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SOVIET DEVELOPMENT OF NEEDLE-TIP FIELD-EMISSION CATHODES FOR HIGH-CURRENT ELECTRON BEAMS

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10. ABSTRACT

Summarizes recent Soviet theoretical and experimental work on cathodes for very high-current charged particle beams, work led by Fursey at Leningrad State University and Mesyats at Tomsk. Field emission from needle-tip cathodes is based on explosive emission from the tips, accompanied by explosion-derived plasma setting up intense local electric fields. A cathode fabrication method is described that gives stable operation through 10,000 to 100,000 pulses of about 3 nanoseconds each, for currents of 500 to 1000 A. A liquid cathode produces stable current pulses within 6 percent of 2000 A. In a large needle array, 80 percent to 100 percent of the tips maintained current value dispersion within 20 percent. Operational cathodes of the controllable tip-and-dielectric type have been developed for 500 keV and 50 kA, and of the multiple-tip types for 1 MeV and 50 kA. Soviet scientists apparently feel that such beams can solve many problems, including controlled thermonuclear reactions, high-intensity microwave, flash X-rays and gamma rays, and high pressure effects in materials.

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Soviet Development of Needle-Tip Field-Emission Cathodes for High-Current Electron Beams

Simon Kassel and Charles D. Hendricks

A Report prepared for

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PREFACE

This Report was prepared in the course of a continuous study of Soviet research on the production, diagnostics, and application of high-current relativistic charged-particle beams. That study, in turn, is part of an ongoing program, sponsored by the Defense Advanced Research Projects Agency, which undertakes the systematic coverage of selected areas of Soviet scientific and technical literature.

The development of charged-particle beams in the high power range ($> 10^3$ A, $> 10^6$ ev) is the subject of numerous theoretical and experimental research reports published in the Soviet Union in recent years on the work of leading scientists and research organizations. The scope of this material indicates that Soviet scientists are engaged in a fairly intensive effort, based, it appears, on the premise that charged-particle beams are a viable alternative means of solving a series of such diverse technological problems as controlled thermonuclear reactions, high-intensity microwave beams, flash X-rays and gamma rays, passage of high-energy beams through the atmosphere, and high-pressure effects in materials.

This account of Soviet activities as reflected in open publications dating mainly from 1970 and 1971 is being made available to American researchers as a potentially useful contribution to their own work under government-sponsored programs.

SUMMARY

A mechanism of field emission from high-current needle tip cathodes is advanced in the course of a comprehensive study of electron accelerator diodes capable of producing electron beams in the kiloampere range. The mechanism is based on explosive emission from the tip accompanied by the formation of explosion-derived polarized plasma setting up local electric fields with intensities as high as 10^8 V/cm. The theory is applied to the development of multiple-tip needle cathodes, and a cathode fabrication method is given ensuring stable operation through 10^4-10^5 cycles for currents between 500 and 1000 A. A variant of the multiple-tip cathode, further enhancing the stability of operation, is the liquid cathode, with the liquid surface perturbed by vibration to create protrusions. The liquid cathode produces stable current pulses within 6 percent of 2000 A. In a large needle array, between 80 and 100 percent of needle tips are found to maintain current value dispersion within 20 percent. Operational cathodes of the controllable tip-and-dielectric type for 500 keV and 10 kA, and of the multiple-tip type for 1 MeV and 50 kA are developed.

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I. INTRODUCTION

Intensive theoretical and experimental work on field-emission cathodes suitable for the production of high-current electron beams has been pursued in the Soviet Union by members of the Institute of Atmospheric Optics in Tomsk (headed by G. A. Mesyats) and G. N. Fursey of the Leningrad State University. Through their publications, the group's comprehensive study of the problem has been in evidence since 1966.

According to Fursey [1], the extremely high emissive capability of field emitters makes it possible to obtain large electron currents from small electron sources. For example, with a current density of 10^7-10^8 A/cm^2, a current of 10^6 A can be emitted by a cathode whose linear dimension is of the order of 1 mm. However, very high anode voltages are necessary to produce such currents. To obtain 10^4 A, we need over 10^6 V, with an emitter having a radius of curvature of 10^{-2} cm. One method of reducing the voltage requirement without sacrificing current values consists in the use of multiple-tip cathodes. The aforementioned group has devoted itself to a detailed investigation of the entire emission process as it occurs first in a single tip, and the application of the results to multiple-tip structures. Mesyats had advanced an early theory of this process in his doctoral dissertation, in 1966, in which he emphasized the basic role of microprotrusions, or microtips, on the surface of field-emission cathodes in the generation of heavy currents of the order of 10^5 A and higher [2].

The electric field intensity at the microtips is very high and produces electron current from the tips by field emission. Current densities may reach 10^9 A/cm^2 in very short times as a result of processes in the microtip which cause vaporization and formation of a plasma at the tip. High currents are then extracted from the plasma region around the tip.

II. SOLID CATHODES: OPERATION DIAGNOSTICS

In a series of direct experiments, reported in 1967, Mesyats showed that the transition from initial field emission to the heavy current of a vacuum arc coincided with a cathode flare (in C, Cu, Mo, Al, and W cathodes) propagating at (2-2.5) x 10^6 cm/sec toward the anode [3, 4]. He concluded that, since the emission was practically the same in all these materials, the electric-field gradient and plasma formation, rather than the work function, was the main determinant of emission properties.

The time behavior of the transition from the initial field emission to a vacuum arc was measured more recently in greater detail. Using 20 kV pulses with a 1 nsec front and 5 nsec length, the rise rate of current was found to be 5 x 10^{10} A/sec [5]. The proposition that cathode flare is due to the explosive destruction of microprotrusions on the cathode surface by the field-emission current, first advanced in 1967 [3, 4], was verified later [6] through determination of the plasma expansion velocity caused by such tip explosions. The experiment showed that the expansion velocity of plasma derived from the tip explosion is the same as the cathode-flare velocity of (2-2.5) x 10^6 cm/sec, and only weakly depends on cathode-field intensity. For example, for very steep pulse fronts the velocity is 3.5 x 10^6 cm/sec.

In a series of further experiments, Mesyats and Fursey also obtained a more detailed picture of the microtip explosion process [7]. The experimental parameters were as follows: The vacuum was 10^{-9} torr; the voltage-pulse length ranged from 5 to 33 nsec; the pulse-front length was less than 1.5 nsec; and the pulse amplitude was continuously variable from 3 to 50 kV. Single-crystal tungsten needle emitters were used with a tip radius of 3000 Å. A significant finding of these experiments was that the operation of the emitter proceeds in at least two stages:

1. Explosive erosion of the needle tip when the current density reaches a critical value of approximately 10^9 A/cm^2.
2. Vaporization of remaining portions of the needle during the vacuum-arc stage as a result of the suddenly increasing current caused by the onset of the arc. Since the pulse length was no more than a few nsec, only the electronic component of current must have been present. The appearance of this component is attributed to emission from the not-yet-vaporized remainder of the needle under the action of the external electric field. This field is enhanced greatly by the formation of a positive space charge (cathode sheath) in the plasma formed of the material from the initial erosion of the tip.

The initial explosive erosion of the needle tip stops when its emitting area increases to a value for which the current density is too low to continue flash vaporization.

After termination of such erosion, and during the transition from field emission to vacuum arc, a characteristic feature appears in the form of submicroscopic tips pulled out from the surface of the emitter. Part of the needle emitter is in a liquid phase during the transition period, and the electric field is strong enough to produce a whisker in a few nanoseconds.

To obtain more information on the rapid increase of emission following the explosive flash vaporization of the tip, the voltage pulse was modified to a segmented step-down shape (see Fig. 1), with a 30 percent voltage difference from step to step [8]. Three steps were used in all, the first producing only field emission, and the second and third accompanying vacuum breakdown. This technique made it possible to approach breakdown initiation with considerable control. The experiment confirmed the coincidence of explosive vaporization of the emitter tip with a sudden increase of electron emission, which reached an initial rate of 10^9 A/sec.

In many cases the tip explosion occurs as the current pulse falls off, apparently indicating that energy is stored in the tip, causing its destruction even as the energy input rate is decreasing. Such a case is shown in Fig. 1.

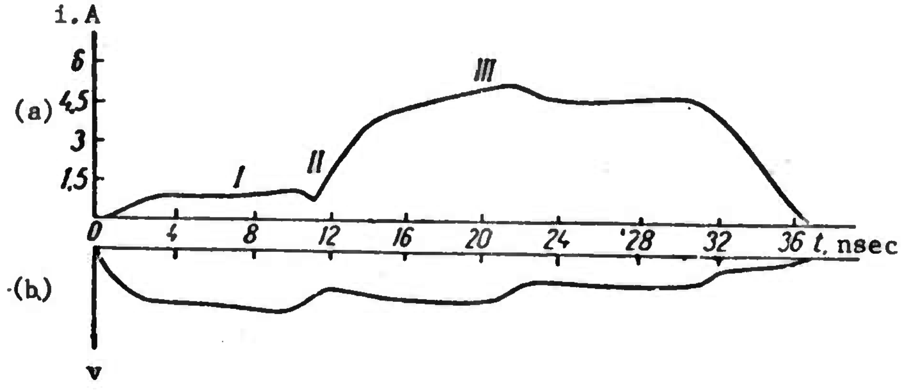

Fig. 1 -- Emission current (a) and voltage pulse (b)

Step I corresponds to pure field-emission current; steps II and III correspond to explosive emission current and a vacuum arc.

Electron microscope photographs of exploded emitters show that tip erosion depends mainly on current density and not on length of pulse or potential difference. They also show that, during the breakdown, a considerable part of the emitter is in the melted state. The large number of submicroscopic protrusions of the tip formed in the interval of 2 to 3 nsec at the end of the pre-breakdown transition period indicates pulling from liquid phase by a field of at least 10^8 V/cm. This is considered direct proof of a strong electric field around the vaporized tip during the transition period, assumed to be due to the polarization of plasma derived from the initial tip explosion.

It should be noted that emission current practically does not change during step III (see Fig. 1). This means that a strong field is maintained near the emitter during plasma expansion. It is assumed that this is due to the additional supply of plasma from the exploding submicroscopic protrusions pulled out of the melt.

III. SOLID CATHODES: METALLURGICAL ANALYSIS

A parallel investigation of the foregoing problem, providing an interesting viewpoint of metallurgists, was performed at the Institute of the Physics of Metals in Sverdlovsk [9], where the method of field-emission microscopy (liquid-nitrogen-cooled electron projector) was applied to the study of cathode-tip protrusions formed in the course of vacuum breakdown, as in Fursey's experiments. The study was based on Fursey's observation that the electric field gradient, rather than the work function, was the main factor determining the emissive properties [3].

The Sverdlovsk group introduced the following formal definitions:

Break-off (*sryv*). The cathode tip in an electric field is subject to considerable mechanical stress; if this stress exceeds crystal strength, the tip is partially destroyed. The loss of a portion of the tungsten crystal due to the ponderomotive force of the electric field is called a "break-off." In this condition, the tip always shows traces of a pronounced inhomogeneous plastic deformation, and the surface assumes a very sharp profile.

Vacuum breakdown. The main characteristic of this phenomenon is the melting of part of the crystal. If the vacuum breakdown can be retarded, the melt rapidly crystallizes on the tip surface, forming a complex protrusion emitter.

The difference between the two phenomena is that the first consists of partial destruction caused by mechanical stress, and the second of partial melting caused by increased local current. Sometimes, the break-off becomes vacuum breakdown, causing both valleys and protrusions to appear on the tip surface. The latter may then become independent microtips.

Thus, a break-off can first occur without heating of the tip. However, the resulting inhomogeneity of the surface favors the initiation of vacuum breakdown, thereby leading to the appearance of an emitting protrusion. The protrusion has a perfect tip shape, i.e., the traces of plastic deformation are eliminated by an annealing effect that accompanies the entire process of protrusion formation. The perfect tip formation has been observed in small (60 Å) as well as in the usual large (several hundred Å) microtip protrusions obtained in the course of a vacuum breakdown.

IV. MULTIPLE-TIP SOLID CATHODES

The theory of explosive emission formulated on the basis of the foregoing experiments thus postulates the following sequence of events [8].

The emitter tip is exploded by the critical emission current → the tip melts and increases in radius → the field is maintained at the surface of the tip by polarized plasma derived from the explosion → microtips are pulled from liquid phase → the microtips explode, and additional plasma enters the near-surface region.

According to Mesyats and Fursey, the above mechanism, rather than the Fowler-Nordheim field-emission model, is responsible for the nanosecond heavy-electron-beam pulses and flash X-rays.

In a further development of this research, the Mesyats-Fursey mechanism was applied to interpret the behavior of multiple-tip cathodes [10]. Three types of multiple-tip cathodes were used:

Type I, with 1100 tips;

Type II, with 400 tips held by series-connected straps for heating the tips up to 2000° C;

Type III, representing bunches of 30 μ wires.

Type I cathodes were developed and studied by a team from the Physico-Technical Institute of the Ukrainian Academy of Sciences under I. M. Mikhaylovskiy. In 1967, the Ukrainian team presented a method of preparing needle tips of small-curvature radii (∿ 100 Å and larger) with a minimum parameter dispersion and a method of equalizing field intensity in the resulting pack so that synchronization among tips was achieved regardless of dispersion of initial parameters and mutual shielding conditions. A field-emission cathode was prepared of 1200 tips, capable of producing a current of 500 A for 200 kV and pulse length of 2×10^{-7} sec [11].

The dispersion reduction was achieved by electrolytic etching in a three-layer bath, patented by Mikhaylovskiy et al. (patent certificate No. 171929) [12]. The atomic diffusion method of equalization proposed by W. P. Dyke [13] was not considered satisfactory.* On the other hand, the three-layer bath was said to increase the reproducibility of geometric dimensions of the tips and to decrease their radius. The bath has a layer of mercury topped by a layer of nonconducting liquid, such as carbon tetrachloride, topped in turn by a layer of electrolyte. The wire blank is lowered vertically into the bath, so that its lower end is immersed in the mercury. Platinum wire in the electrolyte layer serves as the second electrode. The etching is achieved with 50 Hz ac. The nonconducting layer stops etching automatically, allowing for the production of a large number of tips (100 and over) in a single operation.

An equal field intensity over all the emitting tips is the condition for simultaneous operation of all tips in the pack and, consequently, for the proportionality of total current emitted to the number of tips.

Equalization of field intensity over emitters in the pack was the subject of a later patent of the same authors (patent certificate No. 206728) [14], based on ionic vaporization of metals in strong electric fields and consisting of successive vaporization of tips with high local field intensity. The selective vaporization, blunting the tip, continued until field intensity was reduced to a value corresponding to the strength of the emitter material. An ion-field-emission microscope was used to evaluate field-intensity dispersion around the tips of the working cathode pack. This did not exceed 1 percent.

The operating pack retained its characteristics, with a pulse repetition frequency of 5 to 10 Hz, for over five hours [11].

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*Dyke's method of equalizing tip radii at high temperatures is based on the decreasing migration rate of surface w atoms with increasing radius. However, the method achieves only a partial decrease of radius dispersion (up to 10%) and also fails to eliminate the effect of mutual shielding within the needle pack, necessitating reduction of tip density and increase of tip size. Even a reduction of parameter dispersion down to 1 percent does not eliminate hot spots [11].

In Fursey's experiments with multiple-tip cathodes [10], negative voltage pulses of 40 to 400 kV and up to 30 nsec long were applied to the cathode. The vacuum was 10^{-7} torr. The maximum current values were 700, 450, and 780 A for cathodes of types I, II, and III, respectively (see Fig. 2).

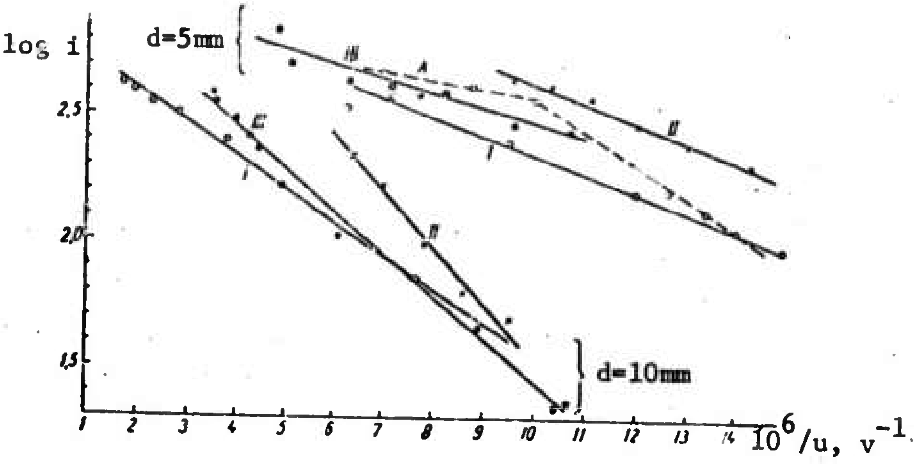

Fig. 2 -- Voltampere characteristics of multiple-tip cathodes
$\log i = f\frac{1}{u}$ (i -- emission current, u -- anode voltage); d -- electrode spacing. Line A represents the results of the Ukrainian team.

The reproducibility of current values from pulse to pulse was 15 to 20 percent, and it improved with increasing anode voltage and number of power cycles. Type I cathode was switched on 10^5 times, type II 3×10^4 times. The tip radius of type II cathode was eroded from 10^{-4} cm to $1-3 \times 10^{-3}$ cm after 3×10^4 cycles. The final radius of the eroded tips was close to that obtained after a single explosion, indicating that the main damage occurs during the early cycles. Microwhiskers with an average radius of 1.5 μ appeared on most of the melted tips. The mass transferred from a single emitter tip per pulse was 6×10^{-9} g, assuming that most of it was transferred during the first ten pulses.

Oscilloscopic traces of current show the presence of pulsations whose period apparently corresponds to the time of flight of plasma formed in the tip explosion between neighboring elements of the multiple-tip cathode. For a 0.1 mm spacing between the tips, the pulsation period was ∿ 3 nsec. It was also noted that the application of a second voltage pulse much lower than the first produced a second electron current pulse, whose amplitude in a number of cases exceeded that of the first current pulse.

The results of Fursey's experiments again confirmed the validity of the Mesyats-Fursey mechanism of beam formation. The voltampere curves are nonlinear; current increases much more slowly with voltage than predicted by field-emission theory, and in a number of cases the curves have negative slopes. Statistical analysis of the electron-microscope images of the tips of cathode type II shows that, out of 400 elements, only 15 percent could have participated in field emission, with a resulting maximum field-emission current one order lower than the observed value.

The sequence of events reconstructed from this series of experiments is analogous to that given at the top of page 7.

V. LIQUID CATHODES

Another variant of cathode structure investigated by Mesyats and Fursey within the framework of the proposed mechanism was the liquid cathode [15]. While in solid cathodes the emission centers are represented by the initial protrusions on the cathode surface, in liquid cathodes it is possible to form microtips by perturbing the liquid metal surface in the presence of a strong electric field. One advantage of liquid cathodes is the greater reproducibility of breakdown parameters because of the constancy of initial and boundary conditions for generating the necessary protrusions. Furthermore, liquid surfaces lend themselves to controlled artificial generation of microtips.

In the United States liquid cathodes have long been considered possible sources of high-current electron beams. It has been known that in mercury vapor rectifier tubes, the initial application of voltage to the anode produced emitting ripples on the mercury-pool cathode. In many instances, the fields at the cathode were inadvertently made high enough to spray mercury inside the tube. Recent studies on the use of liquid emitter for space-propulsion thrusters have provided information on the use of liquid surfaces for both positive and negative emission. In many of the experiments, the effort was specifically directed toward the generation of positive and negative ion beams from the liquid surfaces. In others, however (for example, the work of Swatik and Hendricks at the University of Illinois and the work of Conen, Hendricks, and others at the laboratories of TRW), attention was given to the production of electron beams from liquid emitters. Hendricks suggested as early as 1963 that stimulation of the surface by means of ultrasonic waves could disturb the surface so as to form a pattern that would provide well-controlled emission sites for the generation of both positive ions and electrons. Specific work in this field has been sparse in the United States, with more attention being given to ion sources. However, Swatik in his doctoral dissertation (1969) reported the use of a single liquid-tip electron emitter giving 10 mA of current for very low voltages (less than 1000 volts between anode and cathode). The electrons were noted to arise from a region only a few angstrom units in extent at the liquid tip. An increase in the applied voltage gave rise to extremely high currents, indicating that a plasma emitter had been formed at the emitting tip. At the same time, a burst of gas from the tip was noted by means of vacuum measuring equipment.

In the Soviet experiments, high-purity gallium and mercury were used as cathodes in a vacuum of 10^{-5} torr. A pulse generator was used, with continuous amplitude variation from 20 to 75 kV and pulse-length variation from 10^{-8} to 10^{-5} sec. The field intensities producing whiskers were 4.3×10^4 V/cm for mercury and 3.6×10^4 V/cm for gallium. Under these conditions the current through the gap was 5 to 7 A.

The results were significantly improved by resort to artificial production of whiskers. To this end, the liquid metal was placed on a vibrating piezo-quartz or barium titanate plate that formed standing waves on the surface of the metal. Thus the method generated controlled protrusions whose geometry depended on the configuration and frequency of the vibrating plate. With a frequency of 2 to 12 MHz the density of the protrusions varied from 190 to 6×10^3 cm^{-2}.

Another improvement due to the vibration technique was the increased stability of the measured emission current values (see Fig. 3). Without vibration, the values of electric charge accumulated at an external capacitor varied by 10 to 15 percent; with vibration, the stability improved to 6 percent. The increase of electron current following the artificial creation of a large number of microprotrusions can be attributed to the expanded active surface and increased number of simultaneously exploding emitters.

As reported in 1971, the conclusions were the following:

A. Microprotrusions are created by a strong electric field on the surface of the liquid cathode in the breakdown initiation stage and in the transition to arc discharge.

B. Artificially created microprotrusions on the cathode surface reduce breakdown voltage and significantly increase the reproducibility of breakdown conditions.

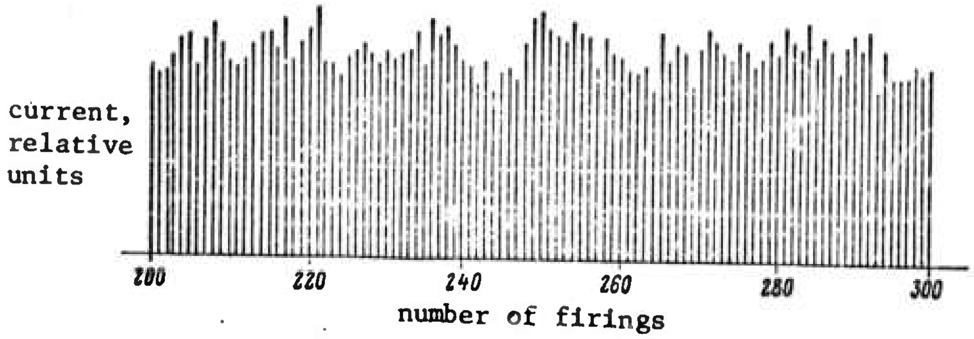

Fig. 3 -- Stability of electron emission of a liquid cathode with artificially excited protrusions.

C. During breakdown an explosive electron emission is excited at the liquid cathode; the stability and intensity of the emission are determined by the condition of the liquid cathode surface.

D. The creation of a large number of artificially excited microprotrusions produced stable pulse currents with an amplitude up to 2000 A within 6 percent from pulse to pulse [15].

VI. EFFECTIVENESS OF MULTIPLE-TIP CATHODES

In considering the reproducibility of breakdown parameters and synchronization of all or most of the cathode tips, Fursey introduced the measure of "effectiveness" of a multiple-tip cathode represented by the ratio of emitting elements whose current dispersion does not exceed 20 percent to the total elements of the system. To achieve this he proposed a treatment method, some elements of which are similar to that of the Ukrainian team described on page 7.

Fursey reports an effectiveness of 70 to 100 percent in recent experiments with his method [1]. He prepared tungsten emitters by electro-spark-cutting of the tips from foil, followed by electrolytic sharpening. A Muller field-emission microscope was used to study the cathodes. Equalization of tip radii was achieved by surface diffusion of atoms at high temperatures. Thus, as a rule, an initial voltage caused about 1 to 3 emitting-tip images to appear in the electron microscope. As the equalization proceeded, the number of emitting tips increased, and at the end of the process reached 70 to 80 percent of all the elements of the multiple-tip system. A more precise measurement of current density distribution among the cathode tips was based on densitometric analysis of the images on the screen. In this manner, 100 percent effectiveness was reached in some cases.

The voltage pulse varied from 5 to 70 kV with a length of 10 to 15 nsec and pulse front of 1.5 nsec. The vacuum was 2 x 10^{-9} torr. Stable operation was obtained in a system of 25 tips, current of 200 A and anode voltage of 50 kV, and current density per tip of 2 x 10^{8} A/cm^{2}.

The problem of timing the explosion emission has also been considered by Mesyats in relation to tip-and-dielectric cathodes [2]. The tip of the emitter is in contact with the surface of a dielectric plate metallized on the opposite side. A voltage pulse between the tip and the metallized side causes tip explosion when an accelerating voltage is applied between anode and tip. In such a system, electron emission is determined by the contact between the tip and plasma derived from the dielectric and the tip. Controllable cathodes with dielectric can fill the diode with plasma and increase beam perveance by a factor of 10.

According to Mesyats, two types of accelerators based on explosive emission have now been developed: a controllable tip-and-dielectric type of cathode for 500 keV and 10 kA, and a multiple-tip cathode type for 1 MeV and 50 kA.

High-current field-emission cathodes of the solid-needle type have been manufactured in the United States by the Field Emission Corporation of McMinnville, Oregon. But there seems to be little, if any, high-current cathode development in America. It is quite clear that the Soviet Union is considerably ahead in the research and development of cathodes for use in apparatus for generation of high-current, relativistic electron beams. With cathodes of the type described in the work of Mesyats and his collaborators, currents of 10^6 A are desirable and attainable.

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