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THE DUOPLASMATRON SOURCE FOR THE CERN-PS LINAC

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Introduction

In order to improve the performance of the CERN-PS, the development of the DP ion source and associated high gradient column was undertaken. This paper describes the conception, construction of the DP and the results obtained during the first few months of operation.

Design Conception

Requirements for a proton source for the PS Linac were as follows:

a) proton current of the order of 0.5 A;

b) low emittance, <0.55 cm mrad norm;

c) stability and reliability.

a) The high beam intensity does not present a great problem. It can be obtained by more efficient operation (greater arc current, higher H_2 pressure, better plasma transport to the emitting surface) and by scaling up the source.

b) The magnitude of emittance depends upon

ion temperature (transversal momentum of protons),

form of the extraction surface

aberration in beam optics.

The ion temperature is determined by the nature of discharge itself and the type of the source, and one cannot do much about it.

The form of the plasma surface from which ions are extracted is governed by the form of the plasma extraction cup, the extraction electrode and extraction voltage, on the one hand, and by the plasma density distribution on the other.

Distorted plasma surfaces which give rise to warped emittances have to be avoided. The exact form (plane or spheric) depends upon the subsequent optical requirements of the column. For a parallel beam and constant plasma density, Pierce geometry (67.5°) would be indicated, but as the plasma density usually falls off towards bigger radii, a steeper cone in the plasma cup is necessary. Some means of governing the plasma density distribution (e.g. axial magnetic field) would be helpful in adjusting the source for minimum emittance.

In order to avoid aberrations due to subsequent matching lenses, a high gradient column is used, but one finds that there exist some regions (extraction grid meshes, anode screen, output hole) which have a lens action. Lens action of the openings in the extraction grid is small if the electrical field intensity is similar on both sides of the grid. Aberration of the other two can be minimised by making the lens several times bigger than the beam diameter so that only the central linear part of the lens is used. At the beginning of the DP and short column project, the alternative was to use either a Pierce accelerating structure or to use a simple parallel gap structure. It was decided in favour of the latter, for several reasons: easier fabrication because of the smaller number of intermediate electrodes, and the fact that a Pierce structure, once chosen, gives the right field shape for one selected current only. This second point appeared to lead to a too rigid design. If the current coming from the source is too small, aberrations occur; if too big, intermediate electrodes can be struck by protons disturbing the potential distribution, since the current in the potential divider resistor chain is usually much smaller than the proton current. High voltage breakdown problems are also more severe if the Pierce solution is adopted. This can be illustrated by the following example: supposing the beam diameter to be 20 mm (which is required by the existing beam transport system to the Linac), the proton current 0.6 A and the accelerating potential 540 kV, one gets the necessary length of the Pierce structure

$$l = \sqrt{\frac{4\epsilon_0}{9}\sqrt{\frac{2e}{m}}\frac{U^{3/2}}{Ji}} = 60 \text{ mm}$$

where = permeability of vacuum
= elementary charge
m = mass of the ion
U = accelerating voltage
Ji = ion current density.

The maximum field strength would be 120 kV/cm. It would be rather difficult to maintain this field strength in the column without sparking under normal conditions of operation.

A constant gradient column chosen has not the rectilinear flow qualities and freedom of aberrations of a Pierce structure, but does permit acceleration of proton beams of various intensities. At the same time it features lower electrical field strength, 45.5 kV/cm in the case of the CERN column, which facilitates its practical realisation.

c) Stability of a source is affected by the stability of power supplies, stability of the cathode emission and of plasma oscillations.

A source should need no servicing, at least during a normal run which, in the case of the CERN PS, is about two weeks. Cathode life appeared to be the most serious difficulty at the beginning of the project.

Description of the Source

A duoplasmatron source was chosen in order to satisfy the requirements of high current output (Ref. 1). Plasma expansion cup (Refs. 2,3,4,5) allows lower extraction voltages to be used. Cylindrical plasma expansion cup (PEC) (Refs. 6,8) does not permit the formation of a smooth plasma surface and the emittance of the beam obtained was rather big and warped (Fig. 1). Following the idea of Rose (Ref. 7), a cone was fitted to the expansion cup, in order to shape the extraction field so that a smooth plasma boundary could be formed. Different inclinations of the conical part of the cup were tried (10°, 15° and 45° between the axis and the cone). Bigger angles have not yet been tried.

The best inclination of the cone should be calculated from the plasma density distribution at the supposed plasma boundary. The lack of measurements on plasma density distribution in duoplasmatrons (few measurements have been published on other types of sources, Refs. 3,9,10,11) necessitated the installation of an axial magnetic field which could influence the plasma density and its distribution. It was felt that it would be possible to "match", in this way, the plasma density distribution to an otherwise not perfect cone. Measurements have shown that for a given extraction geometry and extraction field intensity, keeping other parameters of the source constant, a magnetic field intensity and polarity can be found for which the emittance is minimum (Ref. 13, Fig. 2). The same set of measurements corroborated the results of different authors that the magnetic field acts adversely on the plasma boundary and gives rise to a contorted emittance (Refs. 8,9,11,12). This was true even for that magnetic field for which the emittance had a minimal value. A shielded coil situated near the anode of the duoplasmatron was therefore chosen. Its magnetic field falls off very rapidly towards the plasma boundary and apparently does not distort it (Ref. 13, Fig. 3). A cone with the 45° angle (between axis and the cone edge) was installed. In spite of the overall satisfactory emittance of the CERN PS ion source, it is impossible to suppress completely the "secondary spectrum" (part of the beam which branches off the main portion of the beam in the phase plane) over all radii. Perfect overlapping of the two "spectra" is possible either at the axis or towards the periphery of the beam (Fig. 4). Those measurements indicate that a steeper ($45^\circ < \gamma < 67.5^\circ$) is needed for a better initial focusing of the beam (Ref. 12).

The extraction electrode is fitted with a grid in order to avoid a beam spread-out before entering into the accelerating gap. A compromise between the transparency, heat resistance and "scattering" (aberrations on the tiny electrostatic lenses formed by the grid meshes) leads to the choice of 0.1 mm diameter molybdenum wire grid, with a mesh size of 1 x 1 mm. The distance between the plasma boundary and the extraction electrode is 18 mm.

Because of the danger of sparking between the extraction electrode and the negative electrode of the column, the extraction electrode is recessed by 16 mm in respect of the positive HT electrode (Fig. 5). The pulse transformer supplying the extraction voltage is protected by a spark gap.

The mechanical design of the source was governed by requirement for easy servicing and sufficient flexibility so that different electrode shapes can be fitted.

Parts which form the magnetic path are fabricated from Armco steel. High voltage electrodes (expansion cup, extraction grid holder, etc.) are made of titanium for its excellent voltage-holding properties (Refs. 15,16).

The snout and main magnet coil are oil-cooled. The heat is removed by an oil-air heat exchanger placed on earth potential. Nylon reinforced PVC tubing is used for oil transfer (540 kV across 1.5 m). A modified Frölich storage type cathode is used because of its long life and resistance to accidental air exposures (Ref. 17). Manufacture procedure is given in the Appendix. The width of the cathode is 15 mm and the length 115 mm. Heater current is 65 A, voltage 3,8 V for 950° C and 1 Torr of hydrogen.

Power Supplies

The arc pulser is a power amplifier with current feedback, driven by a square wave generator. Because of the current feedback, the pulser is capable of maintaining a constant arc current in spite of variations of source impedance. The arc impedance depends on the hydrogen pressure, arc current and the magnetic field, supposing that the cathode emission is space charge limited (Fig. 6). The pulser is capable of delivering 1600 V, which are necessary to start quickly the arc (t ionization < 1 µs, Fig. 7). The maximum current is 80 A.

Because of the high current on the extraction grid (up to 1 A) the extraction voltage supply must have a low internal impedance. Therefore, a hard valve amplifier with voltage feedback was designed. The pulser features low stored energy (1 Joule) so that the damage of electrodes in case of sparking is negligible.

The pulser can deliver up to 75 kV during 50 μs. The main magnet as well as the magnet in the expansion cup are fed from commercial (Kepco) current stabilisers (stability ~10^{-4}).

It is necessary to maintain the cathode temperature at a prescribed value in spite of mains variations and the cooling effect of the hydrogen in the source, because the cathode life depends strongly on the cathode temperature. The cathode heater current is supplied by a magnetic stabiliser with two feedback loops, one which stabilises against mains variations and another which gets its signal from a thermocouple vacuum gauge. The heater current is corrected in this way for the hydrogen pressure variations in the source.

Hydrogen pressure is regulated by a commercial needle valve servo. Unpurified 99.9% hydrogen is used.

Measuring Technique

For current measurement toroidal current transformers are used. Their indication was often checked against calorimetric measurements.

During the setting-up procedure for best brightness, two methods were employed: pulsed emittance analyser and the slotted-plate quartz plate method. The slit images on the quartz fluorescent plate were photographed and used as records.

An emittance analyser with a pulsed magnet was developed which can measure the angular spread, the proton percentage and the variation of angular spread during the pulse. A pulsed magnet is mounted on a movable chariot between two 0.1 mm slit diaphragms. A sample of the beam coming through the first slit is deflected by the growing magnetic field and swept over the second diaphragm. The angular density distribution of the fan-shaped beam (after the first diaphragm) is transformed into a time-dependent voltage, which is displayed on the oscilloscope. Moving the chariot across the beam, the device explores it at all radii. By suitable connection of the signals (Faraday cup current, magnetic field intensity and chariot position) it is possible to obtain either the usual r,r' plot or other measurements indicated above (Fig. 8).

The adjustment of the source was made by variation of the five parameters: arc current, hydrogen pressure, main magnetic field, expansion cup magnet and the extraction voltage. It was tried to obtain the best possible emittance for a given current. The influence of different parameters could be seen immediately on the pulsed emittance analyser. Good working points were marked and a photograph of the emittance from the quartz plate was taken and evaluated.

Results

The duoplasmatron and short-gap accelerating column have been in operation since May 1966. They are running stably and with only a few minor breakdowns. The source has not been opened since then, and the cathode life up till now (22.9.1966) exceeds 2500 hours. The mean current accelerated to 540 kV during this period is 650 mA, of which 450 mA fell within the acceptance of the Linac (0.55 cm mrad). Peak current possible with the present set-up is 1 A. Mean Linac current has been 100 mA with peaks up to 135 mA. The brightness against current curve is shown on Fig. 9. Pulse shape shows irregularities (low frequency plasma oscillations?) during the first 10 μs, but after that time the pulse amplitude has been stable. The first irregular part of the pulse had to be removed by an electrostatic pulse-chopper. Pulse-to-pulse variation in intensity is below 5%. Long-term stability is good, and the source does not need adjustment during a fortnight's run. The proton percentage under normal operation conditions (arc current 70 A, expansion cup magnet current 180 mA, extraction voltage 70 kV, cathode current 65 A and hydrogen pressure 1 Torr) exceeds 85% (Fig. 10).

Acknowledgements

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APPENDIX

Manufacture of the Storage Type Matrix Cathode

Support material: purest Ni wire mesh; 0.2 mm wire; 169 meshes/cm^2.

Emissive material: 70 g Ni powder, cobalt free (Merck)
17.15 g $SrCO_3$, pro analisi, (Merck)
12.85 g $BaCO_3$, pro analisi, (Merck)

The powders are mixed for six hours in a porcelain ball mill with 100 ml amyl acetate added. After mixing, the amyl acetate is allowed to evaporate until a pasty consistency is obtained. The mixture is then ready for use.

The previously cleared (Ref. 19) and degassed Ni-mesh is brush-painted until a smooth surface is obtained. The thickness of the layer ought to be such that the grid structure is just not visible. The cathodes are slowly dried by a hair-dryer.

Attention. At this stage of manufacture, the adhesion of the powder to the cathode is extremely weak.

Formation Procedure

Slow heating up to 950° C, keeping the pressure $<10^{-4}$ Torr. Several 10 sec flashes were made to up to 1100° C, then hydrogen was introduced (1 Torr) and the anode voltage applied (pulses of 1000 V, 60 μs duration, internal impedance of the supply 15 Ω). The arc was established and the voltage drop of the discharge measured. Cathodes which show an arc voltage of less than 50 V after a few minutes' running are considered good and stored in stainless steel containers filled with dried nitrogen.

N.B. After formation, the nickel powder is sintered to the supporting mesh and the cathode can be handled without danger.

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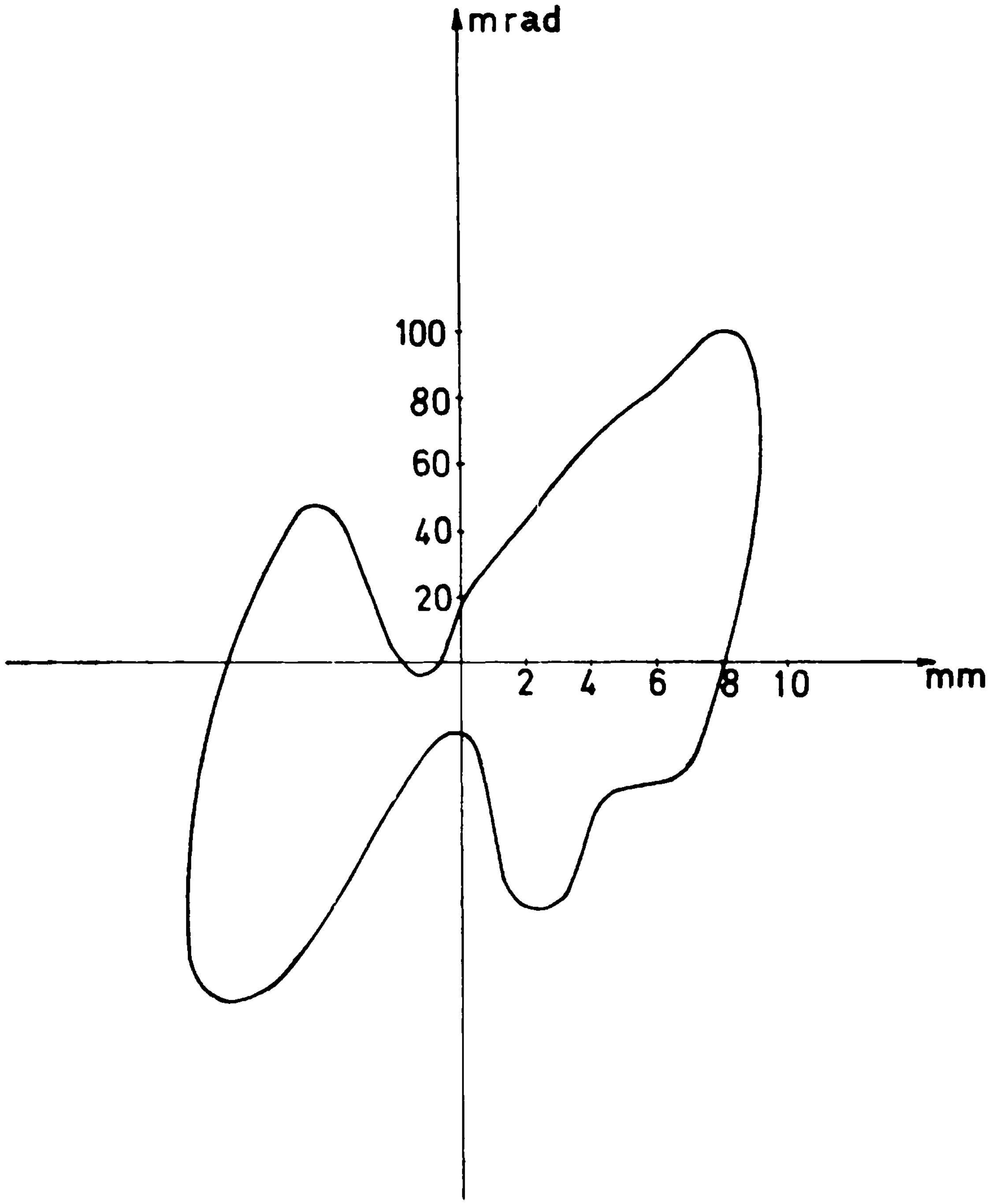
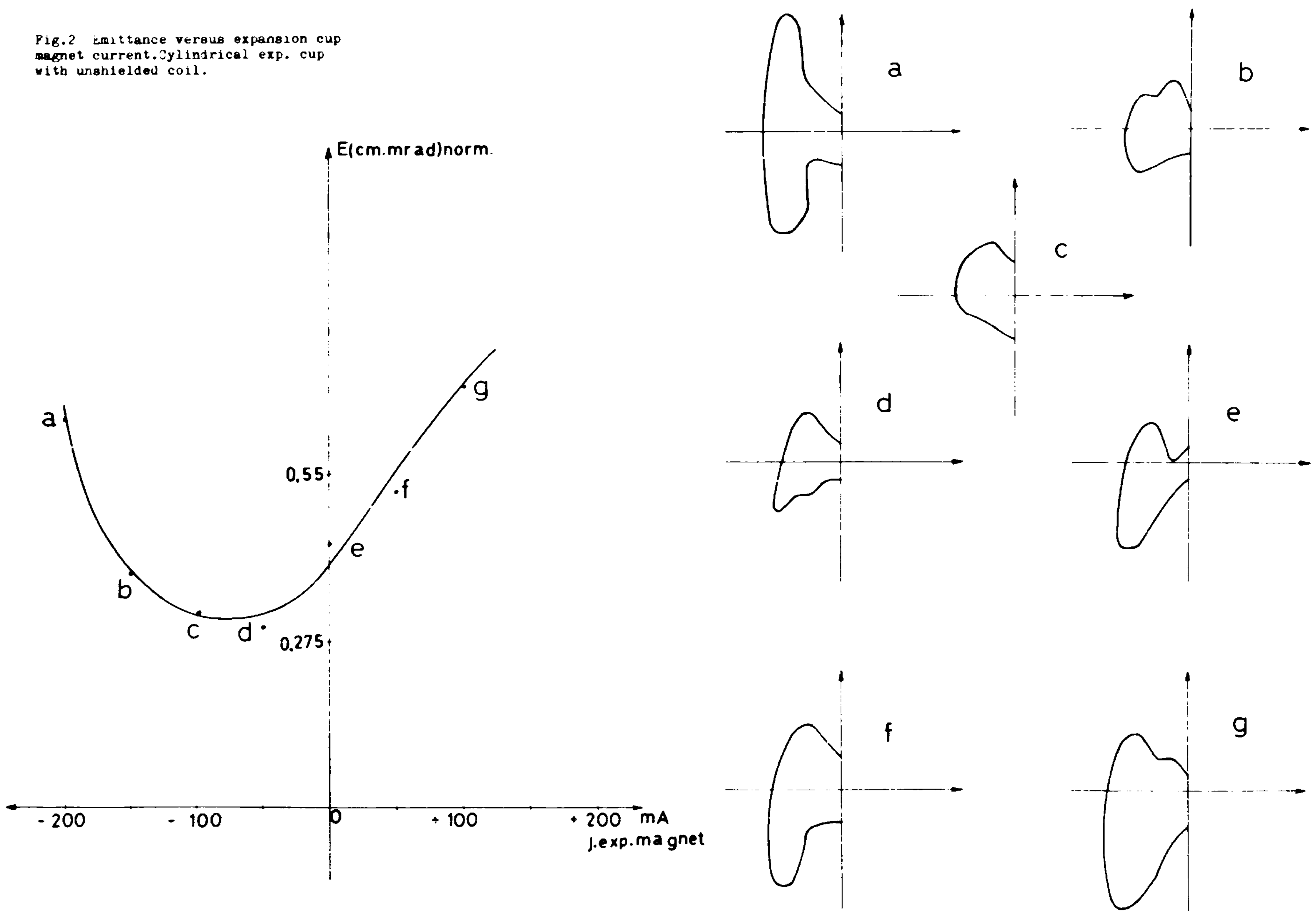
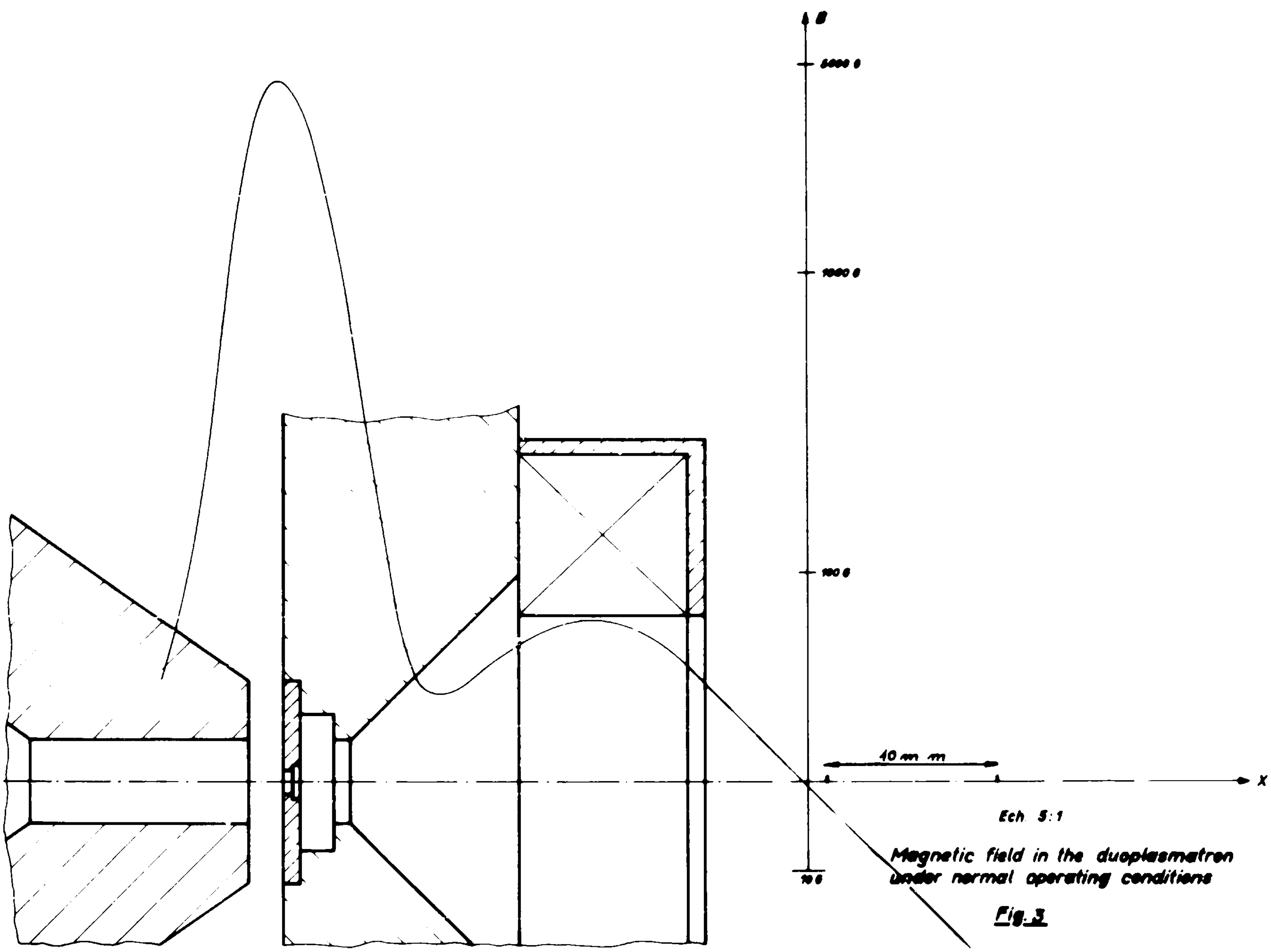


Fig.1 Emittance of the duoplasmatron beam at 3o kV.Cylindrical expansion cup.

Fig.2 Emittance versus expansion cup magnet current. Cylindrical exp. cup with unshielded coil.





Magnetic field in the duoplasmatron under normal operating conditions

Fig. 3

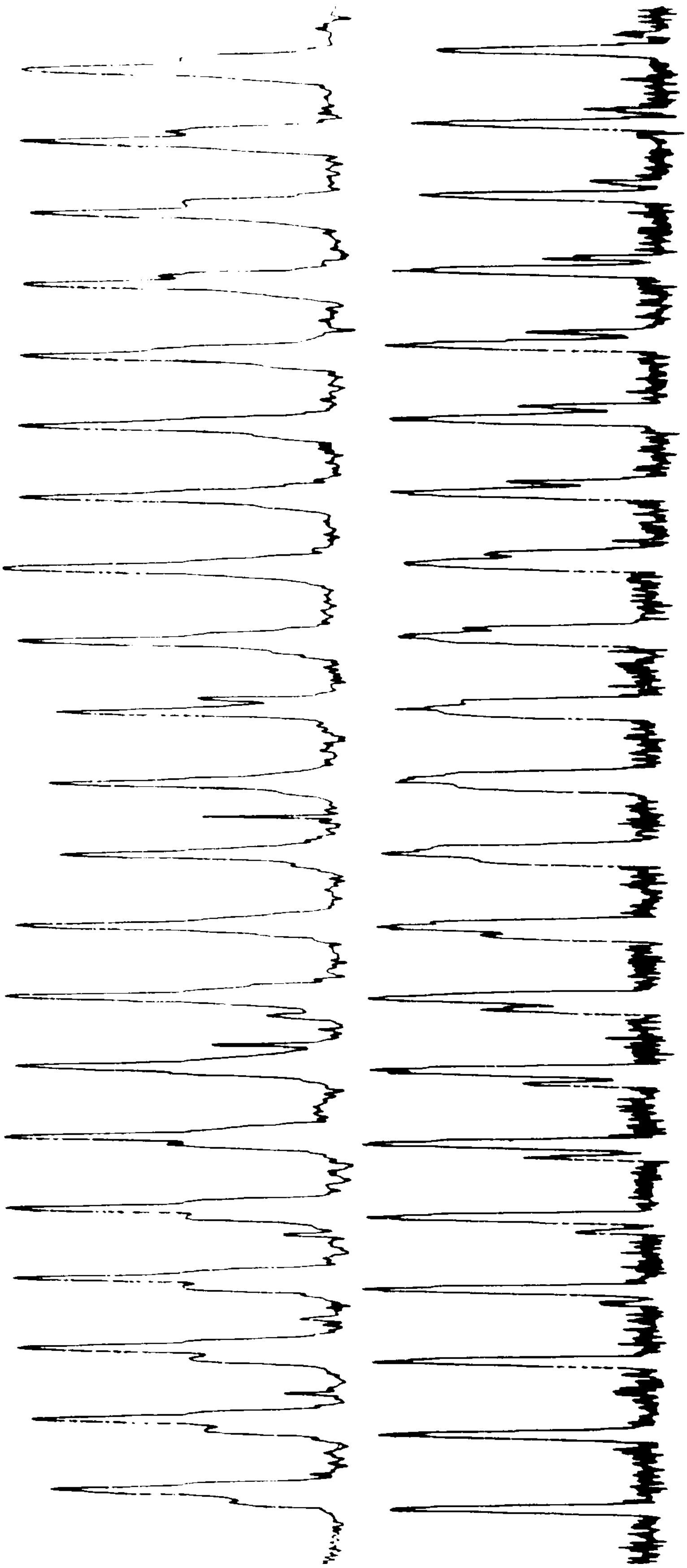


Fig.4 Photometric plot of slit images showing bending and imperfect overlapping of the two "spectra".

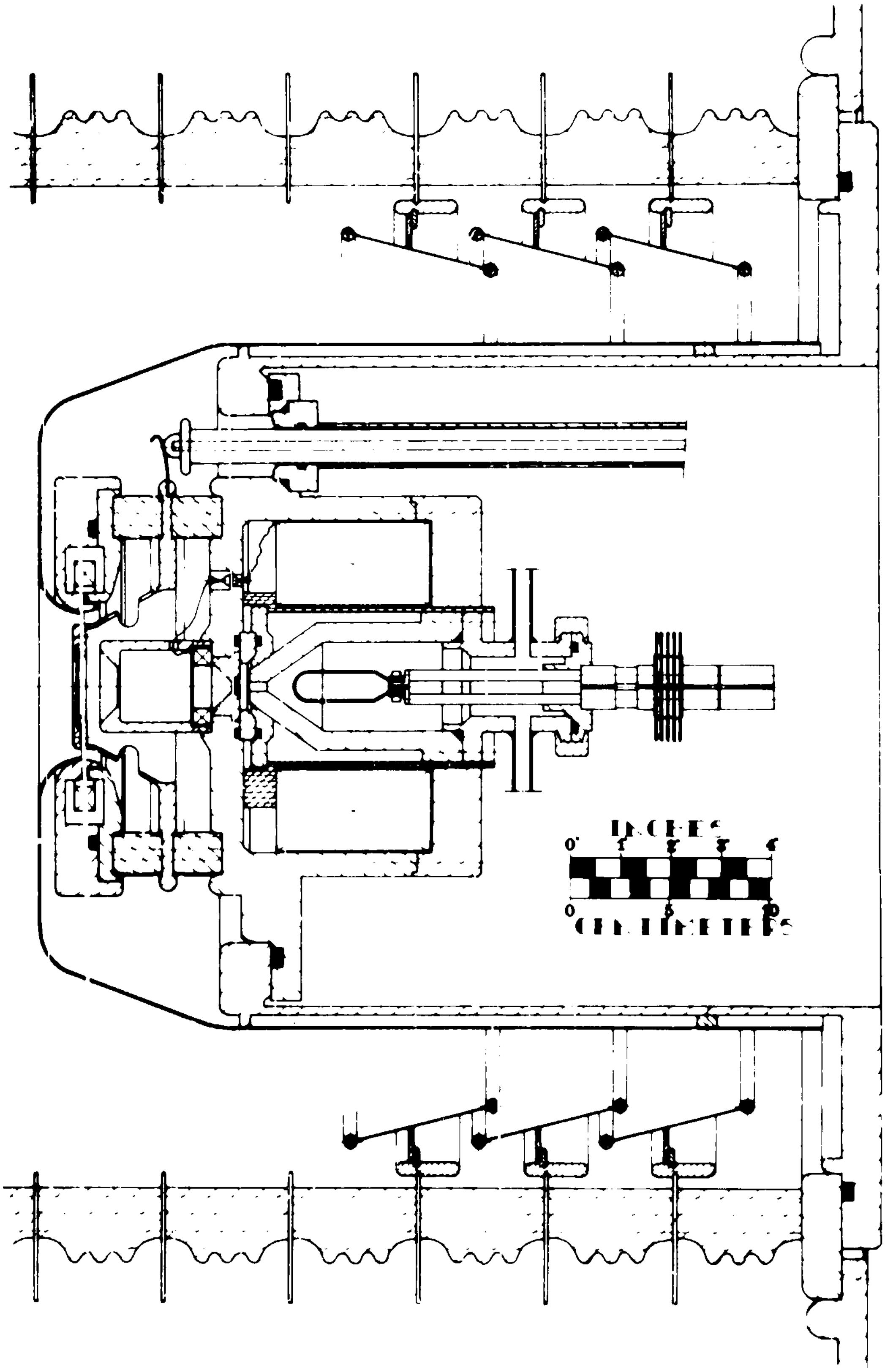


Fig.5 Section of the source.

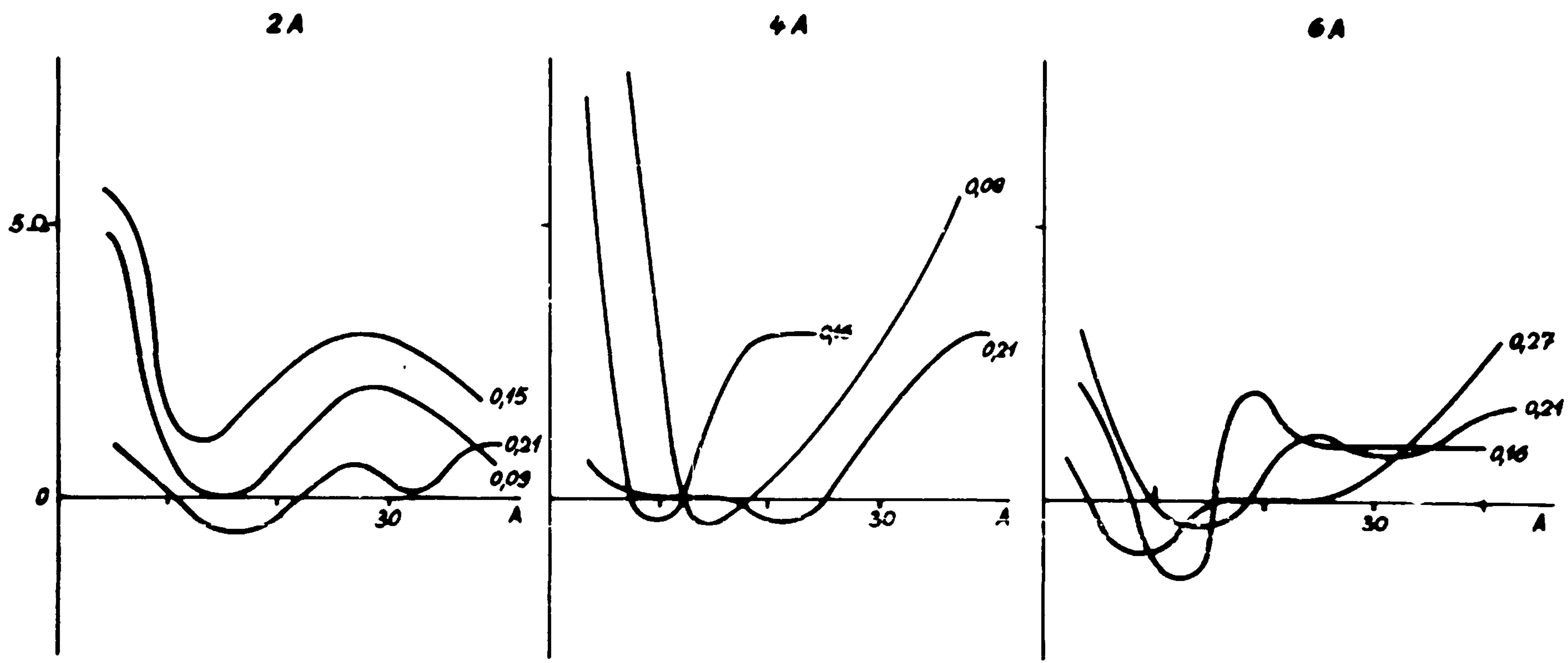


Fig.6 Arc impedance versus arc current plot for different magnet currents and hydrogen pressures / in Torr /.

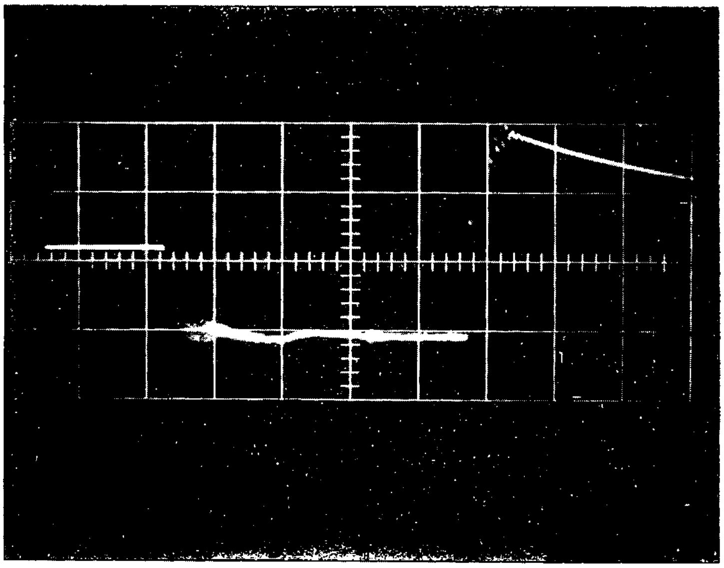


Fig. 7 Arc voltage oscillogram.
100 V/div.; 5 us/div.

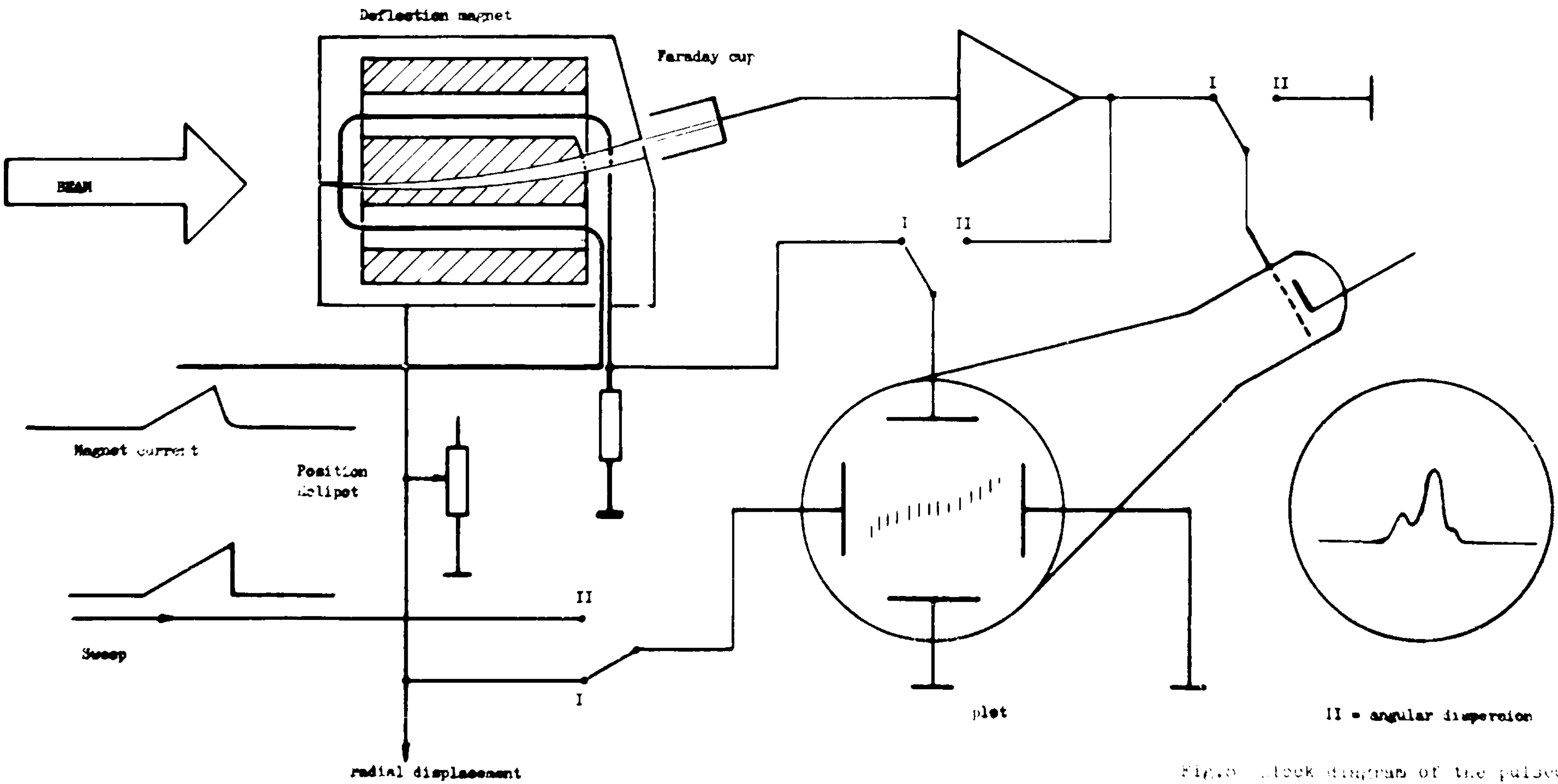
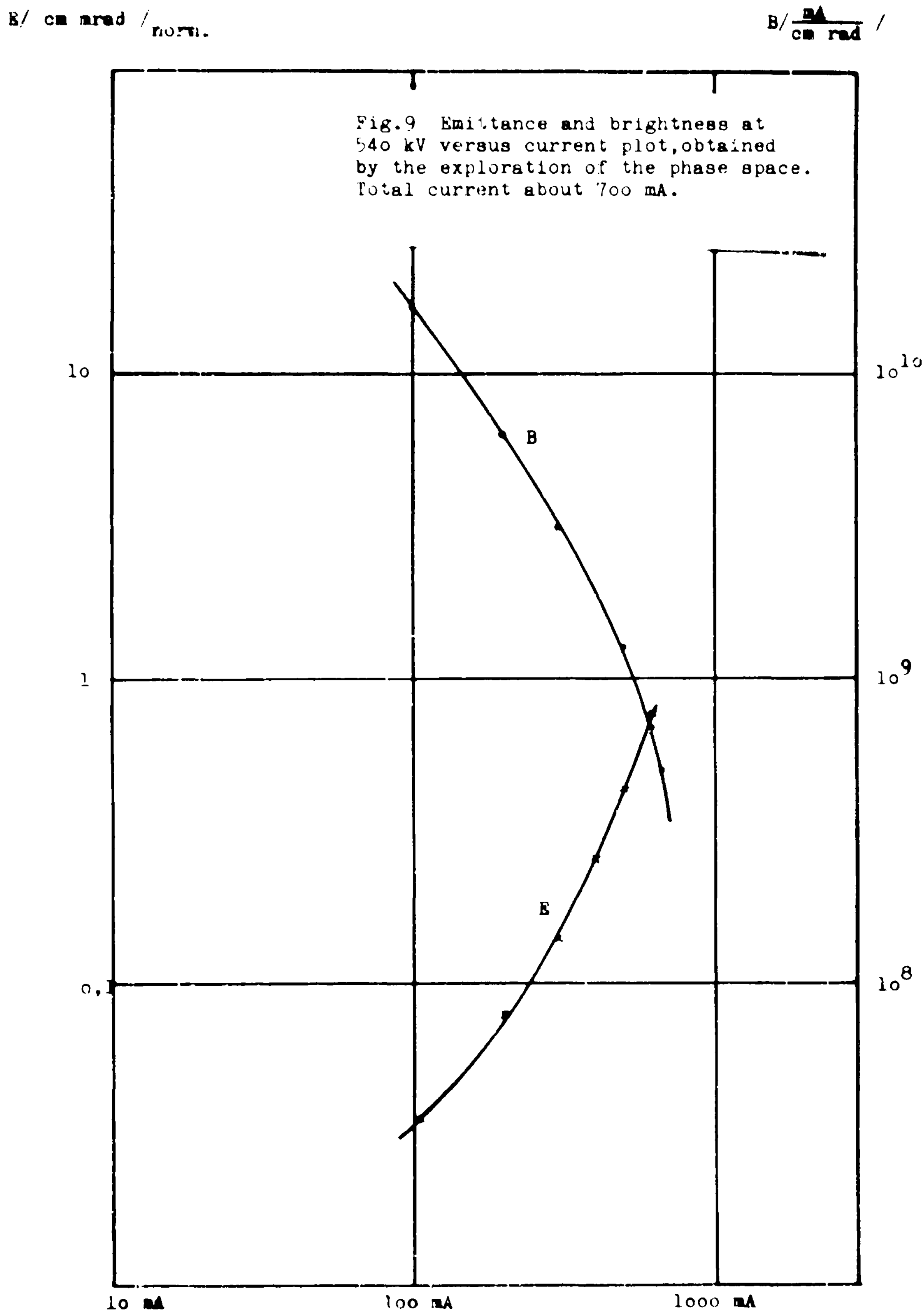


Fig.8 Block diagram of the pulsed emittance analyser.


E/ cm mrad /norm.
B/ mA/cm rad /
Fig.9 Emittance and brightness at 540 kV versus current plot,obtained by the exploration of the phase space. Total current about 700 mA.
10
1
0,1
10^10
10^9
10^8
B
E
10 mA
100 mA
1000 mA

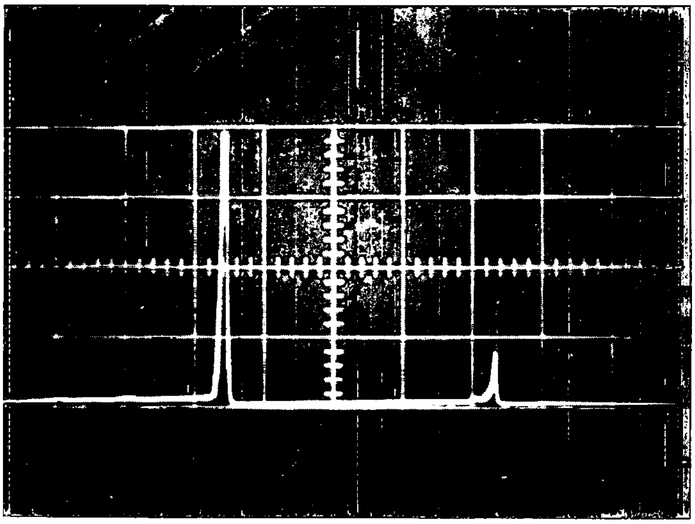


Fig. 10 Mass spectrogram of the beam at 540 kV. The left line is H_1 , the right line being H_2 . Spectrogram obtained with the pulsed emittance analyser.

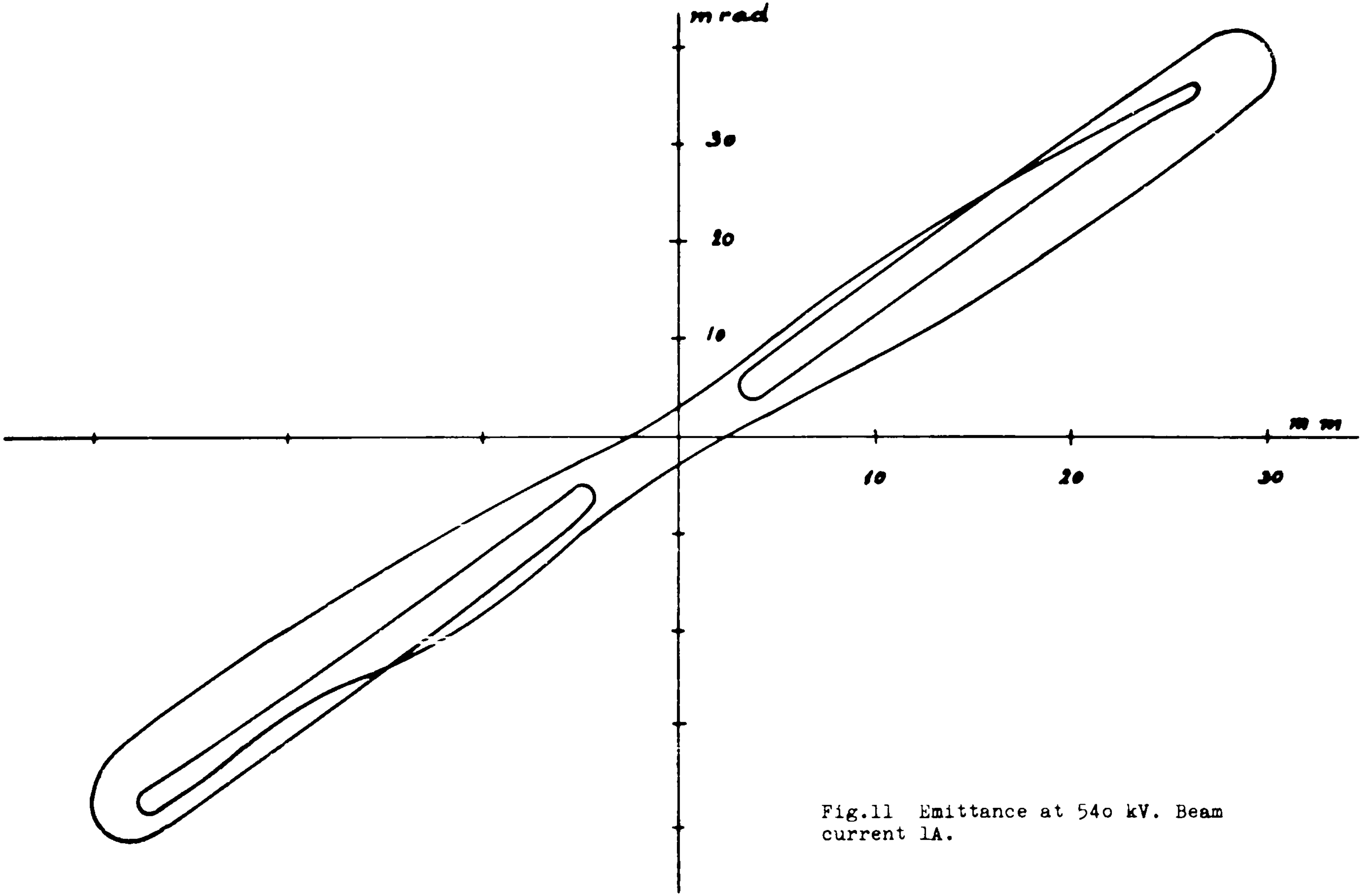
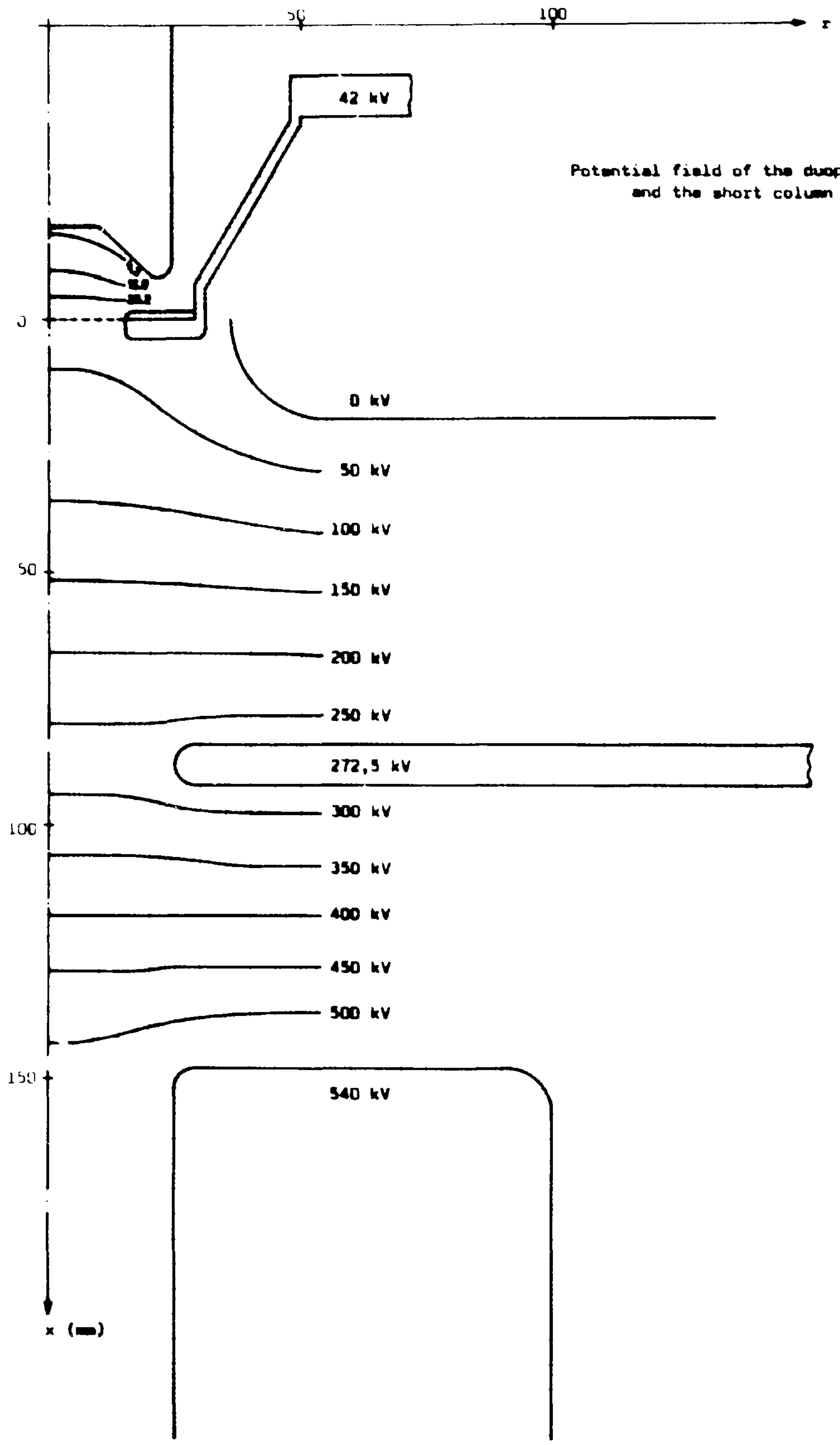
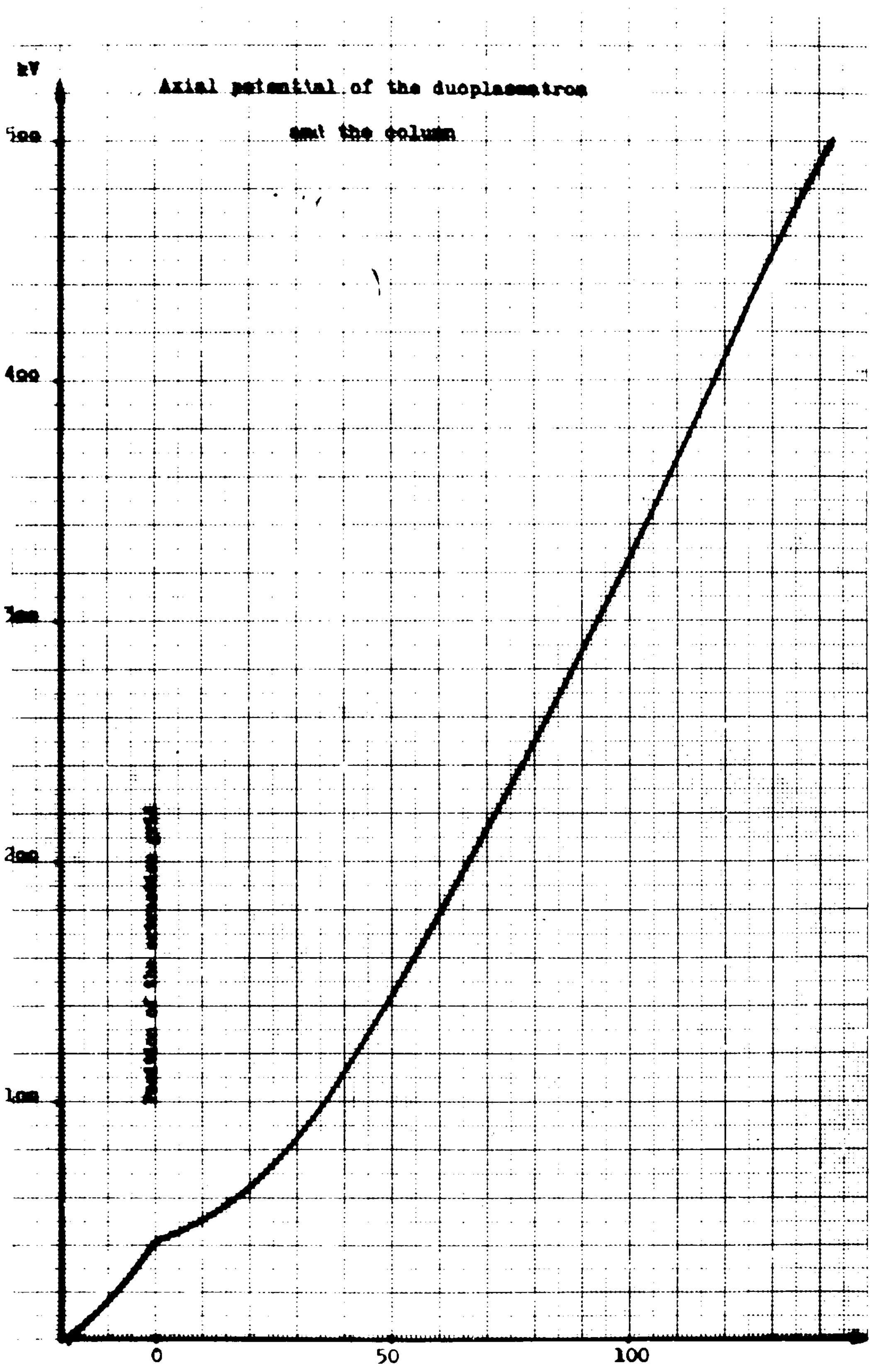


Fig.11 Emittance at 54o kV. Beam current 1A.



Potential field of the duoplasmatron and the short column


kV
Axial potential of the duoplasmatron
and the column
500
400
300
200
100
0
50
100

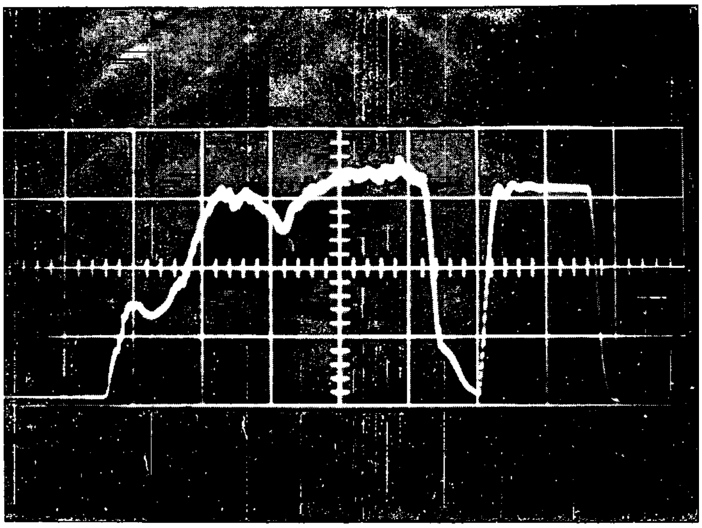


Fig. 14 Beam current at the output of the column. Calibration pulse 500 mA.

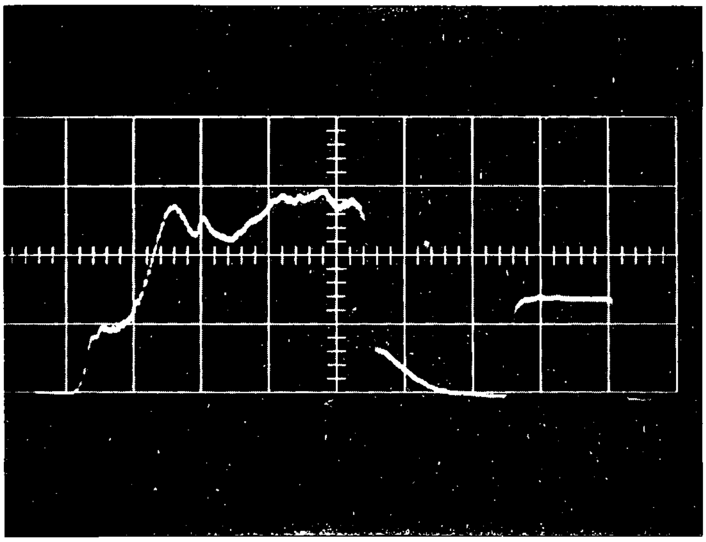
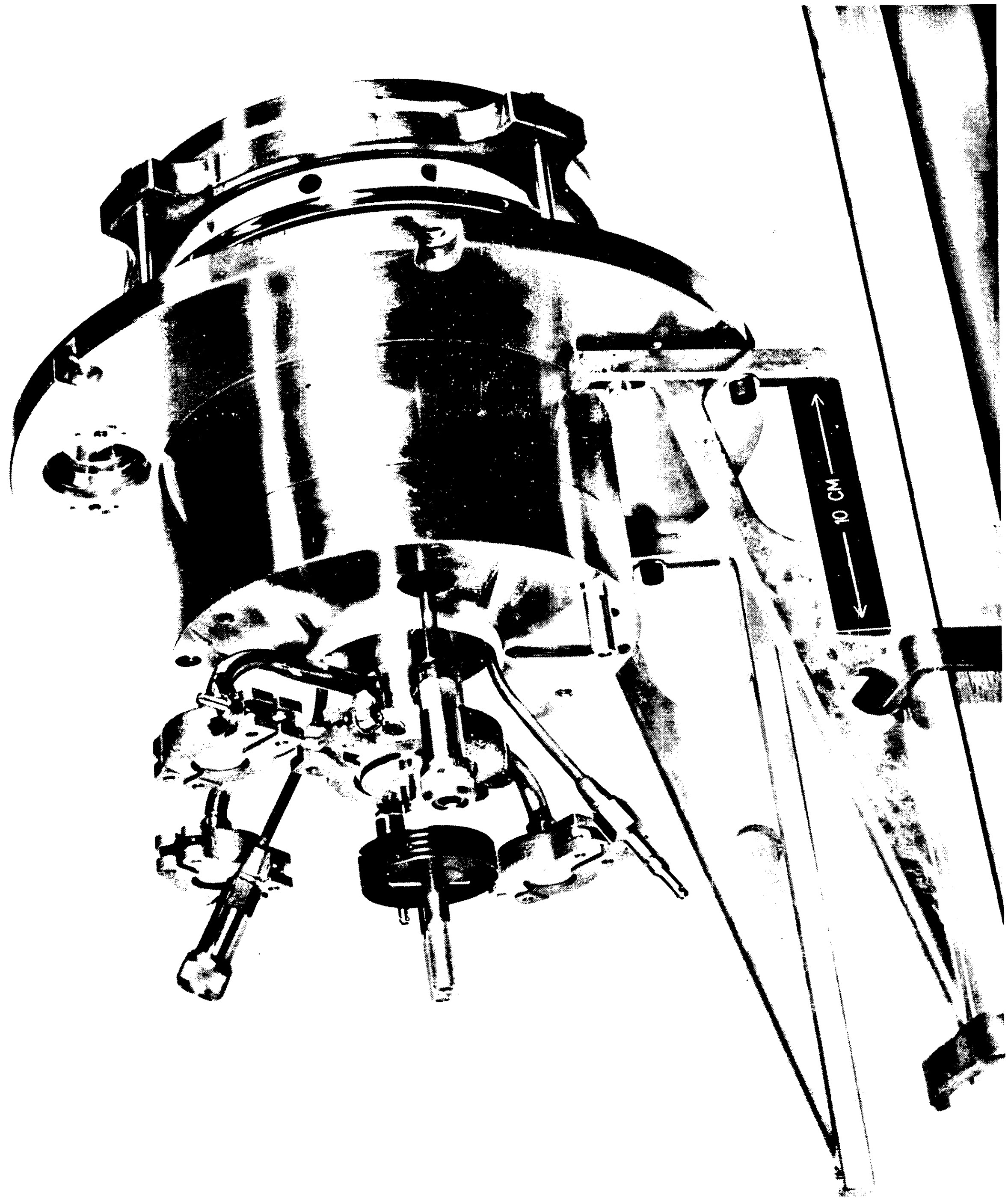


Fig. 15 Beam current at the output of the column. Calibration pulse 500 mA.


10 CM