A 600 KV proton injector for a linear accelerator

by

Yu.N. Antonov, L.P. Zinov'ev and V.P. Rashevskij
(Joint Institute for Nuclear Research, Dubna)

Report No. P346 of April 1959

Translated at CERN by P.C.P. Mollet

Genève
August 1960

A 600 kV proton injector for a linear accelerator

by

Yu. N. Antonov, L.P. Zinov'ev, V.P. Rashevskij

Abstract

The present report describes a proton injector with a pulsed current of 50 mA and a beam energy of 600 KeV. It includes a description of the proton source, the accelerating column and their power supplies. It also deals with beam focusing in the column.

1. INTRODUCTION

To produce the injection current for the 10 GeV Synchrophasotron of the Joint Institute for Nuclear Research, the authors had to construct an ion source giving a high current proton beam, to extract this beam and to focus it for acceleration up to 600 KeV. The geometry and angular divergence of this beam at the output end of the column had to satisfy the conditions required for injection into the linear accelerator.

2. ION SOURCE

The work involved an ion source for the production of a gas discharge plasma, with a double constriction of the plasma thread, using the oscillation of electrons in an arc discharge. The source was designed at the Institute of Physics of the Academy of Science of the Georgian S.S.R., and, jointly with V.M. Blagoveshchenskij, T.I. Gutkin and Yu. V. Kursanov, of that Institute, subsequent modifications and constructional improvements have been made in our laboratory.

A schematic cross-section of the source is shown on fig. 1.

The source cathode (1) is made from a standard ТГИ 1 - 90/8 thyratron. The cathode lead-in wires (2) are cooled by circulating water and insulated from the flanges (5) of the cathode by P.T.F.E. insulators (4). Hydrogen is fed into the discharge tube via a palladium filter fitted to the pipe (3).

The inner cavity of the intermediate anode (6) forms the cathode region of the discharge; the presence in the intermediate anode of a channel (15) 9 mm in diameter and 10 mm long causes the formation of a hemispherical boundary, whose spherical part faces the cathode and which leads to a constriction of the plasma thread. The intermediate anode is also cooled with water circulating in the cavity (7). A coil (8) is wound directly on the intermediate anode to create an axial magnetic field which constricts the plasma between the channel (15) and the outlet (17). The intermediate anode, the envelope of the source (16) and the outlet flange (12) form a magnetic path.

The copper anode (10) has an aperture 9 mm in diameter in line with the channel (15) and the outlet; the electron oscillation takes place in the gap between the last two. Inset in the outlet flange of the source ("anticathode") is a piece of non-magnetic material (13) (tungsten or stainless steel) with an opening 2 mm in diameter and ~0.5 mm long.*

As the source operates at a potential of 600 kV with respect to earth, all the power supplies were mounted on a column 2.6 m high, made of porcelain insulators and equipped with its own 220 V, 50 c/s, 3.5 kW generator to which is connected a 220 V, 500 c/s, 0.6 kW ГCM generator. The drive to the generator from an electric motor at earth potential is provided by a wood and bakelite shaft 2 m long.

---

* It is most essential to design the outlet channel in such a way that one minimises loss of ion current to the wall of the channel; the necessary condition for the outlet channel is therefore $\ell \gg d$.

A schematic diagram of the power supply is shown on fig. 2.

The source cathode is heated by 50 c/s a.c. 7.8 V and 6.4 A from a TP 1 step-down transformer. The hydrogen pressure in the discharge chamber is maintained at about $1.5 \cdot 10^{-2}$ mm Hg; the hydrogen is fed in through a Pa palladium filter and the feed is regulated by a heated palladium pipe.

The magnetic field in the source is produced by a 320 turn winding, the current being of the order of 2A. The induction in the gap between the intermediate anode and the anticathode reaches 1000 Gauss.

The artificial line discharging through the ТГИ1-90/8 thyratron gives a negative pulse on the source cathode for about 500μs; the amplitude of the pulse is regulated by varying the voltage of the B2 rectifier charging the line. The synchronized triggering of the source takes place as follows : the driving pulse fires the MH-3 neon lamp placed at the base of the power supply column, the flash through the light guide is fed to the cathode of the ФЭУ-25 photomultiplier placed on the column, After being amplified and differentiated, the pulse of the photomultiplier acts on the grid of the thyratron of the source line.

The 400-500 V negative pulse from the line feeds the source cathode and fires the arc between this and the intermediate anodes. The arc current, flowing through resistance $R_1 = 200\Omega$, creates between the intermediate anode and anode 10 (fig. 1) a difference of potential, which assures the penetration of the arc into the channel of the intermediate anode.

As the channel disturbs the homogeneity of the gap there is a shortage of electrons in the anode region of the plasma, which leads to the formation of a hemispherical boundary that accelerates and focuses the electrons; as a result the concentration of ions in the anode region of the plasma is an order of magnitude greater than that in the cathode region. The voltage discontinuity in the boundary is such that the production of ions in the region of the anode plasma is sufficient to satisfy the stability condition for a two-directional current limited by space charge :

$$\frac{I_p}{I_e} = \left(\frac{m_e}{m_p}\right)^{\frac{1}{2}} ,$$

when I_p is the directed component of the positive ion current, I_e the directed component of the electron current and m_e and m_p are the respective masses of the electron and the positive ion.

The strong inhomogeneous magnetic field in the region of the anode plasma causes a further constriction of the discharge, which leads to an additional increase in the density of the charge carriers. The double constriction of the discharge and the utilization of the oscillation of arc electrons in the gap between the intermediate anode and the anticathode result in a considerable degree of ionisation in the anode region of the discharge. The ions produced in the anode plasma are directed under the influence of the electric field towards the outlet of the source and are extracted.

The geometry of the discharge chamber of the source was determined experimentally to secure optimum conditions for the firing of the arc. It proved essential for the intermediate anode to be of conical shape. The angle of the cone in the final version is 120°. If this figure is increased or decreased, there is a sharp fall in the ion current extracted; obviously, this configuration of the axial magnetic field essentially affects the dynamics of the electrons and the parameters of the low pressure plasma (cf. ref. 2). The current extracted from the source was also investigated as a function of the diameter of the outlet. If the diameter of the outlet is enlarged from 0.8 mm to 2.0 mm, the current increases approximately as the square of the diameter (cf. fig. 3). However, if the diameter of the outlet is enlarged to 3.0 mm, the firing of the arc becomes difficult, on account of the strong penetration of the field of the extraction electrode into the discharge chamber.

It is most desirable to have a piece of non-magnetic material inset in the region of the outlet. If there is not one, there is an appreciable drop in the extracted current and a deterioration in focusing. In the final version of the source, this piece of non-magnetic material is 10 mm in diameter.*

The extracted current I_p increases almost linearly with the increase in the arc current I_∂ (cf. fig. 4). This is easy to understand, taking into account the fact that ions are produced in the anode region of the plasma mainly by the directed electron current and that, as a result, the ion concentration in the region of the anode plasma must grow linearly with the increase in the arc current. Owing to a factor influencing the extracted current in the opposite direction, it so happens that for any configuration of the magnetic field the constr ction

---

* There are data which show that the current somewhat increases if it is 20 mm in diameter.

From the point of view of the radial motion of the particles, the field distribution in the column can be divided into three regions:

1. Zero field before the column
2. Constant field along the column
3. Zero field at the output end of the column.

The radial motion of the particles in the accelerating column (region 2 in fig. 6) takes the shape of a parabola. At the output end of the column (transition from region 2 to region 3) the particle goes through the scattering field of the output electrode and finds itself at point B instead of point A. The focal length of the output electrode is given by the expression

$$f_e = - \frac{4U\ell}{U} = - 4\ell \qquad (1)$$

where U is the accelerating voltage in the column, ℓ the length of the accelerating tube, a_e and b_e being linked by the relation

$$\frac{1}{a_e} + \frac{1}{b_e} = \frac{1}{f_e} \qquad (2)$$

from which one obtains

$$a_e = - \frac{4\ell\, b_e}{4\ell + b_e} \qquad (3)$$

The radius of the beam at the output end is related to its radius at the input end by the following relation (cf. ref. 4)

$$\frac{r_e}{r_o} = 1 + \frac{2}{N^3 + 1} \cdot \left(\frac{\ell}{B_o} - \frac{N - 1}{4\xi} \right) , \qquad (4)$$

where r_e is the radius of the beam at the output end of the column, r_o the radius of the beam at the input end of the column and ξ a correction factor,

$$N = \frac{U}{V}$$

V being the energy of the beam at the input end of the column. For $U >> V$ and a small aperture, one has

$$\frac{\gamma_e}{\gamma_o} = \frac{\sqrt{V}}{\sqrt{U}} \quad , \tag{5}$$

where γ_e is the aperture of the beam at the output end of the column and γ_o the aperture of the beam at the input end of the column.

Taking (5) into account, assuming $\xi = 1$, which can be done without any major error, and using the expression given in ref. 4 for the relation $\frac{\ell}{b_o}$, one can write (4) as follows:

$$r_e = r_o - 2\ell \ \gamma_o \sqrt{\frac{V}{U}} \tag{6}$$

Considering the aperture is small, one can see directly from fig. 6 that:

$$r_e = \left| a_e \right| \gamma_e = \gamma_e \cdot \frac{4\ell \ b_e}{4\ell + b_e} \quad (7) \text{ and } r_o = a_o \gamma_o \tag{8}$$

Substituting (5), (7) and (8) in (6), one has:

$$\sqrt{\frac{V}{U}} \cdot \frac{4\ell \ b_e}{4\ell + b_e} = a_o - 2\ell \sqrt{\frac{V}{U}} \tag{9}$$

and hence

$$a_c = 2\ell\sqrt{\frac{V}{U}} \cdot \frac{4\ell + 3b_e}{4\ell + b_e} \qquad (9a)$$

The input electrode acts as a focusing lens with a focal length

$$f_o = \frac{4zV'}{E_1 - E_e} = \frac{4z\ell V'}{U} \qquad (10)$$

where $V' = V_o + 0.6\,\frac{\Gamma}{n}$

V_o being the input electrode voltage with respect to the focusing electrode, Z a correction factor and n the number of anti-corona rings in the column.

By analogy with (2), one has

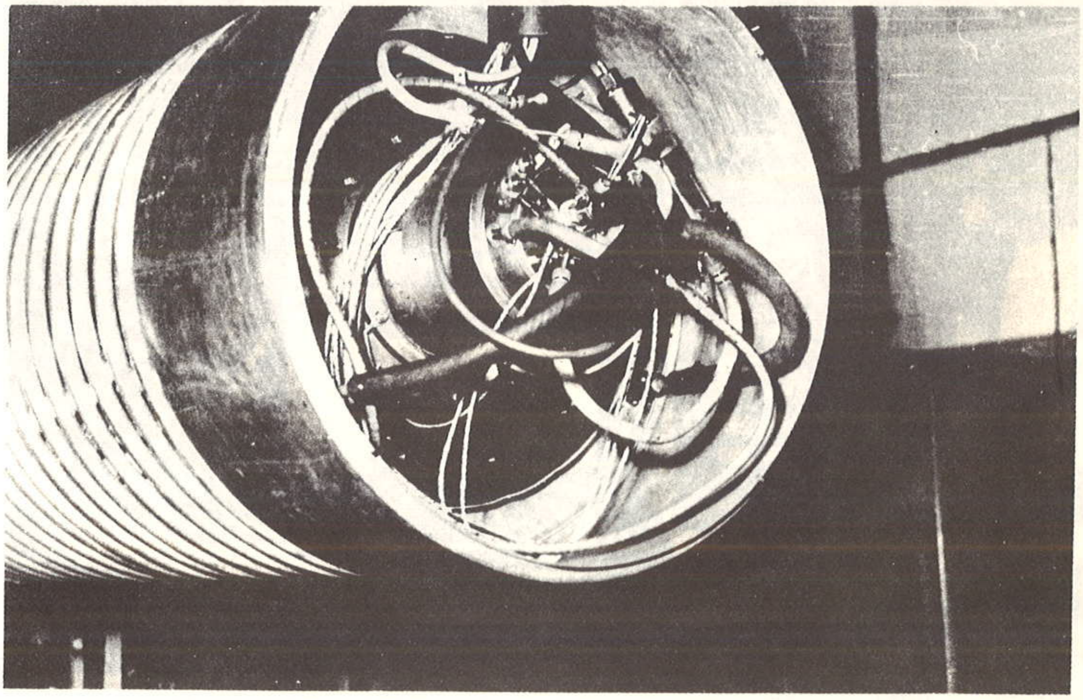
$$\frac{1}{a_o} + \frac{1}{b_o} = \frac{1}{f_o} \qquad (11)$$

Beam focusing at the output end can be adjusted by varying the focusing electrode voltage, i.e. the value of b_o.

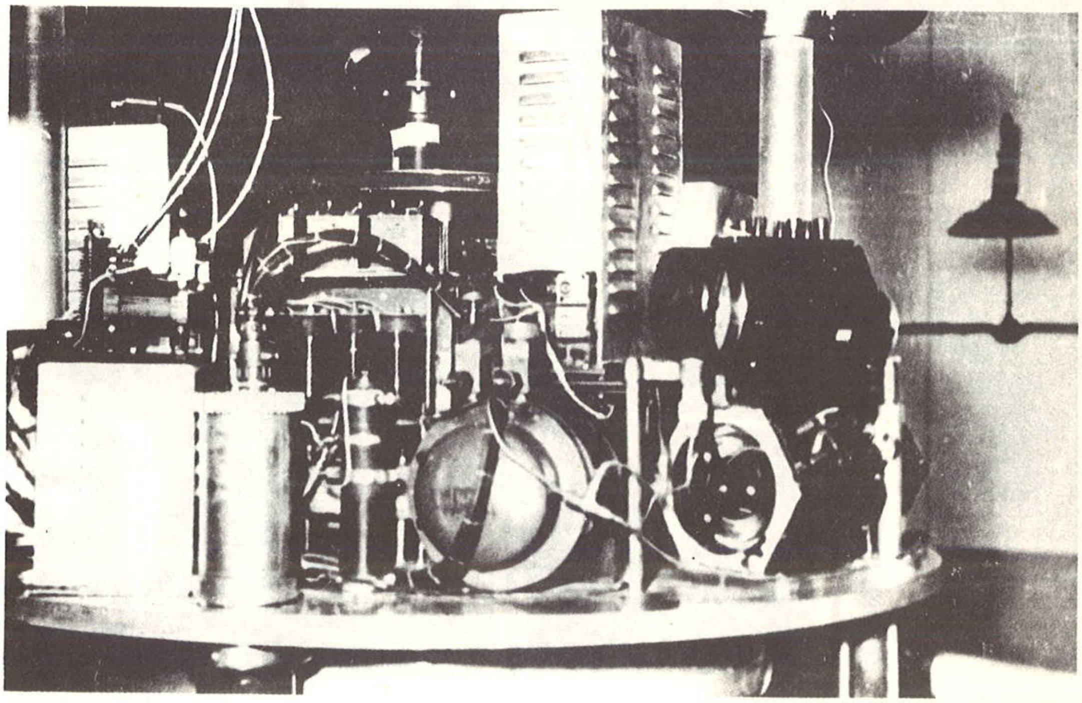
At the output end of the tube the ion current is observed visually by the luminescence of a quartz screen and with the help of a Faraday cylinder fitted with a coil for protection against secondary electrons, which gives on the axis of the cylinder a field of the order of 500 oersted.

Estimation of the angular divergence of the beam at the input end of the linear accelerator gives a figure of the order of 3 10^{-3}. The diameter of the spot at the input end of the linear accelerator (about 6 m from the output end of the column) is 8-10 mm. When the beam is focused at a distance of about 1 m from the output end of the column, the diameter of the spot does not exceed 2 mm.

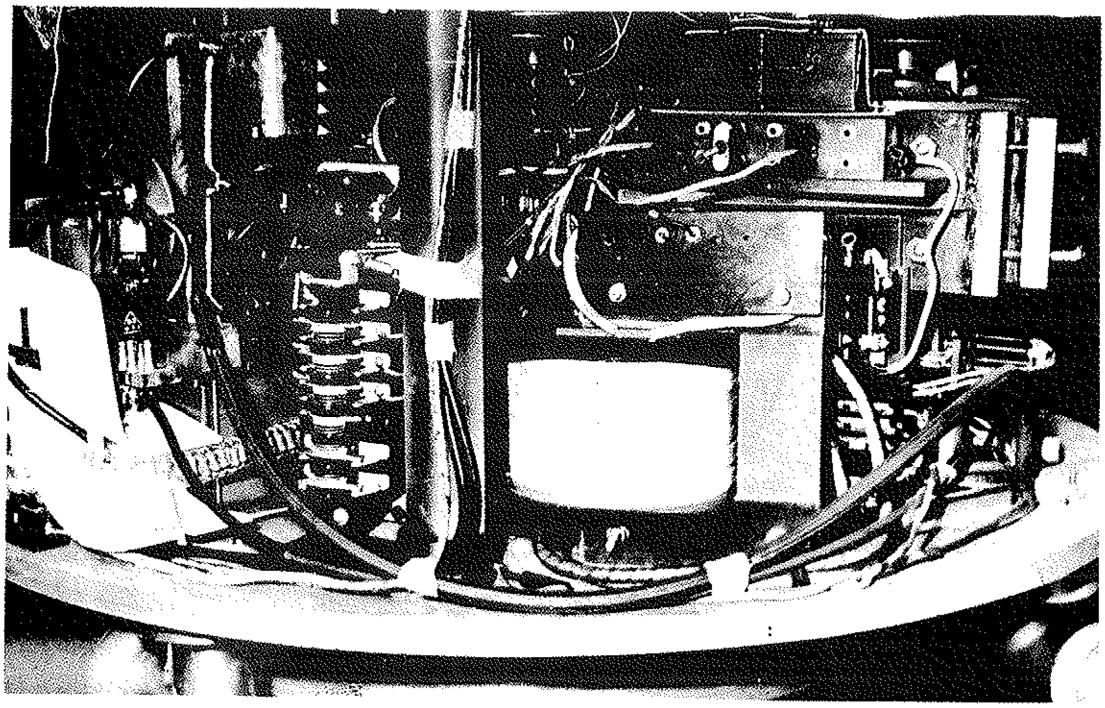
To conclude the authors with to express their sincere gratitude to M.F. Vasil'ev and V.V. Slesarev for the active part they have played in this work.



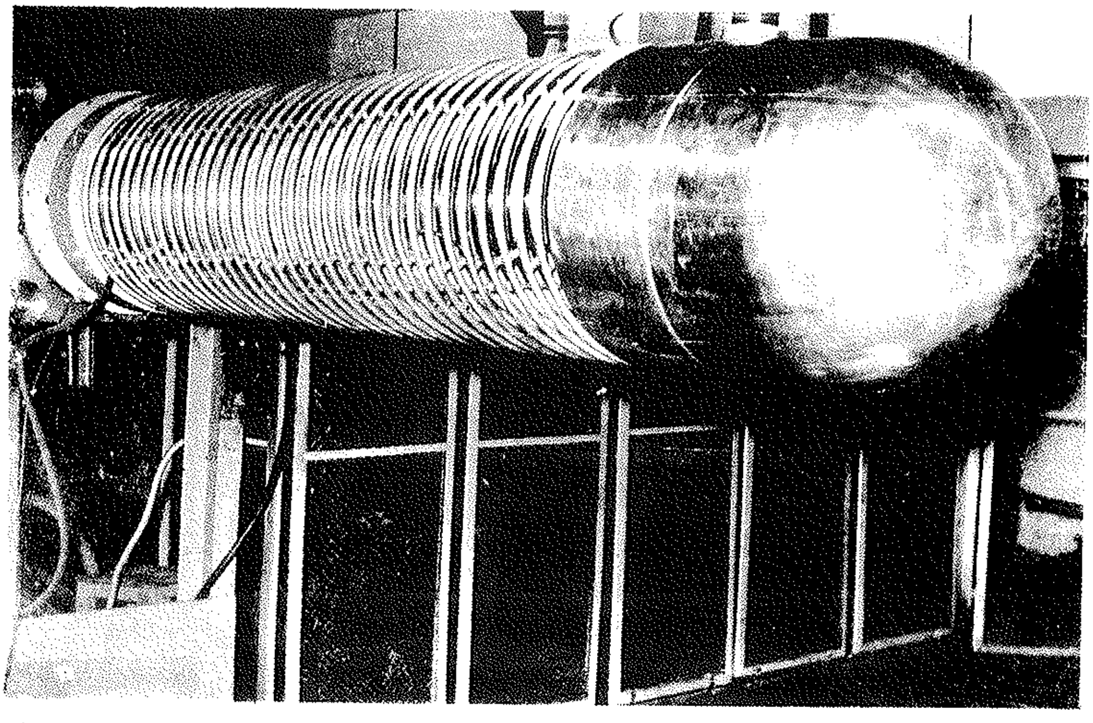
Photograph 1 - The source mounted on the accelerating column



Photograph 2 - Details of the power supply



Photograph 3 - Details of the power supply



Photograph 4 - 600 KV accelerating column

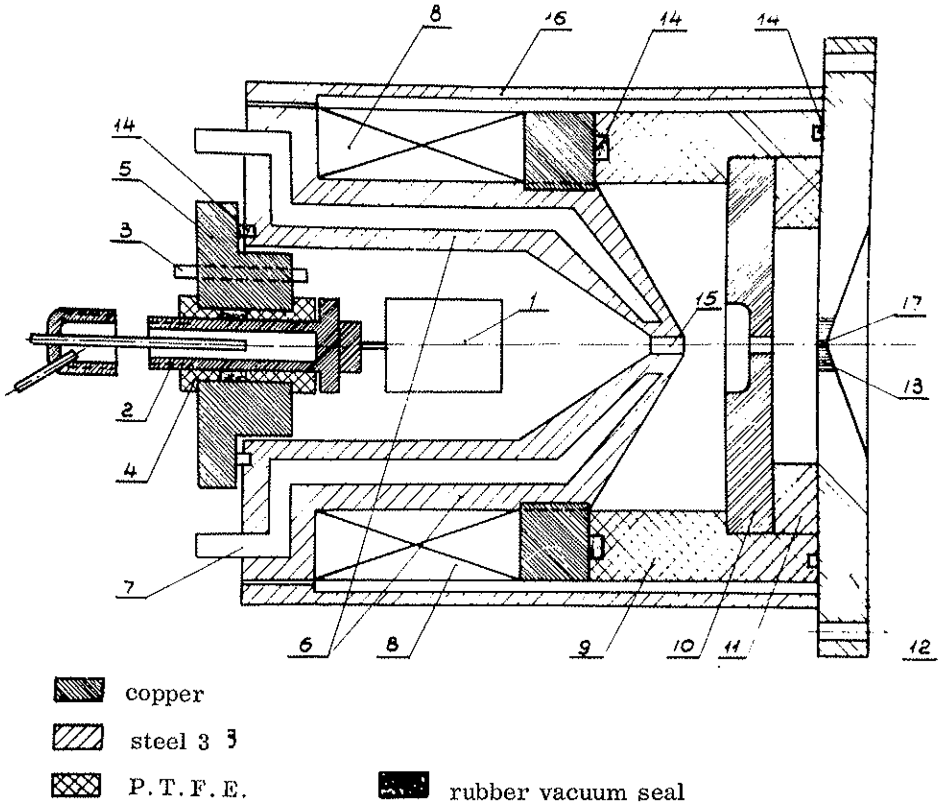


Fig. 1 - Schematic cross-section of the source

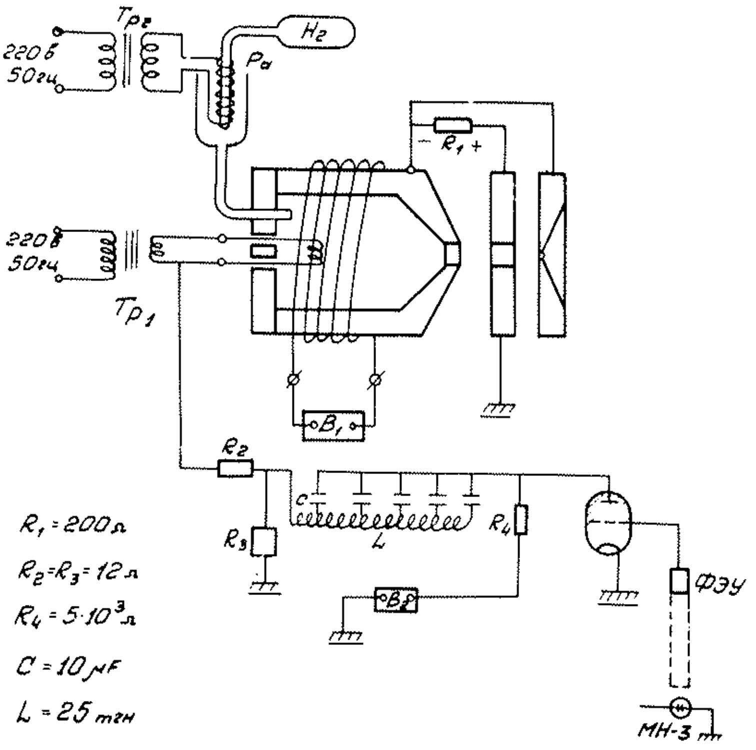


Fig. 2 - Circuit diagram of the power supply

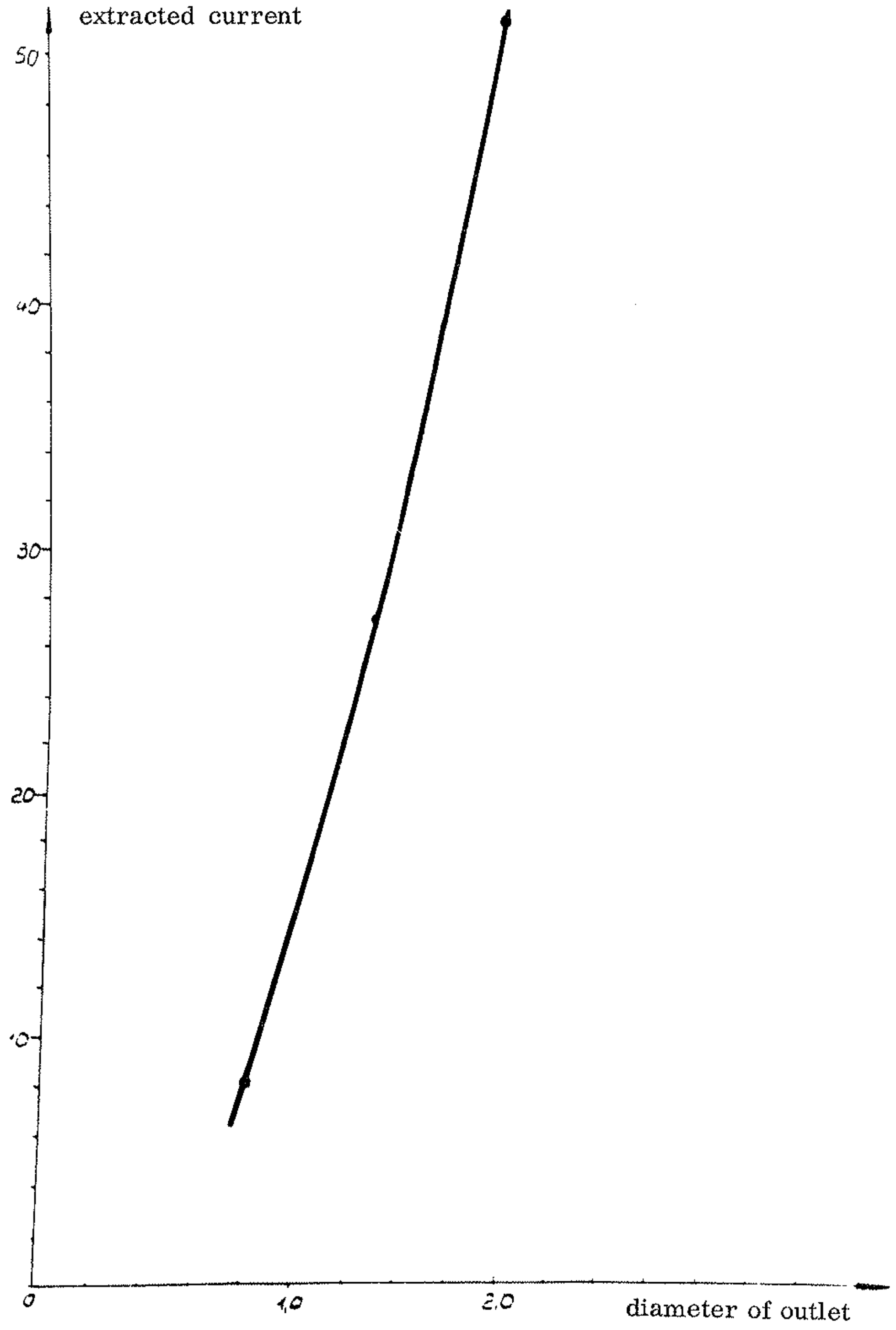


Fig. 3 - Extracted current as a function of diameter of outlet

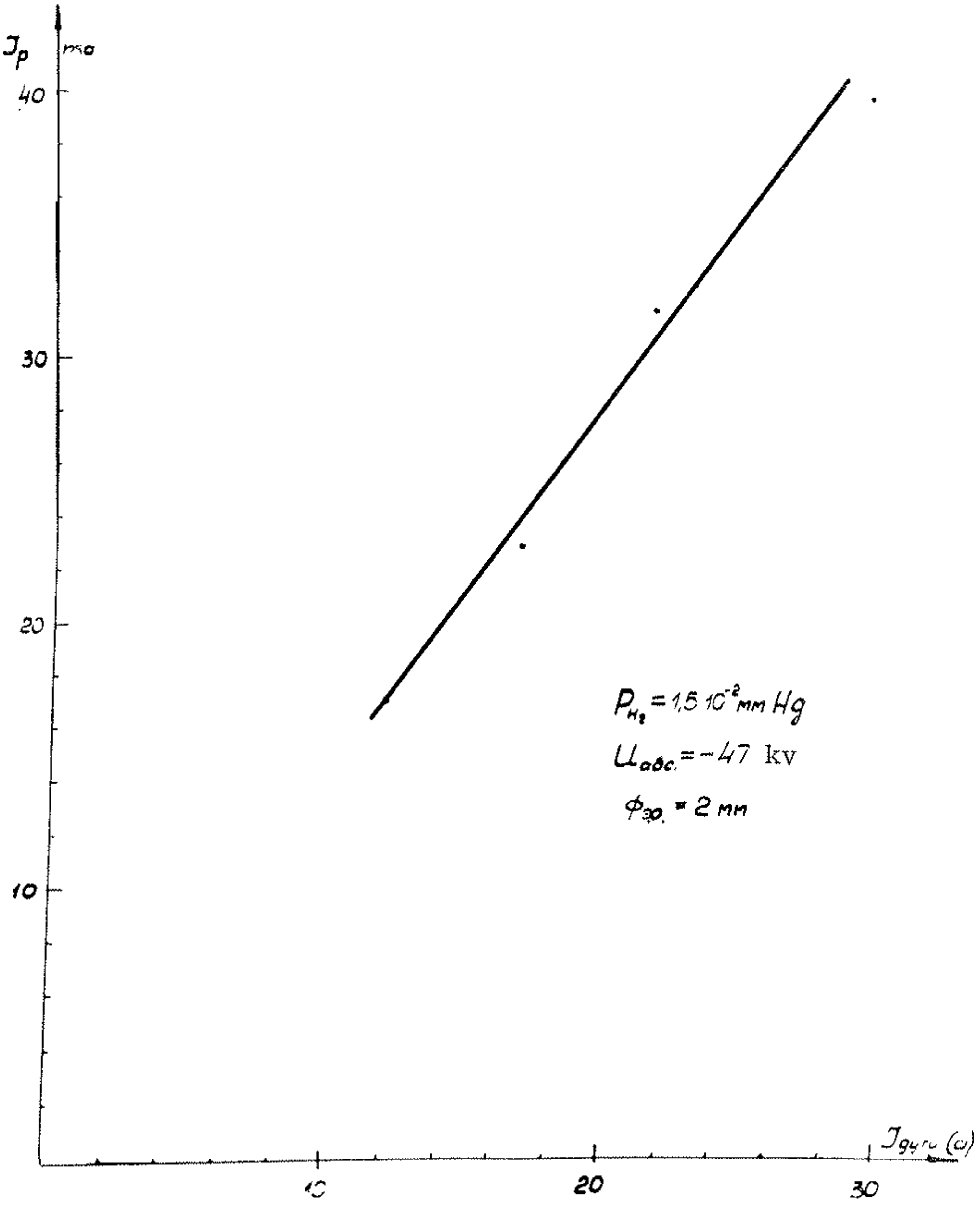
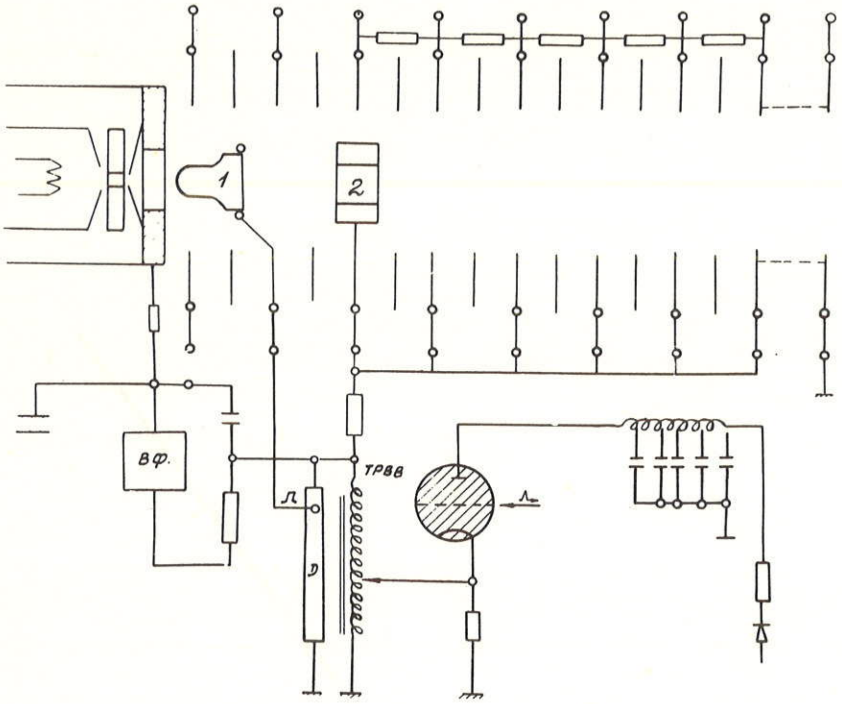


Fig. 4 - Extracted current as a function of arc current



1 extraction electrode

2 focusing electrode

Fig. 5 - Block diagram of extraction and focusing electrodes and their power supplies

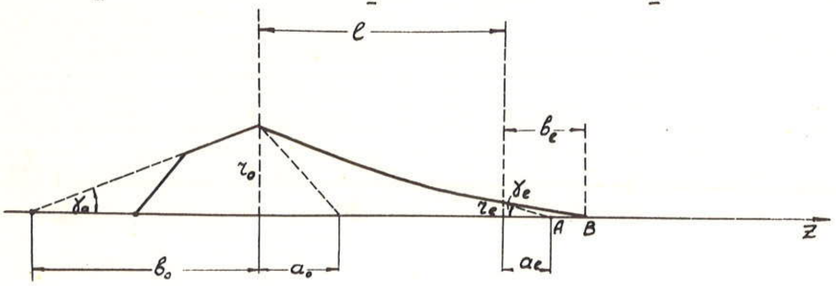


Fig. 6