BROOKHAVEN'S RECENT PRE-ACCELERATOR PROGRESS*

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Introduction

The present linac pre-accelerator has been built to accelerate protons with intensities of milliamperes. In the present structure with a pre-focussing lens and an accelerating field of 6 kV/cm a maximum transparency of around 100 mA can be obtained. The performance of the beam, characterised by its brightness measured at 750 kV, is around 10^8 mA/cm^2 rad^2, suggesting a minimum dilution in the tube of 20.[1] This loss in brightness can mainly be caused by non-linear focussing in lens and accelerating regions[2].

A careful redesign of the conventional low-gradient column can improve the brightness. A second possibility is a high gradient tube without pre-focussing. Theoretically the second solution is very attractive. However, it involves a high voltage technology just in its exploration status.

The new preaccelerator will be discussed in two sections:

1. The ion source and beam performances measured at extractor voltage (~40 kV).

2. The accelerating tube, high voltage behavior and beam performances measured at 750 kV.

1. The Ion Source and its Performance for Large Expansion Cups

The quality of a beam is determined by its intensity, emittance, density distribution and stability. It is not so much an art to increase the intensity to several hundreds of milliamperes. It is, however, difficult to keep the other qualities within reasonable limits.

The space charge limited current J (mA/cm^2) extracted from an emitter on a distance d (cm) from the extractor electrode at potential V (volts) is:

$$J = 5.6 \times 10^{-5}\, V^{3/2}/d^2 \qquad (1)$$

The emittance measured downstream from the extractor is determined by the thermal motion of the ions in the plasma and the geometry of the expansion cup and extraction region. Our requirement for a parallel beam at the location of the extractor suggests a Pierce potential distribution compensating for space charge in a homogeneous beam:

$$V = V_o \left(\frac{z}{d}\right)^{4/3} \qquad (2)$$

*Work performed under the auspices of U.S. AEC.

These formulas determined a second design of the extraction region. It should be mentioned that extensive studies with a solenoid around the extractor to obtain a means for extra beam focussing at a fixed extractor voltage always showed distorted emittances.

Oscillations in the megacycle range are the instabilities observed with the current detector. Beside the pressure, they are much related to the anode aperture and the size of the expansion cup. For instance a complete stable beam was observed for the 4 mm expansion cup diameter. Also the geometry used on the arc side of the anode is of importance in the stability of the beam, but it is not yet clear where it sticks.

The above mentioned considerations and many preliminary runs finally resulted in an experimental program which includes intensity, density, and emittance measurements for expansion cups between ∅ 4 mm up to ∅ 25 mm. For this paper we report the first part of this program obtained by D.W. Mueller‡ and the author for optimum performance of ∅ 4, 8 and 12 mm cups.

The ion source is shown in Fig. 1.

The intensity was measured by a calorimeter[3]. The emittances were obtained in two steps: 1) by visual observation of the pattern of the usual slit-quartz plate technique 2) by a slit-copy paper method. The influence of space charge on the actual emittance values[4] has been calculated, supposing a homogeneous density distribution. For the larger diameter beams (> 10 mm) and the proper geometry choice the correction is < 10%. The distance between the .05 mm slits and copy paper is 2.5 cm; except for the last case this distance was 5 cm and .1 mm slits.

The emittances and corresponding extraction geometries resulting in a non-aberrant or almost non-aberrant beam are shown in Fig. 2, 3, and 4. With the largest cup (∅ 12 mm) one can still observe the second image which is extremely low in intensity. The experimental results are gathered in Table 1.

The intensities measured for the two smaller expansion cups are in agreement with the space charge limited current and a plasma boundary just inside the expansion chamber. With the ∅ 12 mm cup the measured beam intensity is much lower than the theoretical value.

We originally started with larger distances between extractor and expansion chamber to obtain Pierce geometries, however, aberrant free emittances (single straight slit images) and

‡On leave from Los Alamos Scientific Laboratory.

higher intensities were obtained for shorter distances and improved beam output. The dense and narrow slit images in the center and the wider weaker images from the outer slits (so there is a non-uniform beam) explain the higher extractor voltages for space charge compensation in the beam center. The density distribution with the ∅ 8 mm cup was more uniform, so that the extraction voltage could be lower.

The absolute values of the brightness are all of the same order of magnitude viz., 10^{10} mA/cm^2 rad^2. This value for large expansion cups (≥ ∅ 4 mm) is an order of magnitude better than those obtained by H. Wroe[4] for the ∅ 4 mm cup; this is caused by suppression of the lens aberrations. The results obtained by J. Faure[2] for aberrant free low intensity beams correspond well with our present results. Figure 12 is a plot of the above mentioned results.

In recent years brilliances measured at extraction voltage have been improved. However, in most cases no corresponding improvement has been obtained after the electrostatic accelerator tube. So it is more realistic to rely on figures quoted after the accelerating column.

2. Quintet Gap Accelerating Structure

The basic design of this column has been described previously by A. van Steenbergen[5]. The potential distribution follows the Pierce equation for rectilinear beam flow. For a design density of 100 mA/cm^2 the potential distribution is:

$$V_z = 1.5 \times 10^4 \, z^{4/3} \qquad (3)$$

The field within the boundary of the 1-in. beam diameter has been obtained by subdivision of the accelerating gap of 16.5 cm into five sections, positioning thin titanium electrodes (3 mm) at 50, 150, 300, 450, 600 and 750 kV with gap distances from 3.3 cm to 2.8 cm; the gradient increases from 30 kV/cm to 53 kV/cm. The titanium alloy is only used in the high gradient regions; the remaining part of the electrodes is s.s. 304.

The 1 meter long vacuum chamber is subdivided into 15 sections of ceramic rings separated by 3 mm thick AL spacers, joined together with epoxy. The joints successfully tested on small ceramic rings with I.D. of 16 cm failed on the large rings of 62 cm I.D. Sand blasting and proper cleaning procedures have already improved the joints considerably, but the bond is not yet perfect.

The vacuum chamber is double-walled in which SF_6 circulates under a slight over-pressure, improving the breakdown stress by a factor 2.5. The voltage divider resistances (15 x 360 MΩ encapsuled in BN_3 filled epoxy bananas) and the spark gaps are installed in this section. The outside wall of the chamber is formed by 15 profiled epoxy rings (O.D. 132 cm), sealed with rubber O-rings.

The behavior of a high gradient column depends on the materials, their polishing and cleaning procedures.

Table II summarizes the materials used inside the vacuum.

For polishing the titanium electrodes, aluminum oxide sandpaper and diamond paste has been applied for a 2 microinch finish.

Regular cleaning procedures have been followed degreasing with vythane and drying with alcohol; the ceramic rings got an extra wash with alconox and rinse with hot water before drying with alcohol.

Figure 5 shows a drawing of the new preaccelerator as a test setup. Figure 6 is the physical appearance of the column.

2.1. Column Behavior Without Beam

A schematic of the electronic equipment is shown in Fig. 7.

During conditioning the following parameters were recorded: 1) high voltage 2) pressure 3) cathode current measured on the last electrode and including corona currents 4) humidity 5) temperature. The humidity control was essential to obtain 750 kV across the epoxy rings. Without this control the column could not hold higher voltages than 650 kV.

Figure 8 shows a record of the first 40 hours of a 10-day conditioning run. The speed of the conditioning was determined by the amplitude of the micro-discharges superimposed on the cathode current signal; the breakdown rate was kept lower than 10 per hour. The tube operated 150 hours at 750 kV; the breakdown rate diminished to 2 sparks per hour. After this period the mild steel source anode was melted on its downstream surface; this is probably due to a continuous flow of backstreaming electrons originated from field emission. The m.s. has been replaced by a molybdenum insert. There are also melting spots on the restricted extractor opening (see Fig. 9), but this melting can be caused by breakdowns.

The present column is much less "clean" than the single gap tube of CERN[6]. Though protected by the corona rings and shape of the electrode holders epoxy joints are exposed to the vacuum and as mentioned above normal cleaning procedures have been used.

At 600 kV the "deconditioning rate"[6] which is a possible indication of the cleanliness of the system, is lower than 10 kV/h and a sparking rate lower than one per two hours. The deconditioning rate is difficult to measure above 650 kV, however, the breakdown rate is low (two per hour) after a short conditioning period at 750 kV; one can expect improved figures after longer conditioning.

2.2. Column Behavior with Beam

So far the high voltage behavior of the tube (breakdown rate) has not been influenced by the injection of a 100 mA beam. Bad focussing will immediately be observed by pickup from the electron repeller located after the sixth electrode, as well as by the amplitude of the micro-discharges.

Fig. 10 illustrates a 60 mA beam pattern obtained from a slotted plate located after the 750 kV low gradient machine and a pattern of the same beam current after the high gradient machine; both currents were obtained from the same duoplasmatron source and measured with identical emittance detectors. It should be mentioned that the picture from the new column was taken 140 cm behind the sixth electrode without extra focussing; so at the column exit the beam size is smaller than 7 mm.

The emittances for both tubes are given in Fig. 11. One observes a slight aberration for the high gradient column. The brightness of the 60 mA beam is 3.3 x 10^9 instead of 1.9 x 10^8 mA/ $cm^2\,rad^2$ for the present preinjector, an improvement of at least a factor of 16.

Fig. 13 is a review of recent emittance and brightness results measured at high energies (> 100 keV).

The dilution factor (see Introduction) in the high gradient accelerating tube has been improved considerably compared with the conventional column. Though we have not a clear-cut measurement available, there is a strong indication that, for our present intensities, emittances will be preserved within the accuracy of the measurements.

Acknowledgements

Beside all members of the AGS Division who contributed to this column progress I wish specifically to express my thanks to A. van Steenbergen, V.J. Buchanan, R. Damm and A. Soukas, who initiated the project under leadership of A. van Steenbergen.

Many thanks to the invaluable contribution of our more or less permanent staff: R.A. Abbott, R. Amari, R. Boley, R.L. Clipperton, V. Kovarik, R.L. Lane, R.E. Lockey, S.A. Larson, and W. Schneider.

I should like to thank J. Huguenin of CERN for our private exchange of views and H. Wroe of Rutherford Laboratory, who triggered the presented ion-source results by his stimulating experiments at BNL.

References

[1] H. Wroe, "Some emittance measurements on the AGS preinjector with the duoplasmatron ion source", BNL Accelerator Dept. Internal Report (AGS) HW-3, 1966.

[2] J. Faure, "Etude theorique et experimentale de la focalisation des ions afin d'améliorer la brillance du faisceau ionique par la suppression des causes d'aberration, L'Université de Paris, These 1966.

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[4] H. Wroe, "Some measurements of the emittance of the output beam of the AGS duoplasmatron ion source", BNL Accelerator Dept. Internal Report (AGS) HW-2, 1966.

[5] A. van Steenbergen, "Recent Developments in High Intensity Ion Beam Production and Pre-Acceleration", Proc. Particle Accelerator Conference, Wash., D.C., March 1965, IEEE Transaction on Nuclear Science, June, 1965.

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DISCUSSION

TH. SLUYTERS, BNL

HENDRICKS, Univ. of Minnesota: I see you have a very nice built-in palladium leak system. Could you give me some details on that?

SLUYTERS: It is a commercial vendor palladium leak. We have no extra control. Our pressure stays constant for many days. It is, perhaps, advisable to have a closed-loop system to keep the source pressure constant.

HENDRICKS: How do you replace a tube when it is necessary?

SLUYTERS: We have never replaced a tube.

HENDRICKS: What does the pressure run on the high pressure side?

SLUYTERS: 20 psig.

CURTIS, MURA: Do you ascribe the aberrations in the beam emittance for the old column to the focusing section of the column?

SLUYTERS: We ascribe them to both the focusing section and to the column itself.

CURTIS: Another question: I couldn't see the numbers very well on your slide where you presented beam currents from the source in the range of 100 and 400 mA. The normalized emittance appeared to be roughly constant, is that true?

SLUYTERS: We need more measurements before we can really say that this remains constant.

ALLISON, LRL: Keeping the beam small as it goes down the column is extremely important. When we designed the Bevatron Preinjector, we had a 4-electrode matching lens, and we designed it so that the beam radius increases to take care of space charge. We have measured that lens at 100 kV and can pass 300 mA through it. Then, when we put that on the column, there is also a big beam in the column because the column is linear. There is a factor of three blowup going from the 100-K point to the 480-K point, caused, I believe, by the large beam coming near the edge of the lens apertures.

SLUYTERS: We have focusing after the column by a pulsed solenoid, which reaches 50,000 G/cm. We don't know if this really is a practical device because it can damage the column by mechanical shocks. It is very likely that we will go to a triplet, which can have a disturbing effect on the beam performance.

HUBBARD, LRL: I've heard several references to the cleanliness of the work at CERN compared to some of the other work. What do they do besides keep the epoxy out of the column vacuum? What are the cleanliness procedures?

SLUYTERS: CERN uses mercury pumps with many precautions for the cooling baffles. We use evaporion pumps which are very clean. The cleaning procedures are described in the paper.

TABLE I

ION SOURCE RESULTS FOR EXPANSION CUPS WITH INNER DIAMETERS OF 4, 8, AND 12 mm AND ANODE HOLE OF Ø 1 mm

Extraction geometry	Anode voltage (volts)	Magnet current (Amp.)	Pressure (gauge) (10^{-3} mm)	Discharge current (Amp.)	Extraction voltage (kV)	Beam Intensity (I) (mA)	Space Charge limited current (mA)	Phase Space area (A) (cm-mrad)	$\epsilon_2 = \frac{A\beta\gamma}{\pi}$ (cm-mrad)	$B_2 = \frac{I.10^6}{\frac{1}{2}\pi^2\epsilon_2^2}$ (mA/cm^2 rad^2)
Fig. 2 expansion cup Ø 4	160	~ .1	260	35	43	250	228	14	4.5×10^{-2}	2.4×10^{10}
Fig. 3 expansion cup Ø 8	190	< .1	300	57	21	190	165	12.8	2.7×10^{-2} 4.2×10^{-2}	5.30×10^{10} 2.0×10^{10}
Fig. 4 expansion cup Ø 12	140	~ .1	250	25	42.5	400	655	10.8	3.4×10^{-2}	6.8×10^{10}

TABLE II

MATERIALS USED INSIDE THE VACUUM

OF THE HIGH GRADIENT COLUMN

1. Titanium electrodes (7 AL, 4 Mo)
2. Stainless steel 304 electrode holders and bellows
3. Aluminium (6061T6) cans, spacers, corona rings, electrode fixtures, vacuum valve
4. Epoxy joints (Wig, Emerson & Cummings 24 LV)
5. Ceramic insulators (94% Al_2O_3)
6. Poly-ethylene feed through
7. Copper solenoid with
8. Teflon spacers
9. Brass emittance box
10. Light greased viton O-rings

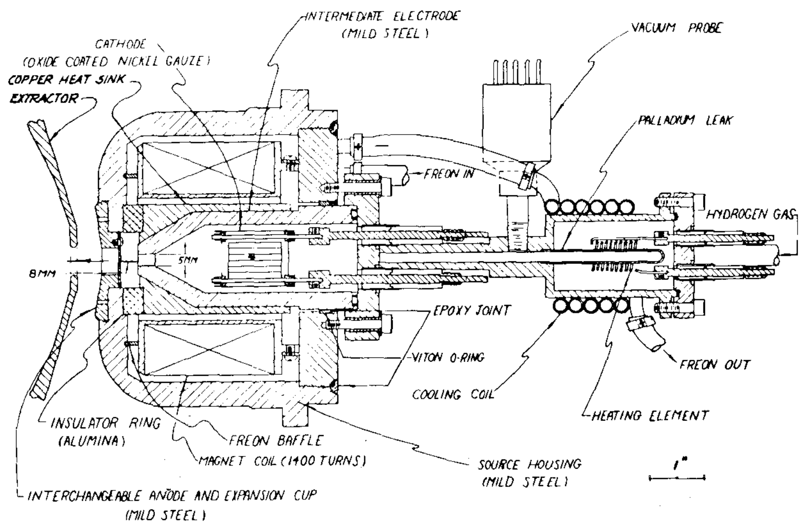

Fig. 1. The duoplasmatron ion source and extractor.

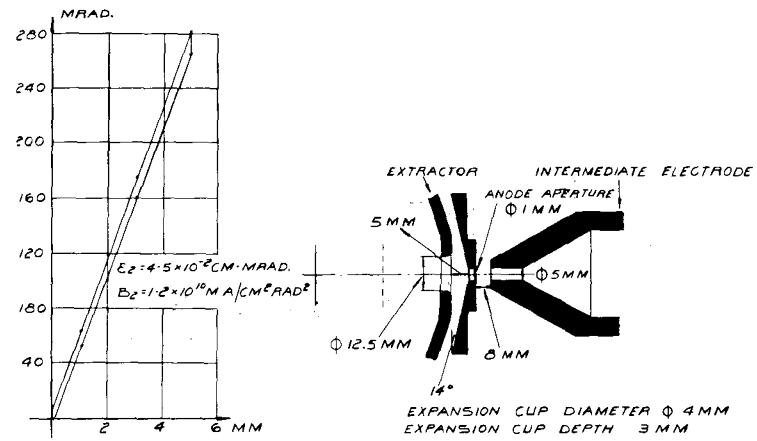

Fig. 2. The emittance and corresponding extraction geometries for expansion cup $\phi 4$.

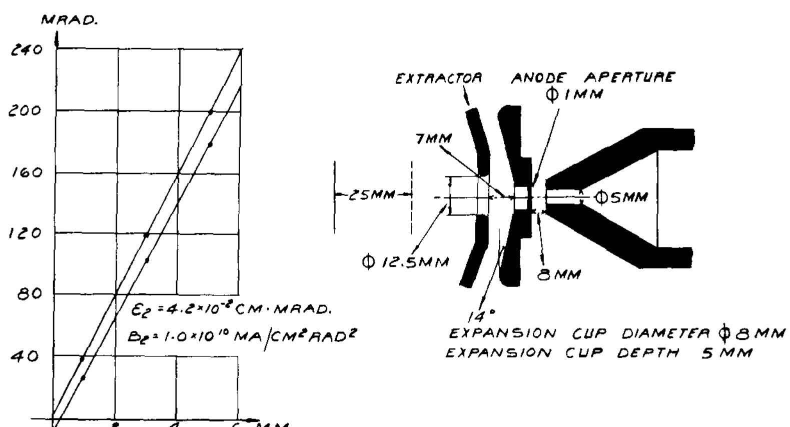

Fig. 3. The emittance and corresponding extraction geometries for expansion cup $\phi 8$.

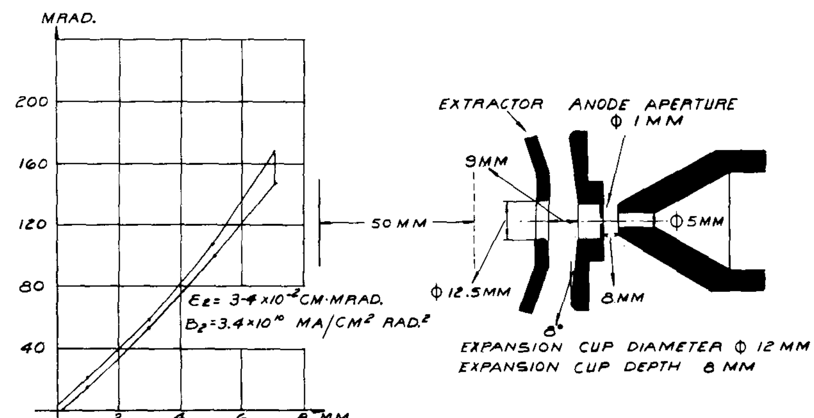

Fig. 4. The emittance and corresponding extraction geometries for expansion cup $\phi 12$.

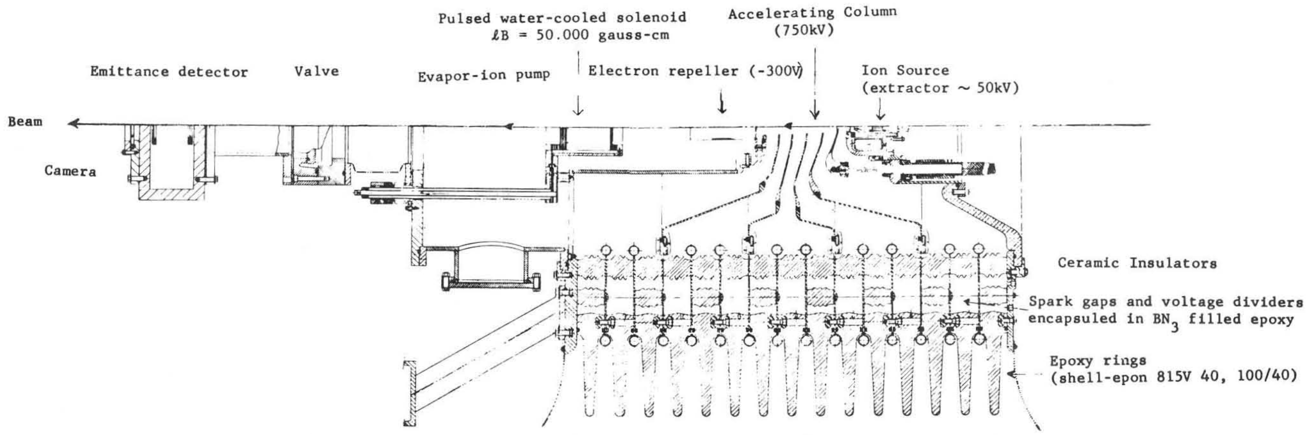

Fig. 5. The 750 kV high gradient pre-accelerator test setup.

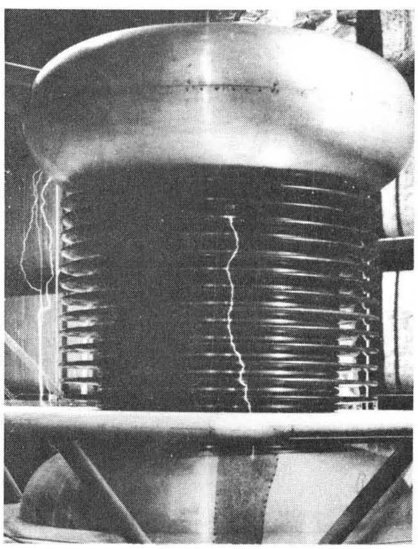

Fig. 6. The high gradient tube without humidity control.

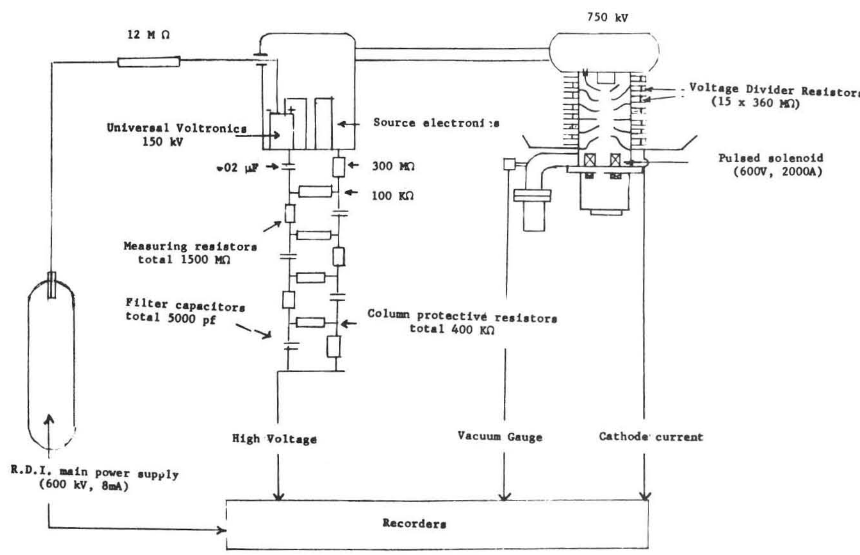

Fig. 7. Schematic of the test equipment.

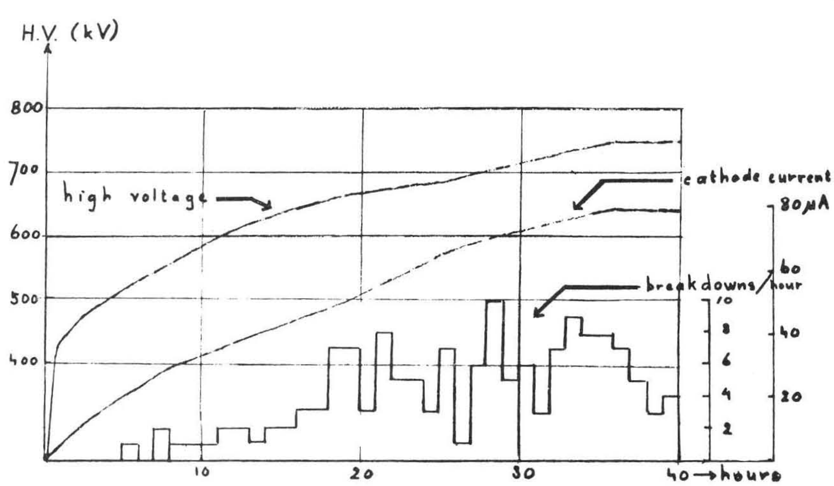

Fig. 8. A conditioning run of the high gradient tube.

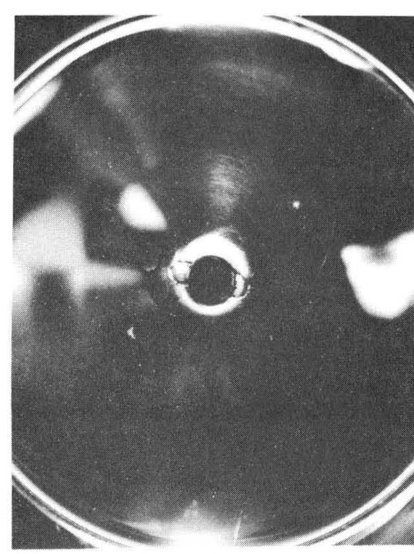

Fig. 9. Anode surface of extractor.

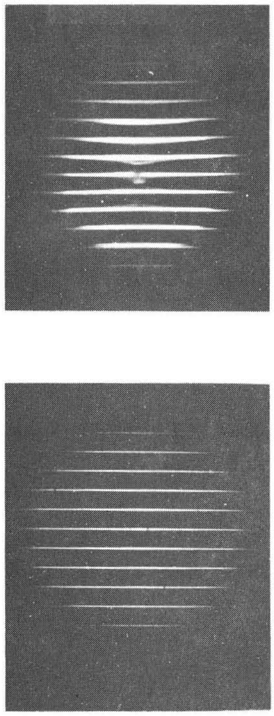

Fig. 10. Emittance at 740 kV for low (top) and high gradient column for 60 mA.

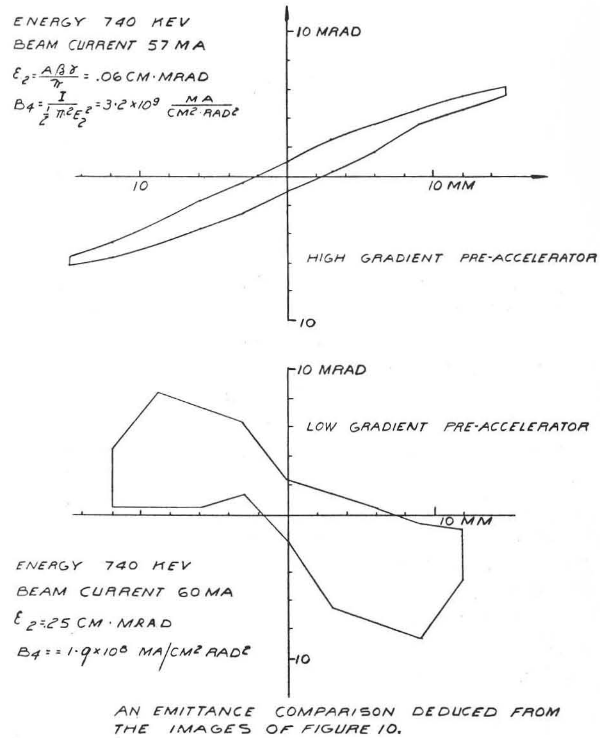

Fig. 11. An emittance comparison deduced from the images of Fig. 10.

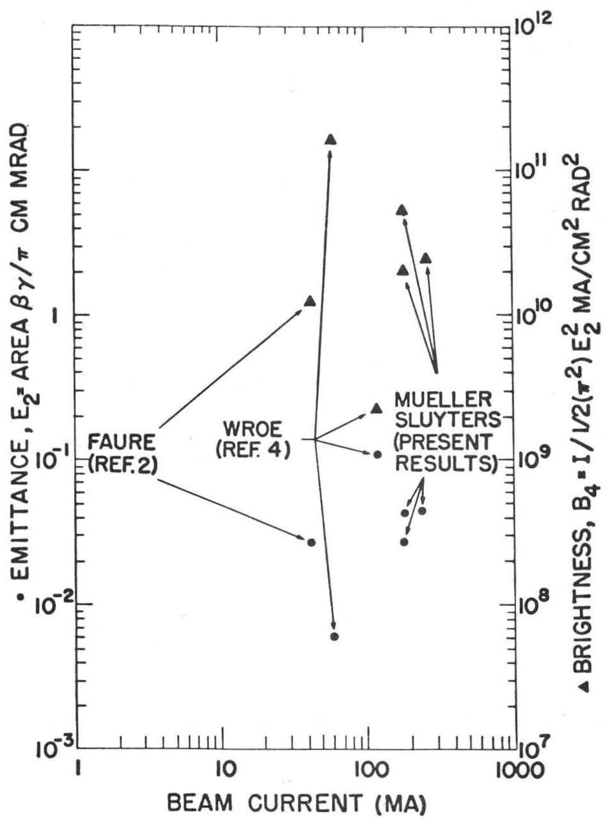

Fig. 12. Normalized emittance and brightness against beam current, measured at low energies (<100 keV).

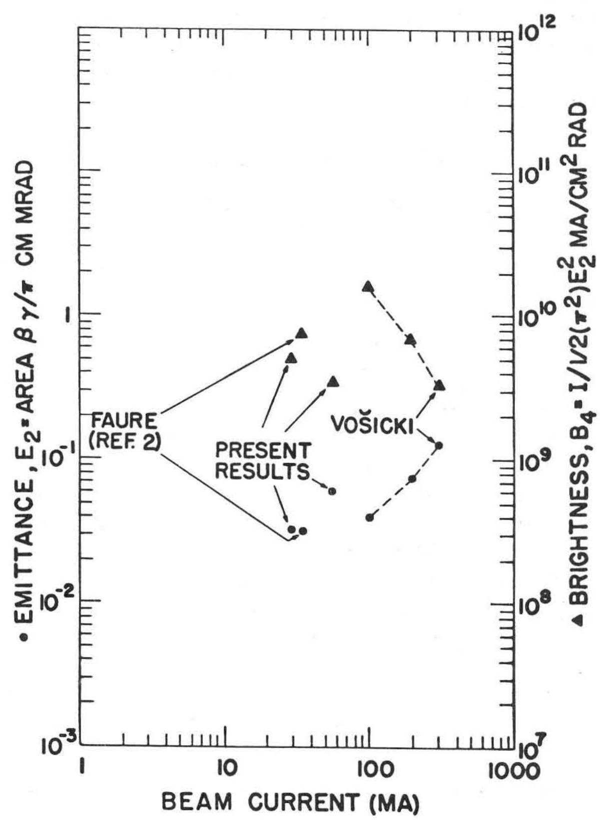

Fig. 13. Normalized emittance and brightness against beam current, measured at high energies (>100 keV).