# CHARGE PARTICLE SOURCE FOR INDUSTRIAL AND RESEARCH ACCELERATORS OPERATING AT THE POOR VACUUM CONDITIONS

Popov E.O., Vitugov A.V., Pashkevich A.A., Popov S.O.
A.F. Ioffe Physicotechnical Institute of Russian Academy of Sciences,
26, Polytechnicheskaja, St.Petersburg, 194021, Russia

*Abstract*

We investigated the original method of fabrication of the great number of emitting tips by pulling liquid metal through the holes in track membrane under influence of electric field. The track membranes are produced by cyclotron of Physicotechnical Institute. This method enables to fabricate up to $10^8$ emitting tips per square cm. Special test facility to investigate emitter parameters operating at different values of background residual gas pressure was designed and developed. The liquid metal multiple tip field emitters possess some unique characteristics which are attractive in accelerators for material irradiation: unlimited life expectancy, large current densities (about 100 mA per sq. cm), practically unlimited surface, stable emission in poor vacuum..

## 1 INTRODUCTION

High current solid multiple tip field emission cathodes are well known. These cathodes provide stable field emission up to current densities from single tip till $10^6$ A/cm$^2$. The principle defect of such cathodes is that degradation of emission causes blunting, explosions, changing of work function due to adsorption. Manufacturing of large number of equal tips is also a difficult problem. Therefore multiple tip solid cathodes are more often used in explosive regime.

In comparison with solid tip emitter the liquid one restores its initial form after explosion, because tip's radius is determined by balance between electrostatic forces of applied electric field and surface tension of liquid metal. The latter circumstance causes practically unlimited lifetime in the explosive and field emission modes of operation of multiple-tip liquid emitter by sufficient reserve of metal.

The working condition of industrial accelerators and consequently demands to electron and ion sources for these devices are much harder than for research ones. The question is about charged particles source lifetime, stability of emission under relative poor vacuum ($10^{-5}$-$10^{-4}$ Torr) and after contact with atmosphere and so on. For sources with large emitting area heat expenditure can be a decisive factor. Application of proposed emitter allows to satisfy many of these requirements.

## 2. EMITTER CONSTRUCTION

We suggested, patented and investigated the original method of fabrication of the great number of emitting tips by pulling liquid metal through the holes in track membrane under influence of electric field [1-5]. This method enables to fabricate up to $10^8$ emitting tips per square cm.

Gallium layer of necessary thickness is deposited on conducting plate and is covered by track membrane. The track membranes presently employed in selective clean-up filters are obtained by bombarding a film with heavy ions such as Ar, Kr, Xe having energy of MeV. After irradiation, the film is illuminated by ultraviolet light and subjected to chemical etching. The diameter of the holes can range from 0.3 to 3 μm, depending on the requirements.

Pulling gallium through the orifices in membrane is forming emitting tips by application an electric field. Height of tips determined by membrane thickness is 10 μm. In our experiments nowadays the cathode area usually has a size about 2 sq. cm. tips density $10^6$ per sq. cm (Fig.1).

It was found that the ends of the wires were restricted and stabilized by tips of approximately the same curvature radius, which was result of balance between electrostatic and surface tension forces. This self-consistent equilibrium state is maintained in wide band of fields by simultaneous alteration of tip curvature radii.

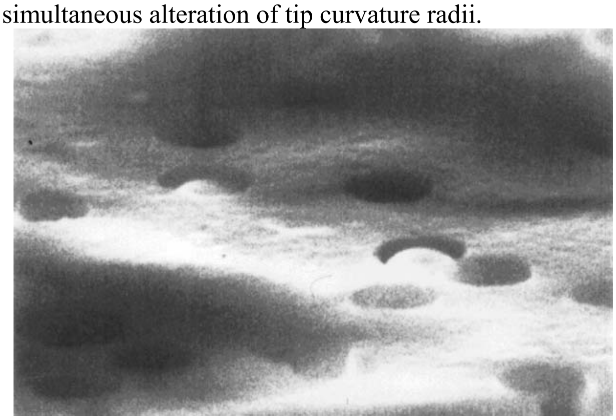

Figure 1: SEM photographs of channels in the nuclear lavsan membrane filled by liquid gallium

## 3. EXPERIMENTAL SETUP

The experimental setup is based on two turbo molecular pumps. The first one is used for qualitative experiments and it consists of three high voltage input systems. The second one having two vacuum compartments is served for quantitative measuring.

The current pulse was detected by a collector and measured with a Faraday cup or flat luminophore glass as a Faraday cup. For providing the investigations the data measuring system and the software were elaborated. To registry the voltage-current characteristics we have used the several dual channel oscilloscopes by own construction for standard personal computer slot. The results of measurements are displayed in Fouler-Nordheim plot [3].

## 4. CURRENT-VOLTAGE CHARACTERISTIC MEASUREMENTS

The emitter has been tested in various current regimes from a direct current to short pulses of nanosecond duration with a repetition frequency of several kilohertz.

The authors obtained longtime (several hours) field emission with current up to 15 mA by sinusoidal (50 and 440 Hz) power supply. The field emission was stable and long-lived, yielding current density more than 0.1 A/cm$^2$, due to small current output from individual tip and great number of tips provide large current densities.

A further increase of voltage led to a situation in which on a background of stable periodic current pulses appeared very high current spikes.

Using the sinusoidal power supply, we may also provide conditions for the controlled transition from field emission to explosive emission. Figure 2 shows (out of scale) time variation of the emission current for a sinusoidal power supply at a frequency of 50 Hz. Here, the explosive pulse of current appears on the field-emission pedestal when the sinusoidal voltage amplitude exceeds certain level. The further increase in the voltage amplitude leads to the appearance of the second pulse spaced by several tens of microseconds from the first one.

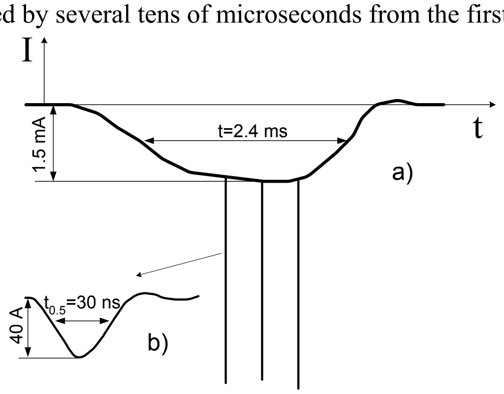


Figure 2: Diagrams showing the current pulses shape (out of scale) in the regime of (a) combined and (b) explosive emission

The authors developed, produced and tested vacuum camera (Fig.3) intending to investigate the emitter at different values of background residual gas pressure (from $1.5\cdot10^{-6}$ to $1\cdot10^{-1}$ Torr). We approached to the high voltage power supply top parameter meaning 10 mA at 75 kV and provided of radiation protection conditions ensuring. Mainly, according to radiation measurements, the protection was provided by several mm thin stillness camera walls and 25 mm Pb glasses as windows.

We specified environment density threshold meanings determining emitters functioning stability. The emitter may stably work up to $1\cdot10^{-3}$ Torr with current fallen down to 2 times.

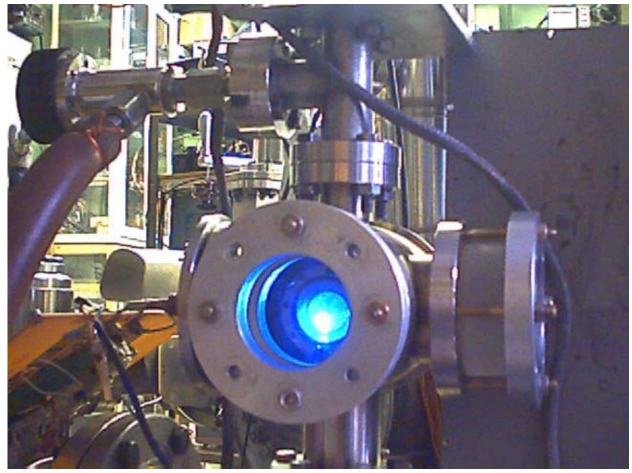

Figure 3: Vacuum camera intended to investigate the emitter at different values of background residual gas pressure

The family of written voltage-current characteristics taken by mentioned digital oscilloscope shows the current and warm stability of developed construction exploration investigation.

We made theoretical evaluation of the working emission points number.

A highly stable emissivity of each liquid metal point is provided by a deep negative feedback not admitting excessive sharpening of the metal points and infinite buildup of the emission current density. According to [6], the feedback is provided by the surface tension of the liquid metal, which tends to blunt the sharp tip of each point. On the other hand, a growth of the applied potential $U$ leads to an increase in the electric field strength at the rounded end of each gallium column, thus extending and sharpening the emitter point. Eventually, the electric-field-induced pull-up pressure becomes equal to the pull-down pressure produced by the surface tension forces.

The form of the end of a liquid tips changed pulsing with $U$. This sharpening is limited every moment by surface tension, which tends to blunt the tip:

$$\frac{\varepsilon_o E_o^2}{2} = \frac{2\sigma}{r_o}, \qquad (1)$$

where $\varepsilon_o$= 8.85 $10^{-12}$ F/m is the dielectric constant, $E_o$ is the equilibrium electric field strength [V/m], a is $\sigma$ the surface tension ($\sigma$=7.12 $10^{-1}$ N/m), $r_o$ - equilibrium point radius [m].

Assuming that each emitter represents a body of revolution and the point end represents a spherical surface with the radius $r_o$, we can use the equilibrium condition (1) to obtain $E_o$.

For an assigned value of $E_o$ and the known work function $\varphi$=3.96 eV for gallium it is not difficult to find the relation between the field-emission current density $j$ and $E_o$ using the Fowler-Nordheim formula for $j$:

$$j = 1.4 \cdot 10^{-6} (E^2 / \varphi) \cdot 10^{4.39/\sqrt{\varphi}} \cdot 10^{-2.82 \cdot 10^7 (\varphi^{3/2} / E)}, \quad (2)$$

where $j$ is measured in A/cm$^2$ and $E_o$ in V/cm$^2$.

It was found that the stable regimes of the field electron emission are characterized by $r$ 40-65 nm and $j$ no more than $10^3$ A/cm$^2$, with is rather modest (not too high) $j$ for field emission. According to formula (2), the point radii within 40-65 nm correspond to electric field strength of $E_o > 10^7$ V/cm.

## 5. MAIN ADVANTAGES

Liquid metal multiple tip field (LMMTF) emitters has some advantages in comparison with solid-state field emitters and explosive electron emitters:

1. The problem of leveling and sharpening of tips array is being solved as the radius of the tip's end is defined by applied voltage. This electrical voltage determines the equilibrium when Maxwell field stresses equal to surface tension of liquid metal. By this reason liquid tip is insensitive to ion bombardment and restores it's initial form after ion penetration into the tip. It was shown that the stable operates in enumerated above regimes could be done under poor vacuum (>$10^{-4}$ Torr).
2. The high stability of the emission current at electronic current densities up to 0.1 A per sq. cm is attributed to the presence of a large number of emitting tips. The maximal field emission current density observed in our experiments was limited by power dissipation in vacuum chamber.
3. Multiple tip liquid metal emitter depending on applied voltage operates successfully and stable in different regimes such as field electron emission, explosive electron emission. The emitters tested in the laboratory operated for many hours without any changes in the parameters of emission. Stable operation is provided by the ability of emitting points to self-recover after each explosion current pulse.
4. The emitter is based on track membrane technology and therefore its surface can be made of various shapes and as large as necessary in size as well.

The large area cold of the cathode based on multiple tip liquid metal field emitter may be very useful for indicator, in flat display construction, for laser pumping, industrial accelerators for material irradiation, powerful X-ray tube, and so on.

In [7,8] it was proposed to apply LMMTF cathode for controlling the gas dynamic flow structures by air ionization in supersonic flow. An electric field of high strength created in the emission region near the tip surface drives electrons to acquire a keV energy over a distance of a few microns. A cathode operating in the field emission or explosive emission mode can generate stable reproducible electron beams of keV energy with a current density up to several hundred amperes per square centimeter. Those circumstances offer a new approach to the problem of introducing an electron beam into a supersonic gas flow.

## 6. ACKNOWLEDGMENTS

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