THE LASL HIGH-DUTY-FACTOR ION SOURCE*

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Introduction

The basic requirement on the high-intensity injector for the LAMPF accelerator is that it deliver to the Alvarez section an average beam current of 1 mA of 750-keV protons. The resulting requirement on the ion source is that it produce a 50-mA current pulse of 500-μsec duration at a repetition rate of 120 cps. The normalized emittance (emittance area · $\gamma\beta/\pi$) from the ion source and accelerating column must be approximately 0.04 cm-mrad. The 50 mA of current allows for the molecular ions, which are extracted along with the protons, and for losses in the beam transport system.[1] The noise or oscillating components of the pulsed current should be less than 5% rms deviation of the peak value above one megacycle and less than 1% rms deviation below one megacycle.

The source should be reliable in the sense that unscheduled downtime will be less than 1% of the scheduled operating time. The source must be clean so that contaminants from its operation will not cause adverse effects on the accelerating column or other downstream accelerator components.

Results of life tests on a prototype ion source operated at the required 6% duty factor (DF) are given, indicating satisfactory compliance with the basic requirements. Some preliminary results of 12% DF operation are presented also.

The Ion Source

The ion source is a conventional duoplasmatron shown in Figs. 1 and 2. Special attention has been given in the design to provide high-velocity cooling water to both the intermediate electrode and the system containing the anode plasma aperture. The glass or ceramic ring (both have been used) between the anode and the intermediate electrode is of large diameter to keep the O-ring and vinyl acetate seals near room temperature. Provision is made to allow replacement of the anode plasma aperture from the back side of the source without disturbing the alignment of the expansion cup with respect to the extraction electrode.

Figure 3 shows the region around the cup and plasma aperture. A laminate of iron and copper is used as the aperture septum to provide both adequate cooling and magnetic shielding for the expansion cup. A field-free region is desired at the extraction plasma boundary to minimize the emittance of the extracted beam.[2]

In testing the ion source, only the first electrode (extractor) of the Pierce accelerating column is simulated, as shown in Fig. 4. The beam is extracted into either a simple Faraday cup, not shown, or an emittance measuring grid (Fig. 5). This latter device consists of water-cooled hexagonal copper bars placed parallel to form slits of approximately 0.003-in. in width. The emittance pattern formed by this device is viewed on a quartz plate placed 1 in. downstream.

Ion Source Behavior

A discussion of the ion source behavior should be prefaced with the remark that the objectives of the tests were only to evaluate the gross features of the ion source necessary for 6% DF operation. Thus, in many cases, no attempt was made to completely optimize the operational parameters or to try to obtain a uniform current pulse shape.

Figures 6, 7, and 8 illustrate the characteristic features of the extracted ion current pulse and the associated arc current and voltage. The ion beam current shown in the lower trace of Fig. 6 was measured using a Faraday cup with a small magnetic field to suppress secondary electron backstreaming. The magnitude of the current was checked calorimetrically by measuring the temperature rise of a given flow of cooling water through the Faraday cup. The extractor current shown in the upper trace of Fig. 6 is negligible except for a small initial pulse. The extracted beam shows a high initial intensity which levels off after the first 50 μsec to 53 mA and then drops slowly to 47 mA during the remainder of the 500-μsec pulse. Characteristic oscillations are observed. The high initial current is caused by the high-intensity arc current used to initiate the discharge and by the high impedance arrangement used to supply the 25-kV extraction potential, allowing the extraction potential to be 35 kV early in the pulse and settling down to 25 kV during the remainder of the pulse. In some of the tests, no difficulty was encountered in sustaining the pulse for 1000 μsec.

The nature of the noise or oscillations present on the ion beam current was examined by using fast oscilloscope speeds. Identifiable components of the noise are 3 MHz (5% rms) and 14 MHz (2% rms). A possible explanation for the 14-MHz component could be that a sheath of electrons knocked off the extractor by the edge of the proton beam travels back along the edge of the beam and reduces the effects of space charge. The beam will then converge because of the focusing action of the 4/3 power potential gradient of the Pierce geometry and the proton beam will miss the extraction electrode and shut off the supply of electrons. The beam now expands because of space charge, again striking the extractor, and the cycle is repeated. Calculations of the particle transit times indicate that a frequency of 14 MHz should be expected. The 3-MHz component cannot be accounted for by this simple model and is probably generated within the ion source plasma, because this component is also observed on the arc current.

Figure 9(a) shows an emittance pattern obtained with the source. The emittance pattern is simply the set of straight lines, one for each slit of the emittance device. This is superposed on an image, shown in Fig. 9(b), which was taken without the 25-kV extraction potential to eliminate the effects of the ion beam. The corrected angular spread for the case shown is 12 mrad, with a beam radius of 2.9 cm diameter, giving a normalized emittance of 0.08 cm-mrad.

From visual observation of the beam size and intensity at the extractor aperture as a function of very short pulse lengths, the time history of the plasma formation in the ion source can be inferred. A beam does not appear until 12 µsec after the arc voltage has been applied. This interval is interpreted as the plasma buildup time in the arc chamber. At first visual observation, the beam is of very small diameter about the size of the plasma aperture. As the current increases with time, the diameter of the beam grows until the expansion cup is filled and a plasma surface of 1.4-cm diameter has been established. Filling of the expansion cup takes about 4 µsec. Thus, a stable plasma surface does not appear until ~ 16 µsec after the arc voltage has been applied. The buildup time of the plasma boundary at the extraction surface is consistent with the transit time of the protons from the plasma aperture to the stable plasma surface (1 cm).

Ion Source Life Tests

The life tests were run under the following approximate conditions: 50 mA of current with 25 kV of extraction voltage applied, a normalized emittance (emittance area · $\gamma\beta/\pi$) of 0.045 cm-mrad, 50% H^+ to H_2^+ ratio, and a hydrogen pumping throughput of 2 cc atm/min. The final results of the ion source life tests are listed here:

6% DF: 1289 h arc on (16 A)
300 h extractor voltage on
12% DF: 170 h arc on (22 A)
170 h extractor voltage on

In the following paragraphs, individual components of the ion source are evaluated on the basis of their performance during these life tests.

Vacuum Pump

The VacIon pump has been in use for over 3549 h with the original titanium plates. Hydrogen has been pumped at 2 cc atm/min for 1846 h.

Cathodes

Cathodes were originally thought to be a problem in ion source maintenance. One cathode, however, was in continuous use for 3500 h heater-on time, 1290 h arc-on time at 6% DF and 16 A arc current, and 300 h with 25-kV extraction. The cathode was kept hot continuously with 25-A heater current except for brief intervals when the vacuum system was opened for changes. Interestingly, the ion source will continue to pulse at rated values even with the cathode heater off. An ultra-clean vacuum system is apparently unnecessary for long cathode life. Glass, stainless steel, mild steel, copper, silver solder, and brass are present in the system. Viton O-rings are used with generous applications of silicon grease; vinyl acetate, Loctite, and Apiezon seals have also been used.

Magnet Coils

Two failures involving breaks in the winding of the magnet coil have occurred. Improved methods of sealing against water leaks by soft soldering the metal jacket around the coil winding, providing a pressure-release vent, and using flexible leads to the coil are now being used successfully.

Cooling-Water System

An independent closed-loop water cooling system using a small pump has operated satisfactorily. Heat is dissipated by convection cooling from the surface of a water storage reservoir. In the final design, the cooling reservoir will be replaced by a radiator.

Ion-Source Insulating Ring

During the life tests, a metallic conducting coating (copper) formed on the insulating ring (see region A, Fig. 10). Fortunately, a nonconducting region remained where the insulating ring was in the shadow of a centering shoulder. Future design will provide more complete shielding. The source of this conducting coating of copper is believed to be the region around the nose of the intermediate electrode (see region B, Fig. 10).

Palladium Hydrogen Leak

A General Electric (commercial) palladium leak has been used to control the hydrogen flow into the ion source. The hydrogen flow has been manually controlled during the life tests by controlling the temperature of the palladium leak. An automatic regulating system was tried, but critical damping of the feedback loop could not be achieved. An advanced design will be tried soon.

Intermediate Electrode

Profuse growth of iron whiskers (see Fig. 11) was found in the copper joint around the removable nose piece after the life tests (see region C, Fig. 10). Although no abnormal behavior of the ion source was noted during the life test, some other whiskers either migrated to or grew on the copper face of the anode near the end of the intermediate electrode (see region D, Fig. 10). These individual whiskers were in the centers of a discolored patch of copper, giving the impression that some discharges had occurred in these regions. A spectroscopic analysis of the whiskers showed their composition to be 99% Fe, 0.1 to 1.0% Cu, 100 to 1000 ppm of Ni and Mn, and lesser amounts of Al, An, Si, Ca, Ba, and Sr. It is gratifying to know that Ni from the cathode or Ti from the ion pumps do not constitute a significant portion of these whiskers.

Plasma Aperture

In the region of 6 to 12% DF, the plasma aperture (see region E of Fig. 10) appears to be the only component of the ion source that must be operating close to the limits at which failure will occur. This marginal situation is associated with the use of soft iron for the thin plasma aperture system used to ensure a nearly field-free region in the expansion cup. This iron septum is 0.005-in. thick with a layer of copper of the same thickness joined to it by silver solder. The diameter of the aperture was 0.040 in. After the 6% DF test, an examination of the aperture showed little damage. After the 12% DF test, the aperture showed some melting with a resulting globular structure (see Fig. 12). Further design improvements will be necessary for 12% DF operation.

Pulser

The transistor pulser unit has worked fairly well, occasionally failing when a transistor burns out. These failures have occurred when the transistors were operated outside their normal range, either by intent or by transient currents caused by high-voltage breakdown of the 25-kV extractor. Protecting zenors and fuses have eliminated most of these failures.

In a test to determine $H^+/(H_2^+ + H^+)$ current ratio, a magnetic field was applied across the beam to separate the ions. The split beam was incident on a fluorescent quartz plate for photographic study and was scanned across a wire for an electrical measurement. Both methods contain several doubtful corrections to convert image response to real current, but both indicate that the ratio is approximately 50%. More accurate measurements using thermocouples will be made on the 200-kV test stand. These same data have been used to obtain an electrical measurement of the angular spread of the beam at the axis. This spread, extrapolated to the entire beam, corresponds to a normalized emittance of 0.06 cm-mrad as compared to 0.045 cm-mrad measured optically.

Acknowledgments

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References

1. Beam transport system is presented elsewhere in these proceedings by Paul Allison and Ralph Stevens.
2. C. R. Emigh, Proceedings of the 1966 Linear Accelerator Conference, p. 398.

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† The cathode is the same as that described by H. Wroe, BNL AGS Division Technical Note No. 17, March 29, 1966.

DISCUSSION

(D. W. Mueller)

LEFEBVRE, SACLAY: Do you have a figure for the lifetime of your cathodes?

MUELLER, LASL: As I mentioned, the one cathode we used for this set of tests was run at the 6% duty factor for 1300 hours. We replaced the cathode at the end of 1300 hours simply to have a new cathode in for the run at a 12% duty factor. There is one more number that is significant; the cathode has been kept hot (25A normal heating current) for over 3000 hours. Actually we haven't reached the point where one of these has given out. They still have a good coating at the end of the test runs.

LEFEBVRE, SACLAY: Could you describe the pumping system used on your setup?

MUELLER, LASL: We are using a Vac-Ion pump, rated at 1000 liters/sec (sometimes called 1200 liters/sec). Hydrogen flows through the 0.040" diameter plasma aperture at the approximate rate of 2 to 3 cc-atm/min (with 100 microns actual pressure in back of the aperture). The pump still is operating normally after pumping hydrogen at this rate for over 2000 hours.

LEFEBVRE, SACLAY: I believe the current is in the order of 18 mA in the pump and the pump is actually quite warm.

MUELLER, LASL: Yes. We have used a one millimeter plasma-aperture to start with and this sometimes runs the pump close to the point of thermal runaway. This may occur after having had the system up to 1 atmosphere on dry nitrogen. After pumping hydrogen for half a day at approximately 2 cc-atm/min the pumping speed increases and the pump runs at a lower temperature.

BENJAMIN, BNL: In your last photograph, of the damage on the back of the aperture in the duoplasmatron, it appeared as if the damage was on one side of the aperture. Could this damage be due to mechanical misalignment?

MUELLER, LASL: The damage area is elliptical in the case shown. Our apertures are not so nicely centered as the Brookhaven apertures. At BNL, centering is done by gluing the intermediate electrode to the anode insulator before final machining of the centering rings. We simply center ours with an alignment gauge. I believe our centering is good to about 0.001" however.

CLARKE, BNL: Clarence Turner did quite a lot of work with an ion pump on a P.I.G. source and I think his work is quite clear on how to use an ion pump on a source using hydrogen.

The comment I would like to make is on the emittance pictures you showed. We have a similar rig out at the linac for doing similar studies. We found that with a similar current shape (highly peaked in the front) the emittance picture was dominated by this peak. As the front of the pulse was cut out, the emittance didn't change until we went beyond this peak.

MUELLER, LASL: I have noticed that by cutting the pulse length back to the first peak and increasing the exposure accordingly, we obtained a better emittance picture, in that the satellite lines were completely gone.

CURTIS, NAL: Is the divergence of your beam after the extractor due entirely to the lens action? Do you have a parallel beam in the gap or do you think there is a divergence due to plasma surface?

MUELLER, LASL: I expect that the divergence, in the present setup that we are working with, is due to our having only one electrode represented. We hope that we will have a nondivergent beam and something more manageable when we go to the 200 kV column. The answer is, yes, there is divergence but I hope the beam starts out plane parallel.

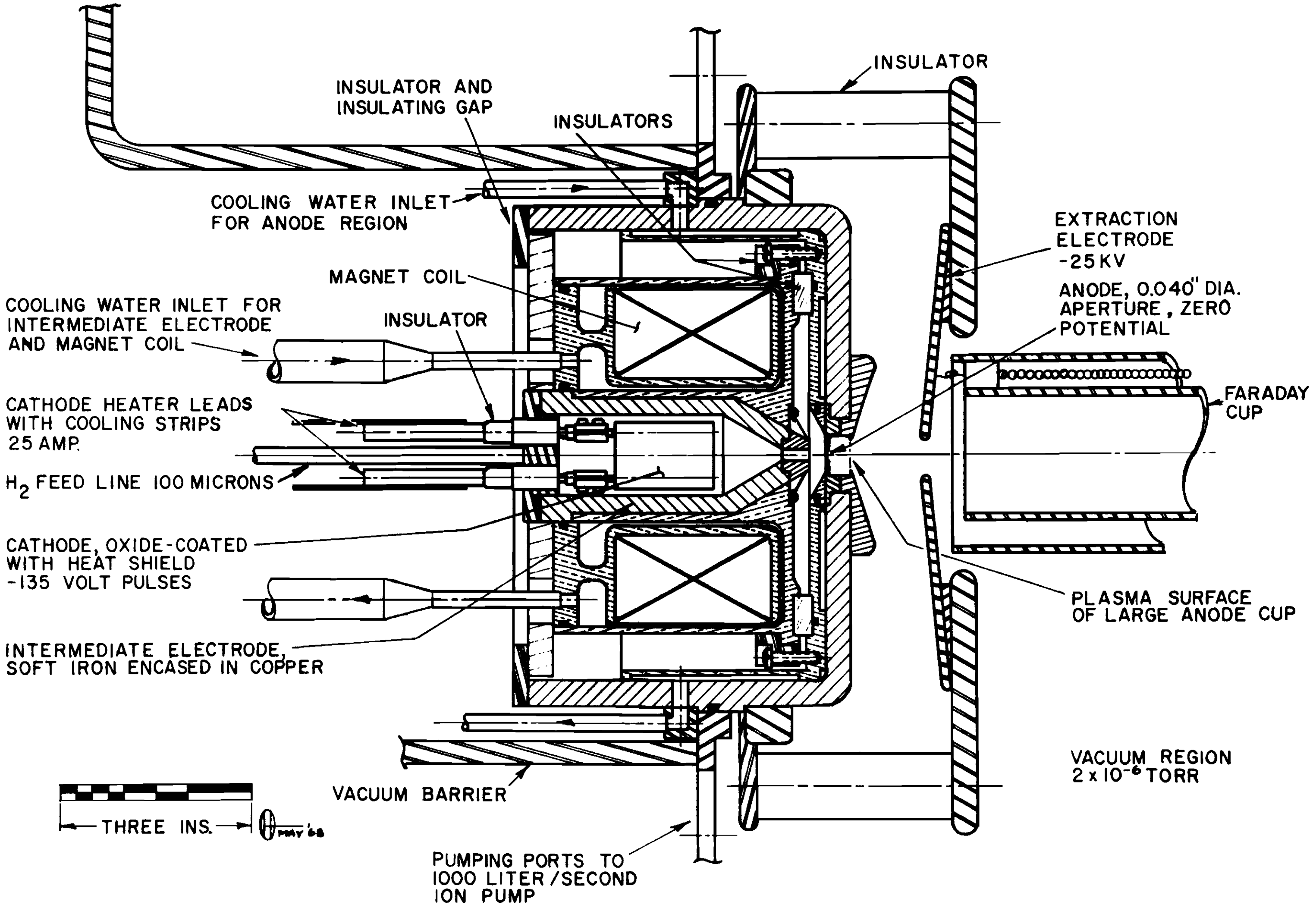

Fig. 1. Ion source detail.

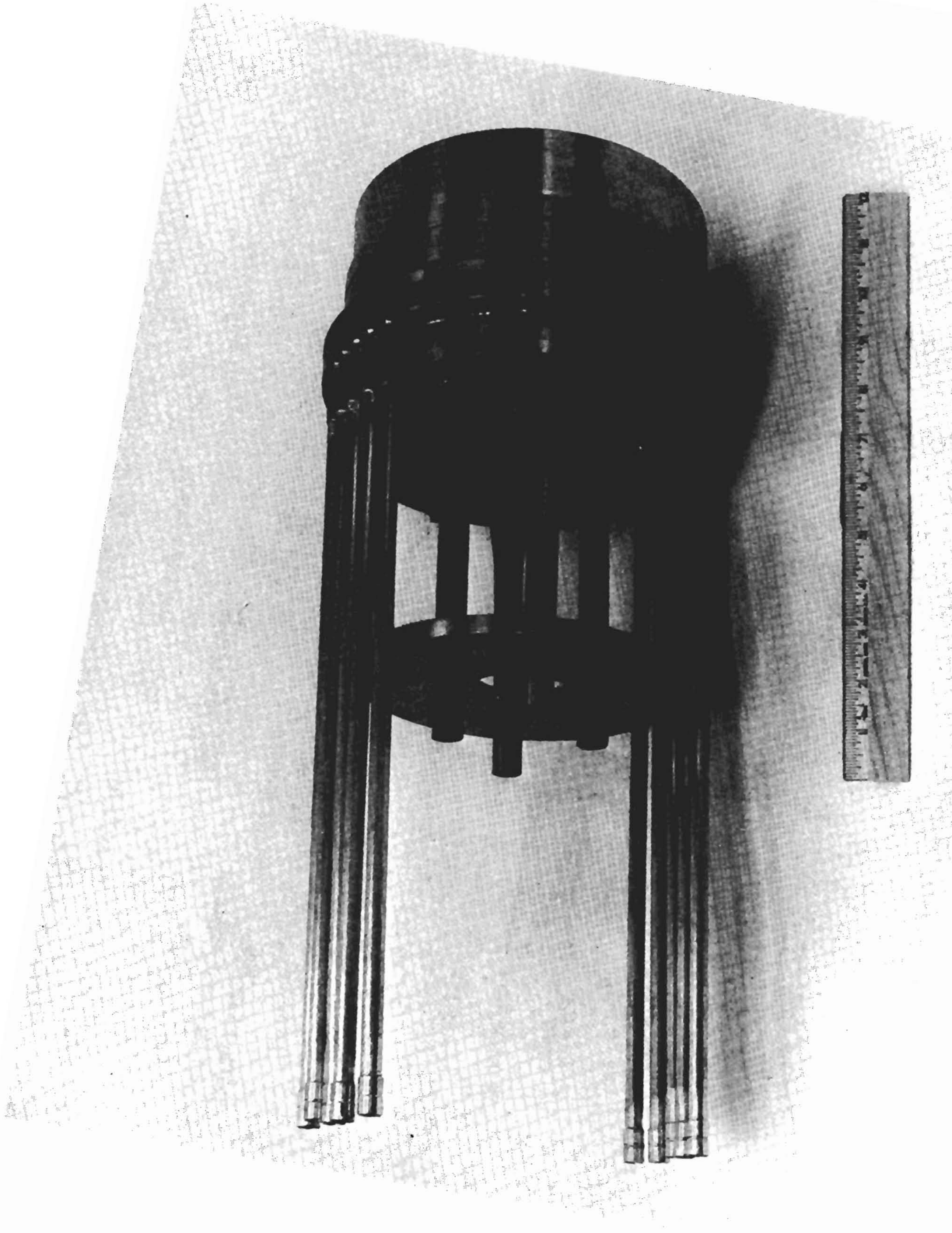

Fig. 2. Ion source photograph.

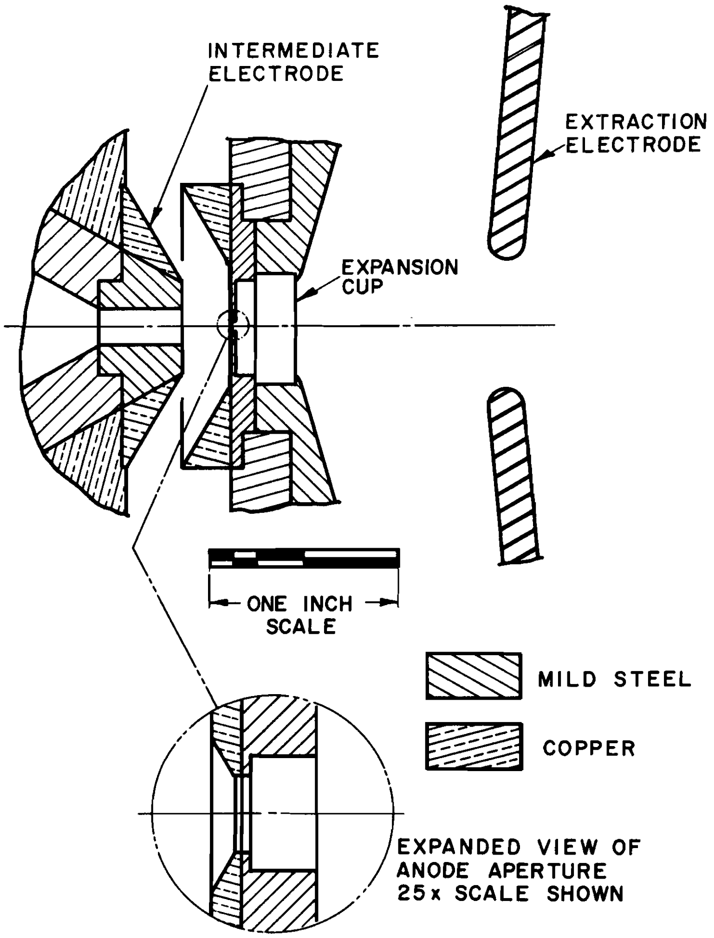

Fig. 3. Region around expansion cup and plasma aperture.

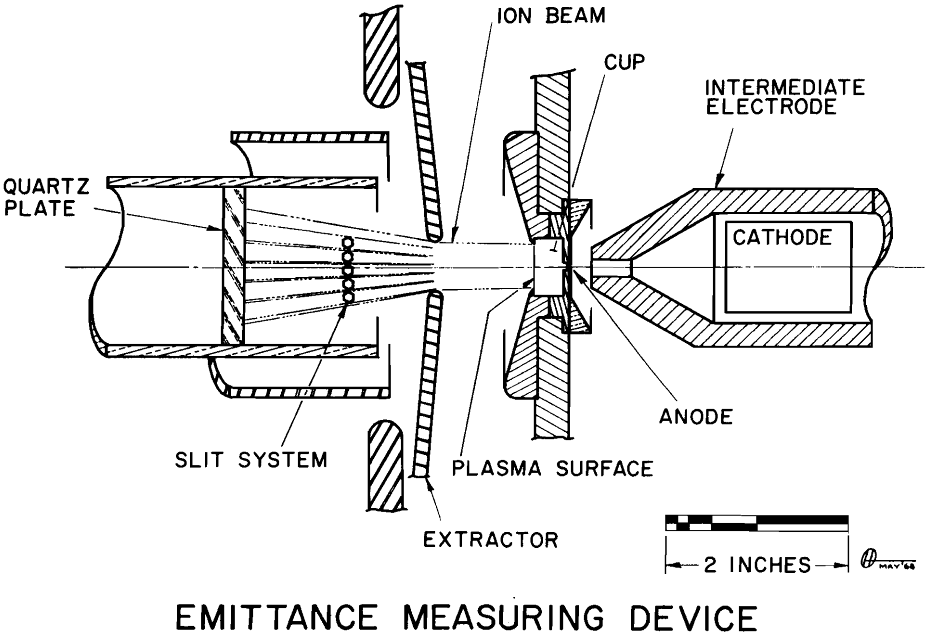

Fig. 4. Schematic of ion source, extraction electrode and hexagonal bar slit system.

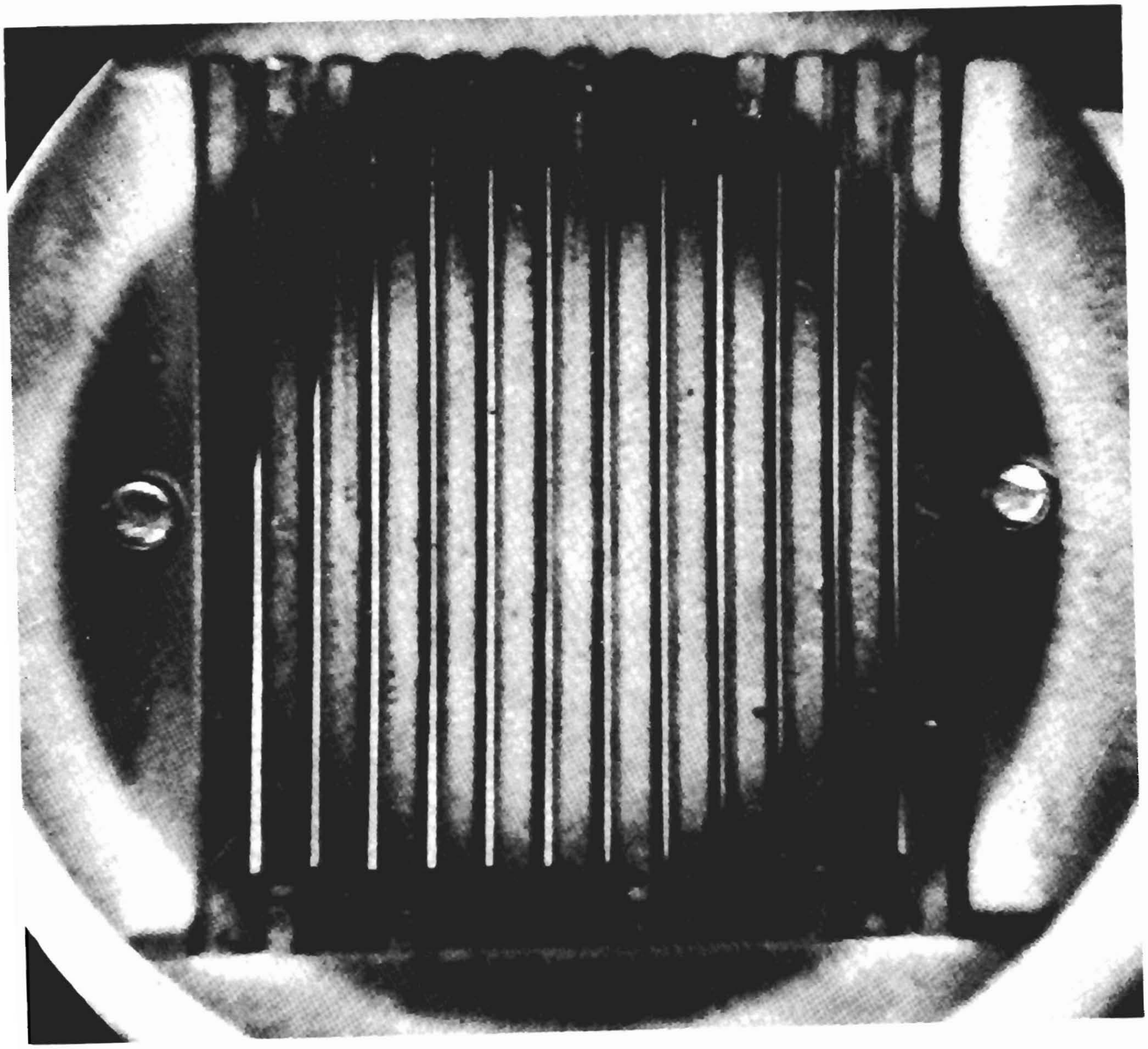

Fig. 5. Photograph of water-cooled hexagonal bar slit system.

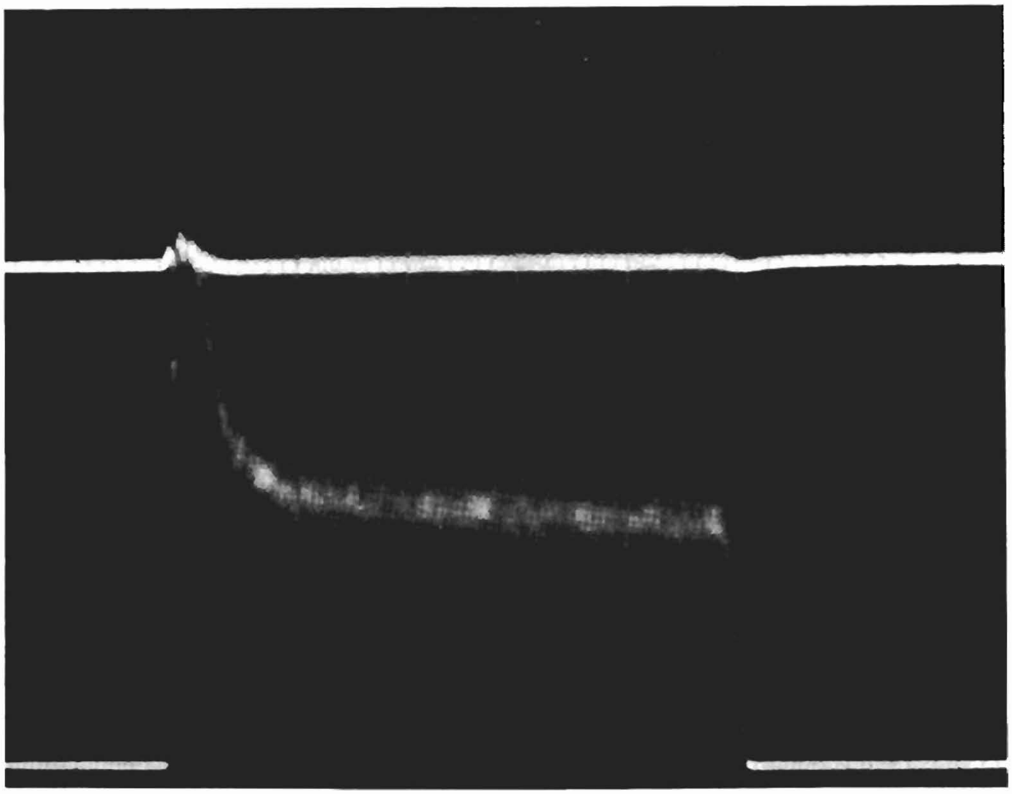

Fig. 6. Beam current, lower trace, and extractor current, upper trace. Beam current about 50 mA after first 50 μsec of 500 μsec.

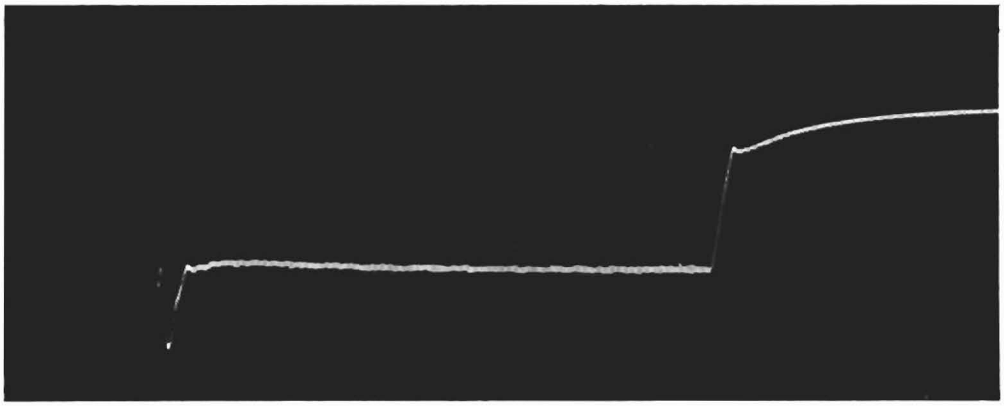

Fig. 7. Arc current, about 12 A after initial peak of 500 μsec pulse.

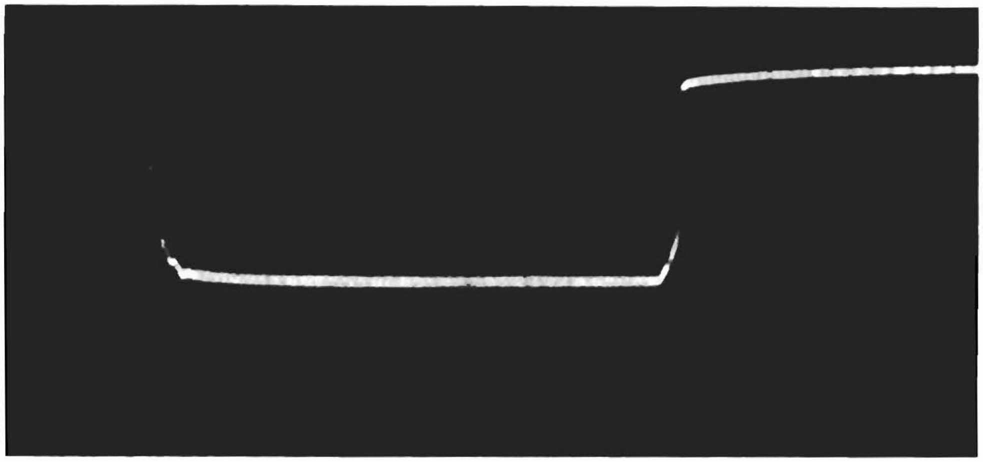

Fig. 8. Arc voltage, about 110 V on nearly flat top of 500 μsec pulse.

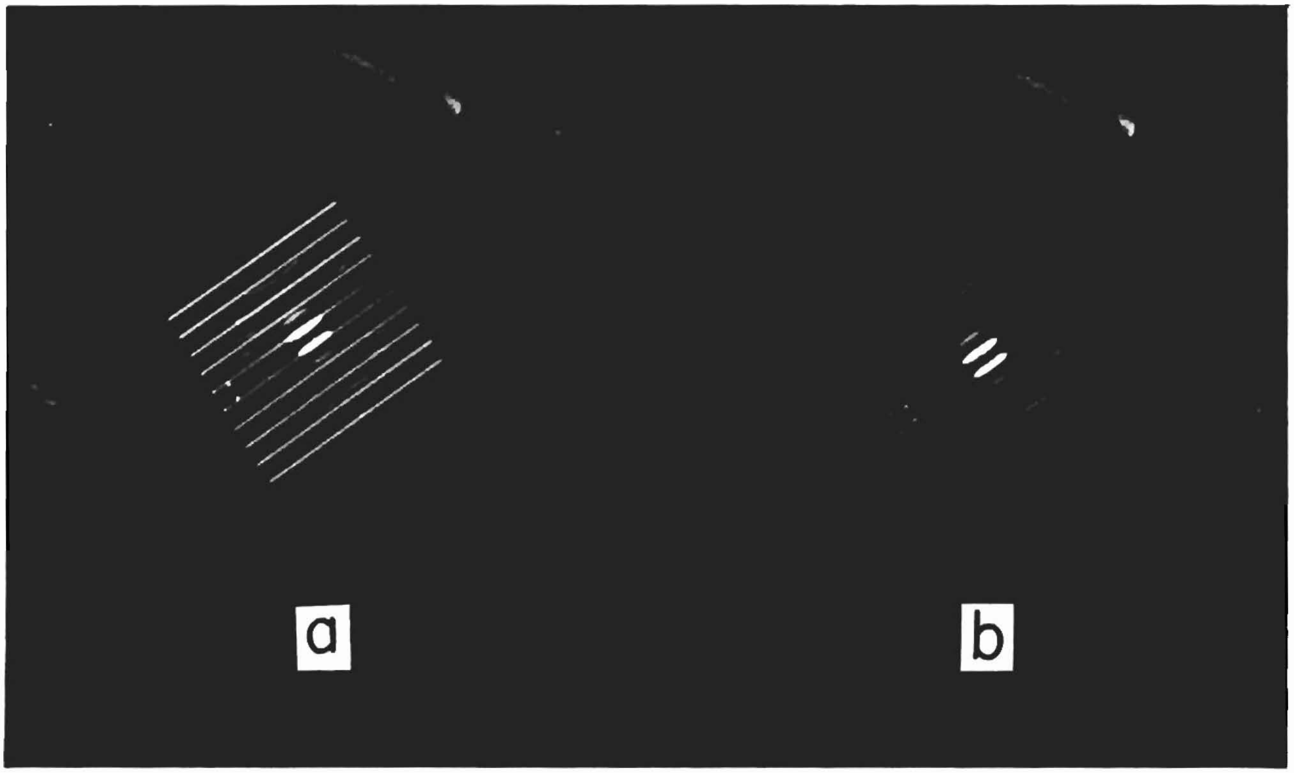

Fig. 9. (a) Beam emittance pattern on quartz plate.
(b) Background image caused by arc light, taken with extractor voltage off.

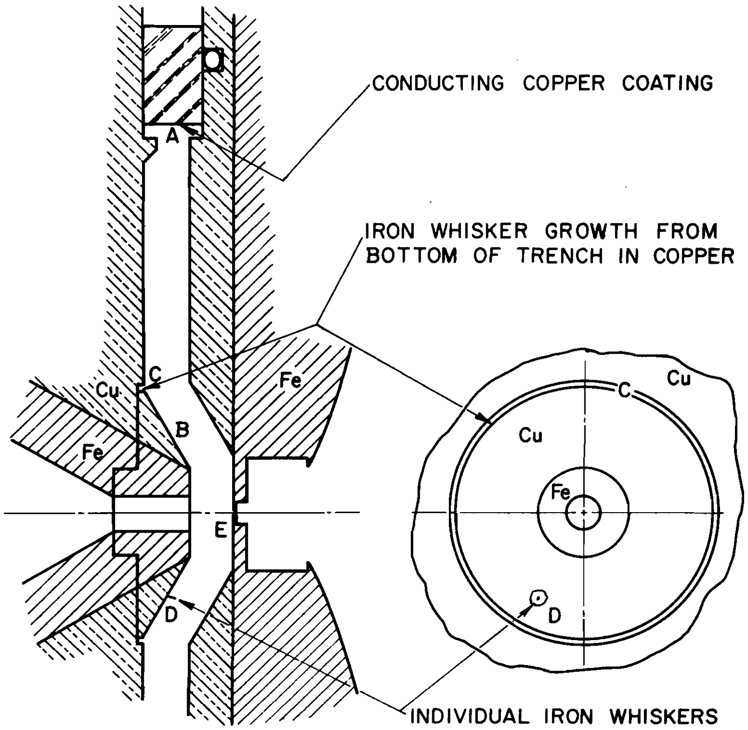

Fig.10. Locations of the iron whiskers growth and the conducting coating on the glass ring.

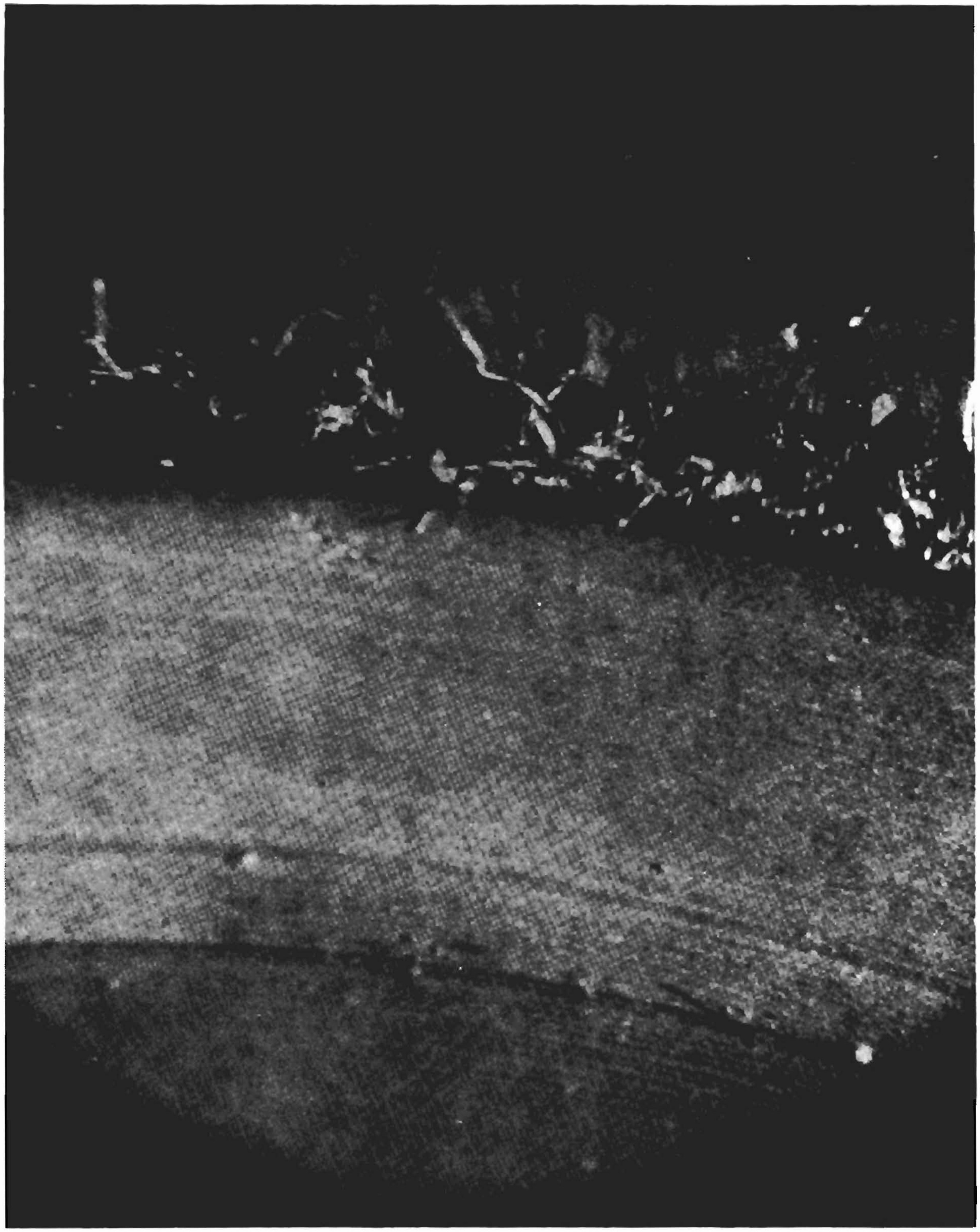

Fig.11. Photomicrograph of iron whisker growth found after sequence of long 6% and 12% duty factor life tests.

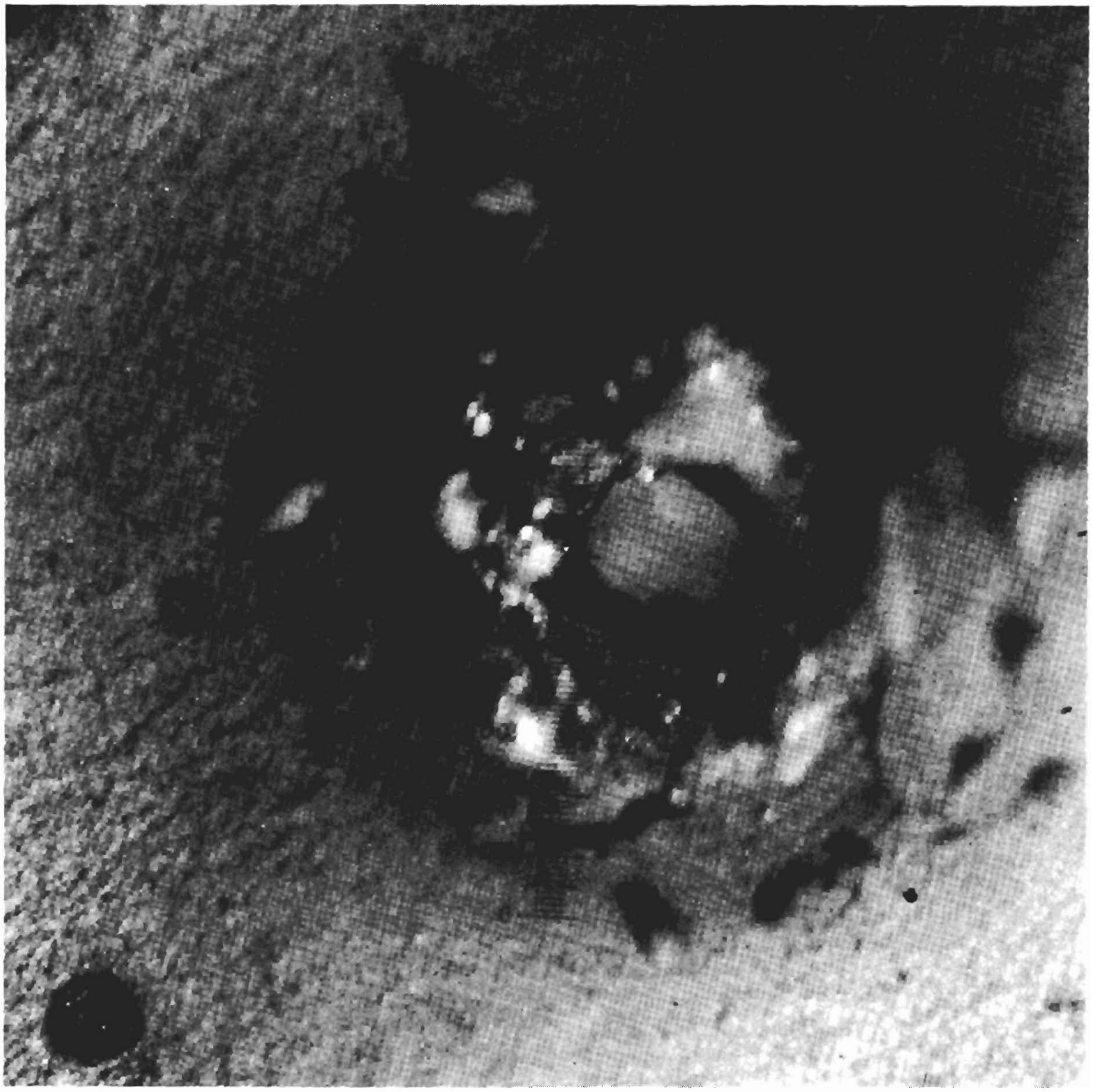

Fig.12. Photomicrograph of plasma aperture from the intermediate electrode side after 12% duty factor life test.