2).

Besides the original concept as an ion thruster, the slit emitter generally may be employed as a high current liquid metal field ion source for terrestrial applications in science and technology.

2 - EXPERIMENT

The slit emitter in principle consists of two symmetrical highly polished metal plates of the shape depicted in Fig. 1. In one or both of the emitter halves there is milled a recess to be of use as a reservoir of the liquid metal supplied to the emitter module by a feeding capillary tube. On certain regions of one of the inside faces there is sputter deposited a layer of nickel with a thickness of about $10^{-4}$ m. When the two halves are tightly clamped together they are separated by the thickness of this layer, thus forming a narrow slit of length $l$, width $w$ and depth $d$ through which the liquid metal can flow and be transported to the edges of the slit by the action of capillary forces. The material used for the emitter fabrication is stainless steel and, more recently, Inconel.
The electrode configuration used to create the proper electric field at the emitter slit edge region is shown in Fig. 1. A plane accelerator electrode with an aperture of width 2b is mounted in a distance a of the emitter slit edge. Emitter and accelerator are kept at voltages +U_e and -U_{acc} respectively vs. ground potential in order to create the electric field necessary to produce and accelerate the ion beam. Actual data for the emitter-accelerator geometry are as follows: \( l = 1,5 \times 10^{-3} \text{m}; \ a = 6 \times 10^{-4} \text{m}; \ 2b = 4 \times 10^{-3} \text{m}; \ d = 1,10^{-3} \text{m}; \ w = 1,2 \times 10^{-4} \text{m} \) and \( 1,5 \times 10^{-4} \text{m} \), respectively. Typical voltages for \( U_e \) range between 0 and 6kV at a constant value \( U_{acc} = -5 \text{kV} \), with a maximum emission current \( I_e = 5 \text{mA} \) for \( U_e = 6 \text{kV} \).

The ultra high vacuum (UHV)-system is equipped with two diffusion pumps connected in series, the first of them operating as a booster stage; the working fluid is Santovac with a vapour pressure at normal conditions below \( 1 \times 10^{-10} \text{mbar} \). The use of liquid nitrogen cooled baffles together with an additional titanium sublimation pump allows of an ultimate total background pressure of the order of \( 10^{-10} \text{mbar} \). Ultra clean and reproducible operating conditions within the ultra high vacuum chamber are highly desirable especially during the initial phase of emitter preparation and Cs-supply. A totally closed Cs-feeding system is used, involving Cs-supply to the emitter from a separated Cs-reservoir through a metal capillary tube either by gravitational and capillary forces or by means of additional positive pressure feeding. The interior surfaces of both the emitter and the Cs-feeding system are outgassed under UHV-conditions at temperatures as high as 450°C by radiation and resistive heating, respectively.

In order to avoid condensation of Cs on uncooled surfaces and to reduce therefore the background Cs-vapour pressure, the ion beam of the emitter is directed towards a cylindrical cold shroud at ground potential cooled to liquid nitrogen temperature. Secondary electrons released by the impact of high energy Cs-ions were suppressed by a cage-shaped wire grid mounted beneath the interior surface of the cold shroud, being biased negative towards ground.

Monitoring of the residual gas atmosphere as well as mass spectroscopic analysis of both the constituents of the ion beam and of the azimuthal distribution of the latter is carried out by means of a fixed quadrupole mass analyzer (QMA), tilting the emitter together with the accelerator electrode around an axis of rotation parallel to and coincident with the edge of the emitter. Visual and photographic observation of the emitter-accelerator region is by means of a high resolution microscope, allowing for linear scanning along the emitter slit edge.
3 - EMISSION SITE DISTRIBUTION

If the emitter is filled with liquid Cs and the surfaces of the slit until the slit edges are uniformly wetted by the liquid metal, a homogeneous linear liquid tip of semicylindrical shape is assumed to exist at the slit edges at onset conditions of emission. The sectional view of this emitter region schematically is outlined in Fig.2, showing also different idealized assumptions on the equilibrium shape of the liquid tip; the tip radius $r_\infty$ depends on both the emitter slit width $w$ and the radius of curvature $r_\infty$ of the emitter slit edges, which are both of the order of 10^{-6}m. Enhancing the electric field, the linear liquid tip is distorted. Due to electrohydrodynamic effects, equidistant spaced emitting sites originate along the extension of the emitter slit. The existence of a matrix arrangement of wavelike instabilities on electrically stressed surfaces of fluids is a well known phenomenon /3/. The linear disposition of emitting features observed on slit emitters /4/,/5/ obviously is related to these surface instabilities.

Fig.2 - Sectional view of the linear liquid metal tip at the orifice of a slit emitter at onset conditions, showing different idealized assumptions on the radius of curvature $r_\infty$.

The mathematical treatment of this problem has been discussed in some detail /6/, considering also standing wave perturbations with no time variations. For wavelike instabilities occurring on the electrically stressed Cs-surface at the orifice of the emitter slit, a simple relation exists between the wavelength $\lambda$ of these instabilities, which is identical with the spacing of the emission sites, and the radius of curvature $r_\infty$ of the semicylindrical liquid metal tip

$$\lambda = \pi r_\infty$$

Within the theoretical figures outlined in Fig.2, the case (a) seems to be most unlikely for an emitter slit edge properly wetted with Cs. The equilibrium configurations according (b) and (c) are more realistic as these depend mainly on the actual wetting properties at the emitter slit edge. Considering actual wetting features, even values of the radius of curvature $r_\infty$ much in excess of the case $r_\infty=2w$ may occur.

With values of $\lambda$ measured for two emitter with slit widths of $w=1,2,10^{-6}$m and $w=1,5,10^{-6}$m, respectively, there result for the radius of curvature $r_\infty$

<table>
<thead>
<tr>
<th>$w$</th>
<th>$\lambda$</th>
<th>$r_\infty$</th>
</tr>
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<tr>
<td>1,2µm</td>
<td>7,5µm</td>
<td>2,4µm</td>
</tr>
<tr>
<td>1,2µm</td>
<td>16µm</td>
<td>5µm</td>
</tr>
<tr>
<td>1,5µm</td>
<td>10µm</td>
<td>3,2µm</td>
</tr>
</tbody>
</table>
The occurrence of a nearly constant value of $X$ verified experimentally for a wide range of emission currents obviously may not be explained in terms of a simple standing wave theory neglecting hydrodynamic effects but has rather to be treated by a flow field theory assuming also mutual interactions of adjacent emission sites. As a qualitative approach, one may assume an emission site distribution mainly impressed by the onset conditions which is not changed considerably with increasing emission current due to the concentration of the hydrodynamic flow of Cs to the apices of the emission sites. Considering the instabilities of liquid columns, a similar idea even has been proposed /6/, i.e. in a viscous fluid the positions of the emitting sites are likely to be stabilized by the fluid flow.

Wetting of the emitter slit and the adjacent areas is the most important but even contradictory feature in the analysis of the emission site distribution. On the one side, perfect wetting of the interior of the slit until the slit edge is essential for the occurrence of a homogeneous Cs-surface which is distorted by the applied field to a linear array of stable emission sites with rather small spacings $\lambda$ of the order of $10^{-4}$m. On the other side, stimulated by the emission process itself, wetting of much larger areas outside the emitter slit edge is a favoured process. Due to the resulting large values of $r_0$ and $\lambda$, rather large emission sites with enhanced inherent instability towards microdroplet formation may occur; finally, even spurious emission initiated by Cs-creeping or Cs-overflow is a phenomenon worthwhile to consider.

4 - ION BEAM DIVERGENCE

For a slit emitter some divergence of the ion beam occurs in both the plane normal to the plane of the emitter slit as well as in the plane of the emitter, denoted by the azimuthal half-angle $\varphi$ and the transversal half-angle $\psi$, respectively. In the present experiment no direct measurement of the transversal beam divergence was possible; the azimuthal ion beam divergence is measured either by the quadrupole mass analyzer (QMA), where the axis of the latter is defined by $\varphi=0^\circ$, or by an ion probe which is turned into the axis of the QMA.

In order to compare the experimental results, the beam divergence profiles are normalized, defining the intensity at $\varphi=0^\circ$ to be unity. A common figure to characterize the angular dependence of the shape of the beam divergence profile is defined by the 'full width at half maximum' (FWHM), i.e. the angular distance of two points of the symmetrical curve at 50% of the maximum amplitude.

For an emitter with a slit width $w=1.5\times10^{-4}$m, the ion beam divergence for different values of the emission current $I_e$ is shown in Fig.3. The divergence characteristics outlined in Fig.3a were obtained directly after the initial Cs-feeding of the emitter; Cs-wetting does not yet reach the external areas adjacent to the emitter slit edge. The divergence profiles are quite similar, following roughly a cosine distribution especially below $\varphi=30^\circ$. These cosinusoidal profiles with a FWHM of about 70$^\circ$ for $I_e=5mA$ are typical for an even new and unconditioned emitter.

Only 5 days later, after rather intense ion emission experiments, the general beam divergence has changed considerably, as it is shown in Fig.3b. The most striking feature now is the tendency towards a lateral maximum of the beam divergence profile at $\varphi=30^\circ$; this tendency is more pronounced for higher emission currents, resulting in an even enhanced broadening of the profile with a FWHM of about 90$^\circ$ for $I_e=5mA$.

An obvious explanation of this feature follows from the corresponding wetting status. Due to numerous emission events, the nearly homogeneous Cs-coverage, which is evident for the beginning of the experimental period, now is superimposed by initiation of Cs-creeping or droplet formation outside the emitter slit edge; this may initiate enhanced spurious lateral emission from emission sites occurring there preferentially with increasing emission current.
Fig. 3 - Normalized azimuthal ion beam divergence as a function of the emission current.
(a) Divergence characteristics directly after the initial Cs-feeding
(b) Divergence characteristics after ion emission during an experimental period lasting for 5 days

5 - SUMMARY AND CONCLUSIONS

Emitter preparation

Imperfect wetting of the Cs-feeding system and the emitter slit itself at the initial Cs-supply is irreversible; Cs-handling at UHV-conditions and outgassing of the complete vacuum facility is obligatory. If the emitter and the feeding capillary are properly degassed, the liquid Cs immediately runs through the capillary into the emitter until to the slit edge. Initially there occurs no continuous exterior wetting along the whole length of the slit edge. Although the vacuum conditions before Cs-supply generally are in favour of excellent wetting, obviously there exist some obstacles for the Cs to surmount the rather sharp edges of the emitter slit.

Complete wetting of the slit edge occurs gradually only by the emission process itself; thermal stress of the emitter slit edge is assumed to be the main reason for this wetting process.

Finally, condensation of Cs at the emitter surface adjacent to the emitter slit edge result in an irreversible Cs-creeping, stimulating sometimes even Cs-overflow.

Emission site distribution

Once the emitter is filled with liquid Cs and the surfaces of the slit until the slit edge are uniformly wetted, a linear array of equidistant spaced emission sites exists at the slit edge which is contributed to wavelike instabilities on the electrically stressed Cs-surface at the emitter slit edge.
The occurrence of a nearly constant value of \( X \) verified experimentally for a wide range of emission currents obviously may not be explained in terms of a simple standing wave theory neglecting hydrodynamic effects but has rather to be treated by a flow field theory assuming also mutual interactions of adjacent emission sites.

- Ion beam divergence

For an emitter not yet fully conditioned immediately after the initial Cs-supply, the azimuthal ion beam divergence roughly obeys a cosine distribution, with a full width at half-maximum (FWHM) of about 70°.

With increasing conditioning and a homogeneous Cs-coverage at the emitter slit edge, the tendency of the beam divergence profiles to show maxima at an azimuthal angle of approximately 30° and a dip at 0° more and more becomes evident; the FWHM increases towards 80°-100°. Finally, if pronounced Cs-creeping and Cs-overflow had occurred, the maxima even are shifted towards higher values of the azimuthal angle.

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