MPS/Int.LIN 66-13
7 December, 1966

THE NEW 500 keV SINGLE-GAP PRE-INJECTOR TUBE FOR THE CERN PROTON SYNCHROTRON LINAC

J. Huguenin, R. Dubois, G. Visconti, R. El-Bez

Presented at the 2nd International Symposium on Insulation of High Voltages in Vacuum, Boston, 1966, and at the Linear Accelerator Conference, Los Alamos, 1966

4. Choice of Method of Assembling the Porcelain Rings

This choice was governed by two considerations: on the one hand the need to reduce as far as possible the organic material exposed to vacuum and HT and, on the other, the need to find a relatively fast method which does not depend on processes completely different from the techniques used for joining together the conventional tubes so far manufactured at CERN. These have always been joined together with araldite. This method was retained, but the out-gassing was reduced by means of a high impedance channel and an indium seal (Fig.6 & 7). As a second consequence of this, araldite is no longer exposed directly to breakdowns, ions and electrons. The intermediate stainless steel disk is in close contact, at A, with the ground portion of the porcelain for a length of 10 mm on the internal side (flatness $\pm$ 0.005 mm). It is then interrupted to leave room for the indium seal. The second disk, concentric with the first, is joined to the porcelain with cold setting epoxy (type Ciba No. AW 106, hardener HV 953 U). An annular groove for the surplus epoxy is provided. The porcelain is sandblasted on the sticking surface. Great care is taken to sandblast very homogeneously (overall flatness $\pm$ 0.01 mm) so as to obtain a rather constant gap for araldite, preventing, during assembly, local overpressures on the liquid cement, with corresponding risk of escape beyond the indium joint to the vacuum side. The araldite joint should be thick enough (0.1 $\div$ 0.2 mm) to allow flexibility. The first tube, glued with a film of only 0.05 mm, was not satisfactory. The epoxy, under mechanical stresses due to normal shrinkage, thermal coefficient difference and pressure changes when putting the tube at atmospheric pressure or under vacuum, was probably overstressed and presented mechanical weakness. It needed frequent leak repairs. For this reason, the present tube was glued with a 0.2 mm joint, defined by the recess machined in the stainless steel plate.

Assembly Procedure

The best assembly procedure, used for the operational tube, was carried out in fifteen steps, taking a little more than two weeks. Only one joint was made at a time, allowing better control and attention. Seven groups of two porcelains were first produced and then put together on the same principle. A set of two porcelains and corresponding discs were cleaned with the same procedure techniques as the electrodes (see para. 3). The glueing phase was then started immediately, so as to prevent humidity absorption of the surfaces or increase of oxide layer. The epoxy was applied to the surfaces, the thickness controlled to a precision of $\sim \pm$ 0.02 mm, and measured with a depth-micrometer. This was important in order to achieve homogeneous behaviour of the whole assembly when pressure was applied to it, and was decided after several unsuccessful trials with more conventional techniques. A small and constant epoxy surplus of $\sim$0.15 mm thickness was produced all around the porcelains, ensuring that the bond was sufficient everywhere. The pieces were put together with the aid of a special centering device (Figs.8,8A) the indium joint being carefully placed in position, its two ends chamfered. A pressure of 15 tons was then applied progressively to compress the indium seal and left for the polymerization time of epoxy, i.e. 24 hours. The indium holds back the araldite during the application of the pressure, preventing it from spreading towards the inside of the tube. Fig.9 shows an assembly detail, taken apart for demonstration purposes. A minute chamfer (Fig.6) on the inside angle of the porcelain rings reduces the mechanical stress and prevents damage. In spite of the risk of the indium seal losing its tightness in time, it is considered that the out-gassing of the epoxy in the tube has been considerably reduced.

5. Choice of shielding electrodes

a) Electrostatic Shielding of Junctions

The above described assembly has one drawback: since the porcelain is not metallised, the high impedance channel A is subjected to a difference of potential which is mainly harmful at the negative extremities and could reduce the breakdown voltage of each stage (Ref.D). It was decided not to attempt metallisation, since it was not known how to make a deposit sufficiently resistant to discharges and geometrically well defined, particularly at the porcelain angle.

It was preferred to reduce the field considerably at the insulator/metal junctions, particularly on the negative side, by means of a cylindrical 316 L low carbon stainless steel electrode (Fig.10).

b) Shielding Against Ions and Electrons

Four main criteria were observed:

1) to protect the porcelain rings from the ions and electrons emanating from the anode and the cathode;

2) to protect the beam from the electrostatic effect of the charges deposited on the walls of the porcelain rings, a condition which is automatically satisfied if the first condition is fulfilled;

3) in order to prevent the secondary electrons produced on the exposed surface of the shielding from being attracted towards the opposite electrode and giving rise to a process like an avalanche moving in the direction of the porcelain rings, to retain them by correctly choosing the polarity of the local field. In the case of overlapping conical electrodes, this condition means that the small diameter of the cones must be directed towards the positive side of the tube;

4) as shown by various reports (Ref.E), to keep the volume B in Fig.10 big enough and the pumping impedance as low as possible between the porcelain and the centre of the tube. This prevents the accumulation of gas when micro-discharges occur along the insulators, thus preventing breakdown. This condition is evidently contradictory to the previous three.

THE NEW 500 keV SINGLE-GAP PRE-INJECTOR TUBE FOR THE CERN PROTON SYNCHROTRON LINAC

J. Huguenin, R. Dubois, G. Visconti, R. El-Bez

1. Introduction

The conventional multigap low gradient DC accelerating tube, serving as pre-injector to the CERN Proton Synchrotron Linac (see Ref. A), was replaced in April 1966 by a "single or two-gap" (adjustable from 7.5 to 12.5 cm) high gradient (~45 ÷ 75 kV/cm) DC tube. This tube accelerates at a duty cycle of 1 μ/sec, 0.6 ÷ 1 A protons, 10 ÷ 30 μsec from a duo-plasmatron source (Ref. F).

This paper describes the conception, construction, testing and operational behaviour of the new tube. Special attention is given to the influence of contaminants and to a measurement technique for evaluating its effect in terms of "deconditioning rate". Deconditioning rates from 1 kV/h, corresponding to excellent vacuum cleanliness, to values as high as 100 kV/h, in the case of heavy pollution, have been measured and analysed. The tube runs, at the present time, very satisfactorily at 540 kV, with a deconditioning rate in the region of 5 kV/h and with less than one breakdown per hour (July 1966).

2. General Design

The vacuum chamber is of the conventional type (Figs.1 & 2). It consists of a stack of 14 (instead of 13 as in the previous Linac tube) porcelain rings, glued to disks of 316 L low carbon stainless steel. The method of assembly has been greatly refined and is described under item 4. In the air, two parallel chains of 2600 megohm resistances divide the potential, giving a voltage of 39 kV per stage, each stage measuring 64 mm, which represents a mean gradient of 6.1 kV/cm. The maximum breakdown voltage of the air structure is about 640 kV. At this voltage, flashover occurs between the anti-corona rings. This limit can be reduced at will by adding protective spark-gaps to each section. Fig.2 shows the air side of the tube. There is a nylon cord bearing a counterweight to relieve the araldite joints of the weight of the source (150 kg with the extraction transformer).

The porcelain rings (made of special high voltage quality, delivered by the firm Langenthal in Bern) are glazed on the air side and roughly sandblasted on the vacuum side. They are protected by stainless steel and titanium shielding (Figs. 1 & 3) which are described under item 5. The inside diameter of the porcelain rings (500 mm) is considerably greater than that of a conventional tube. The source is housed inside the tube and, in addition, there should be sufficient distance between this source and the side cylindrical shielding electrodes (Fig.4 shows the anode envelope). The cathode (Fig. 5) contains a magnetic focusing triplet held by four supporting rods. In order to avoid damage to the low voltage circuits of the triplet by HT breakdowns, the cathode has a system of double earths, carefully insulated from each other. This also allows cathode currents to be measured with any instrument placed on the earth return. A glass ring cemented with epoxy resin between two aluminium flanges provides the necessary cathode insulation, capable of withstanding HT surges. The accelerating gap may be adjusted by displacing the cathode by a distance of between 75 and 125 mm. An electrode at a medium voltage can be placed if necessary between anode and cathode at different axial positions to produce two different accelerating gradients and change the beam optical condition. This can also possibly improve vacuum high voltage hold-off by voltage subdivision.

3. Choice of Material for the Electrodes, Fabrication and Cleaning

a) Choice: pure and alloyed titanium are the basic materials of the tube electrode (see Refs. A, B & C).

b) Fabrication: a first set of electrodes was made of pure titanium (quality T 40, Ugine) for the laboratory tube, since pure titanium can be machined and welded more easily than the alloys and can be delivered more quickly. A second set was prepared for the tube which is now in operation in the Linac. Due to delivery difficulties, some parts were made of

- pure titanium (T 40 from Ugine) for low gradient or low voltage regions
- alloyed titanium for high gradients and high voltage regions, namely T 6% Al 4% Va (Ta 6V from ugine) for the anode and cathode faces.

The electrodes were fabricated in CERN workshops. The difficulties encountered in spinning and welding were enormous but were mastered by the remarkable skill of the sheet metal workers. Alloyed titanium, as well as having a low modular of elasticity and high elastic limit, has also a low ductility, which makes it very difficult to spin. The basic material was 2 mm or 0.8 mm cold-rolled sheet. Spinning was accomplished sometimes using heat treatment to release tensions. Great precautions were taken in the polishing so that no organic compound would be inserted in the material. Classical polishing with a buffing compound was abandoned. Silicium carbide powder was placed on the polishing wheel made of natural fibres. Wet finishing with alumina powder and water, with a grain size down to $0.15 \cdot 10^{-3}$ mm (gamma type alumina) was used.

c) The cleaning procedure was the following:

1) hot perchlorethylene, vapour and liquid
2) ultrasonic dip with detergent and hot distilled water rinse
3) cold acetone dip
4) cold ethyl-alcohol dip
5) vacuum degassing at 10^{-4} and 80 °C for twelve hours in a special tank, followed by dry nitrogen filling of tank to prevent re-absorption of water vapour at tank opening.

dirty surfaces, and most probably by the unscreened insulating materials of different beam apparatus placed in A (Fig. 1) (porcelains, insulated wires, etc.), which could be bombarded by ions coming from normal conditioning discharges and escaping into the vacuum tank A. This particular phenomenon was very clearly proved to exist on a later occasion. A very encouraging fact is that the contamination of electrodes disappeared when the origin of the pollution was eliminated, without having to dismount and clean them.

In April 1966, during the three-month shut-down of the proton synchrotron, the new pre-injector was re-installed in the Linac, taking great care to have a close control of the situation, adding step by step each new element in the system and checking the hold-off after every change. Residual gas analysis was first made, but did not show anything abnormal. The section between pre-injector tank and Linac Tank I had been dismounted, cleaned and remounted grease-free, or with only a minimum of grease. All insulation material in Tank A had been protected by a metal screen against ionic, electronic or beam proton bombardment. Excellent results were obtained in this manner. Only the 550 keV beam stopper was left in pyrex and caused trouble during the time necessary to degas it under beam bombardment. Deconditioning rates, starting at $\sim$12 kV/h at the first formation, went down in three weeks to the very low figure of 1 kV/h, this improvement being produced by time and voltage. Simultaneously, breakdown rates went down correspondingly. On 15 July, as this report is being written, the tube has been working two months continuously on operational regime at 540 kV. Fig. 13 shows the evolution of breakdown rates and deconditioning since April 1966. Let us mention that the cathode current being so low (1 - 5 uA peak in micro-discharges), the mean X-ray dose is about 1 mR at 4 metres.

A remarkable fact was the effect of an air leak at a tube araldite joint, which produced a net increase in breakdowns, disappearing soon after the leak repair. The cold traps have to be degassed in turn once a month by stopping the N_2 filling for 24 hours and letting them warm up at room temperature. We would like to introduce in the future a quick trap-warming-up device to allow increased flexibility. In the laboratory, we had clear evidence of breakdowns correlated to a rise in pressure of a few 10^{-6} mm Hg produced by trap saturation. In such cases, one is also more sensitive to the start of the automatic filling cycle, which would then produce breakdowns: the transfer line from the dewar is first at 20° C and the first N_2 injected is gaseous and not yet liquid. It will warm the trap for about one minute instead of cooling it down. It is foreseen to eliminate this first warm blow by an adequate device. A gas analysis showed Hg, H_2O and light hydrocarbon lines were produced first when trap warms up. A controlled leak of a very minor quantity ($\sim 10^{-8}$ mm Hg) of these components, made deliberately into the vacuum system, produced micro-discharges, so it may be assumed that they are responsible for the HT behaviour observed in connection with dirty traps. Another important fact is that one must be extremely careful to prevent electrons produced elsewhere from entering the tube. Ionization gauges, if placed on the vacuum tank too close to the tube, or vacion pumps if used in this region, must be provided with electron collectors. The back-streaming high energy electrons from Linac tanks are deflected by the triplet magnet field and do not do any harm. Defocused protons producing secondary electrons in the tank can have some bad effects and should be avoided. For the same reason, beam diaphragms should be made of a material with low secondary electron coefficient, such as titanium.

Conclusions

The new tube has proved to work very satisfactorily if the necessary precautions are taken to maintain a high degree of cleanliness of vacuum. The precautions taken in the tube assembly procedure, in the fabrication and preparation of the electrodes, in cleaning and mounting the vacuum system, in the adjustment of cold trap automatic filling, in the choice and proper shielding of all insulating material in the vacuum, in minimizing air leaks, in preventing electrons coming backwards into the tube were all necessary and profitable.

Acknowledgements

We wish to emphasize our indebtedness to Mr, L. Solinas, head of PS Mechanical Section and Drawing Office and Mr. P. Mann, who were responsible for the mechanical design of this project; to Mr. F. Malthouse, in charge of vacuum and the automatic refilling device for the cold traps; to Mr. B. Vošicki, head of the new pre-injector project and Messrs Cl. Germain and F. Rohrbach, NPA Division, CERN, for numerous profitable discussions; to Mr. C.S. Taylor, head of the Linac Group, for his support; to Mr. C. Steinbach, helped by Mr. R. Martin, who designed the beam loading compensation circuit; as well as to our colleagues of Linac, MPS Drawing Office, MPS and SB workshops for their contribution to the project. We would also like to thank Dr. K.W. Arnold, Department of Electrical Engineering, Colorado State University, Fort Collins, Colorado, who, by a private communication, led us to the investigation of alloy Ti 89 Al 7 Mo 4 for electrode material.

ADDENDA

High Voltage Circuit and Compensation Circuit for Beam Loading

The main HT circuit is shown in Fig. 14. The previous conventional multigap tube was protected by only 10 kΩ. In the new tube, due to the higher gradient and possibly to the use of titanium, which is easily sputtered, it is impossible to use such a low value of series resistance, which leads to very bad voltage holding. As mentioned in §7, a resistance R_1 of 6 MΩ was chosen. Going to greater value seems to further

These criteria were observed, while aiming at a relatively simple mechanical construction and also taking into account the difficulty of machining titanium. Fig.10 shows the solution adopted. Each electrode consists of an external cylindrical 316 L stainless steel electrode and a truncated titanium cone held on the outside by a flat ring also made of 316 L. Each part may be dismounted separately. It takes no longer than fifteen minutes to dismount the thirteen shields.

6. Choice of Vacuum Pumping System

To minimize organic vapour in the system, mercury diffusion pumping was chosen. Two pumps (type Leybold Quick 2000) with liquid N_2 trap, having each an effective speed of 800 l/s, are working in series with two mercury ejectors (type Leybold Hg 45). The latter will give a good speed at intermediate pressure, allowing for a quick response for micro-discharge whiffs of gas.

Baked Viton or conventional O-rings are mounted without grease, except at a few exceptional places when a little grease was necessary to prevent leaks. An ultimate pressure around 10^{-6} mm Hg is obtained with the source off. The source on will produce an increase of pressure of 2.10^{-4} mm Hg of hydrogen.

7. High Voltage Behaviour of Tube

Description of HT Conditions and Measuring Apparatus

When the tube has been pumped long enough (ranging from one to twenty-four hours according to the case), HT conditioning is started using a circuit with a capacity of 10.000 pF damped by a 6 megohm resistance. The voltage is raised at a constant speed (ranging from 5 kV/h to 240 kV/h according to the electrode state) and the following values are recorded on a continuous multi-channel recorder: voltage, cathode current, pressure and cold trap filling. Oscilloscope measurement can be used for voltage, cathode and X-ray, the latter being monitored by a photo multiplier (Fig.12). Breakdowns are counted separately on a Sodeco time printer. This allows an improved processing of the available data. Another useful measurement is that of the so-called deconditioning rate. It will be described in the following paragraph.

Measurement of Deconditioning Rate

Putting electrodes in vacuum under voltage will change their surface condition. For a given system, there is a corresponding equilibrium state at each voltage, where the quantity of "pollution" q_1 leaving the surface per unit of time and the quantity of q_2 arriving on it will produce a stable state. This state is reached after a period depending on initial conditions. It can then be said that the system is conditioned at that voltage. The higher the voltage, the smaller the residual quantity of contaminant at the surface. If, after conditioning at a voltage U_1, one drops to a lower voltage U_2, the system remains for a certain time in an "over-conditioned" state. The surface is impoverished (under-critical), q_1 seems to drop to zero, which is visible by the sudden stop of micro-discharges and degassing peaks on the chart-recording (Fig.11). When q_2, representing the amount of pollution to the electrodes by the system, has recharged the surface sufficiently, the critical stable state will be reached again and micro-discharge, accompanied by degassing peaks, will recommence. The time t necessary will be related to the "cleanliness" of the system, and the quotient $\frac{U_1-U_2}{t}$, called "deconditioning rate" will be representative of the ambient pollution. This method is used systematically during tube tests and operation and produces highly useful information.

Results Obtained

The tube was first tested in January 1965, with a gap of 10 cm but without source and matching triplet. After a 640 kV formation was made, it was put on long-term test around 600 kV for two months and then inspected. The porcelain rings were intact, the cathode alone showed some pitting. During this period, the breakdown rate ranged from one to ten per day and the deconditioning rate around 1 kV/hour, which was considered an excellent figure.

Installation of the source and matching triplets impaired the voltage stand-off and increased the breakdown rate up to 30 ÷ 50 per hour and the deconditioning rate to 50 to 100 kV/h. An initial improvement was obtained by removing the molybdenum grid mounted in the cathode, which must have reinforced the electrical field too strongly. However, this purely geometrical effect could not explain the losses of formation, which seemed rather to imply a problem of pollution, which were finally found in welding flux coming from bad welds and oil traces. The possibility of contamination by the barium or barium oxide of the filament of the source was first considered due to the difficulties encountered in similar cases by high power tube manufacturers. 500 keV backstreaming electrons were definitely hitting the oxide surface which was marked at its centre. Nevertheless, this hypothesis was finally disregarded because of the well-screened geometry of the source snout chamber. After removing some of the sources of pollution mentioned, conditions improved (five breakdowns/hour, deconditioning rate 15 kV/h) and the source was put into operation. Full beam current (0,7 A, 20 µsec, 1 p/s) did not cause any breakdown unless the beam was badly focused and was spraying the downstream electrodes and surfaces.

When the tube was mounted in the Linac in June 1965, it was much more difficult to hold the voltage. At 500 kV and 75 mm spacing, we had about one breakdown per second and it was impossible to go above this voltage without filling the tube with 7.10^{-5} mm Hg of helium. The deconditioning rate was superior to 100 kV/h. For this and proton beam behaviour reasons, it was decided to replace the structure in the laboratory, where a good hold off was immediately obtained again after a normal formation (five breakdowns/hour, 15 kV/h). This clearly proved the origin of pollution to be located in the Linac vacuum system, which had many greased O-rings and rather

improve the hold-off. An upper limit is nevertheless given by the sensitivity to small currents in the air or vacuum, leading to unwanted voltage drops at the source terminal.

The source current will cause the stray capacitance of source terminal $C_5 = 300$ pF to drop according to the curve shown in Fig. 15b. A constant beam current will produce a linear drop. Typically, a 20 usec 600 mA pulse will produce a final drop of

$$\Delta U = \frac{20.10^{-6} \text{ sec } 0.6 \text{ A}}{0.3 \cdot 10^{-9} \text{ F}} = 40 \text{ kV}$$

This drop does not include the effect of secondary electrons accelerated backwards because they are deflected by the focusing triplet and prevented from entering the accelerating gap. The maximum tolerable energy spread being in the region of $\pm$ 1 kV, a compensation circuit has been added.

A 5000 pF capacitance, charged to ~60 kV, is discharged with the necessary time constant into the insulating capacitance C_2. Point A will have a voltage according to Fig. 15d, with voltage fluctuations below $\pm$ 1 kV during the beam pulse. The voltage will of course rise again after the beam pulse. In the case of the beam stopping accidentally, a ~55 kV over-voltage, according to Fig. 15c, will occur for a few milliseconds. It was feared that this would produce tube breakdowns, but happily this was not the case. In addition, the stability of the beam from pulse to pulse is good enough so that this type of programmed compensation with a fixed voltage could be used without trouble. Nevertheless, the need for longer beam pulses for multiturn injection will necessitate the introduction of a hard tube pulser circuit so that the secondary supply voltage does not have to be raised too much. At the same time, a feedback circuit should allow the voltage to be regulated during the beam pulse as well as from pulse to pulse.

REFERENCES

A. Insulation of High Voltages in Vacuum, International Symposium, October 19-21, 1964, Boston.

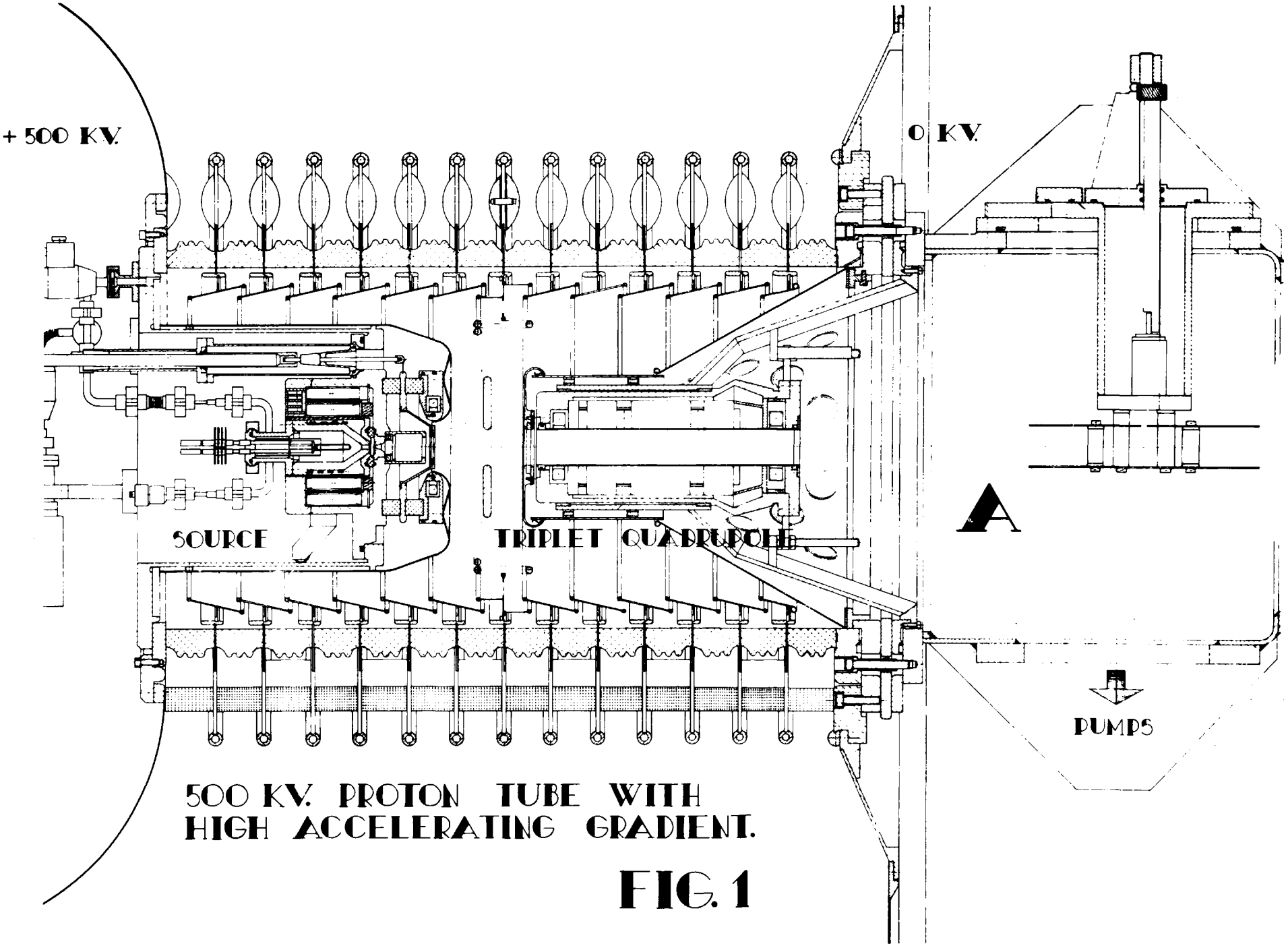
B. "Measurement of a High Gradient Accelerating Tube Model, Investigation of the Properties of Titanium Electrodes", J. Huguenin, R. Dubois, CERN Yellow Report 65-23.

C. Dr. K.W. Arnold, private communication.

D. "Effect of Metal-dielectric Junction Phenomena on High Voltage Breakdown over Insulators in Vacuum", Kofoid, Transaction A.I.E.E., v. 79, p. 999.

E. Report C.E.A. No. 189, H. Bruch and F. Prevot, Commission à l'Energie Atomique.

F. "The Duoplasmatron Source for the CERN-PS Linac", B. Vošicki, M. Buzić and A. Cheretakis, MPS/Int.LIN 66-11.



500 KV. PROTON TUBE WITH
HIGH ACCELERATING GRADIENT.

FIG. 1

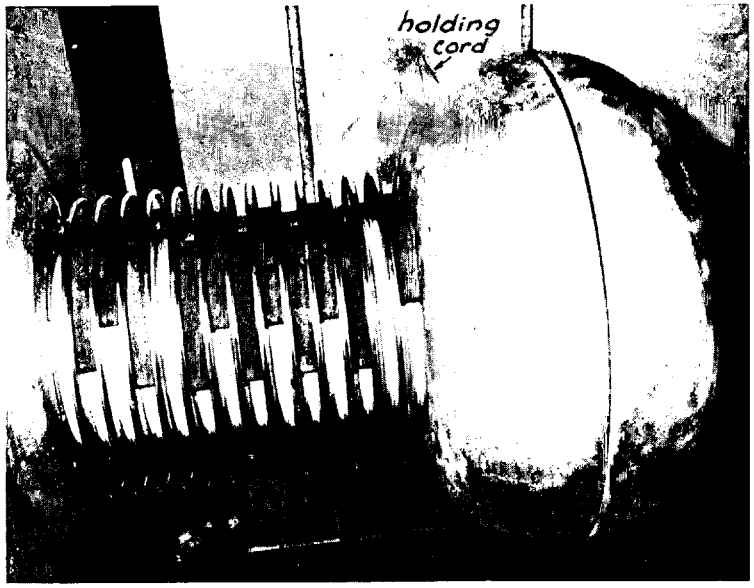


FIG.2 EXTERNAL VIEW OF TUBE

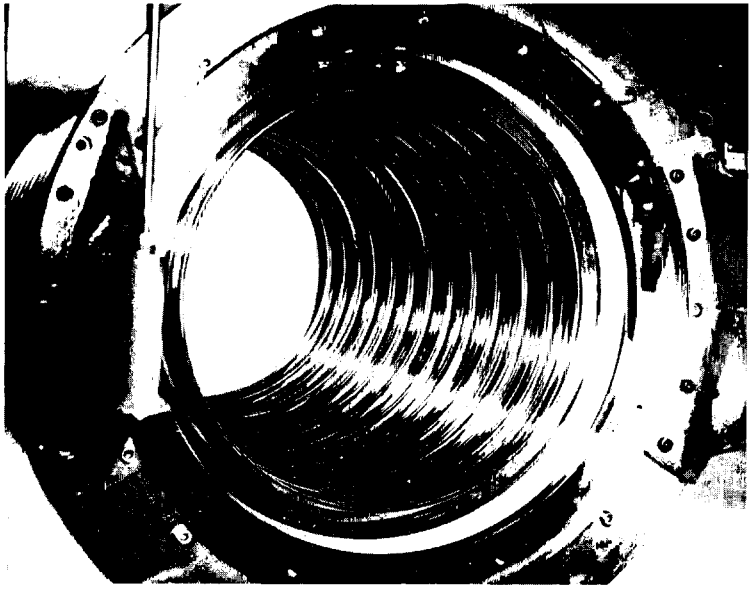


FIG.3 INTERNAL VIEW OF TUBE

FIG.4 DUOPLASMATRON TITANIUM ENVELOPE

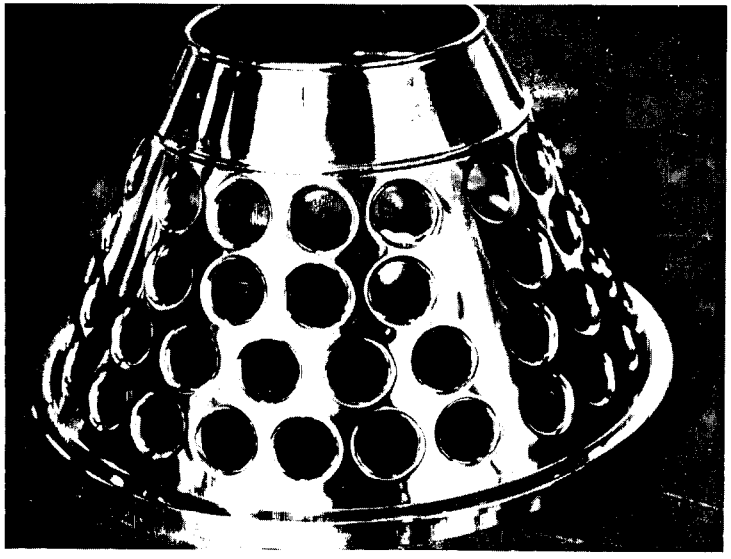
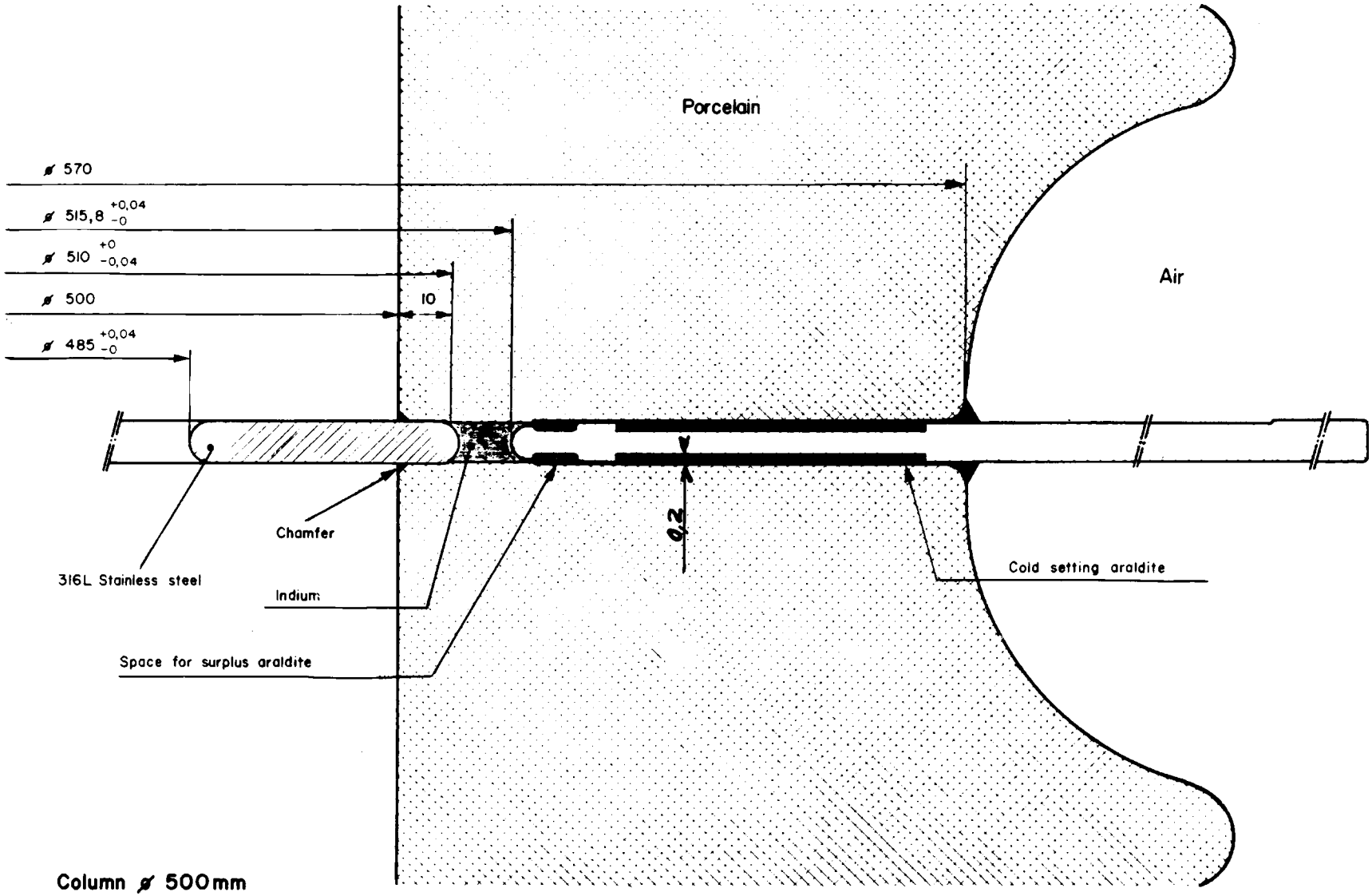


FIG.5 TRIPLET TITANIUM ENVELOPE WITH PUMPING HOLES



Column ø 500mm

Joining of porcelain rings

Fig. 6

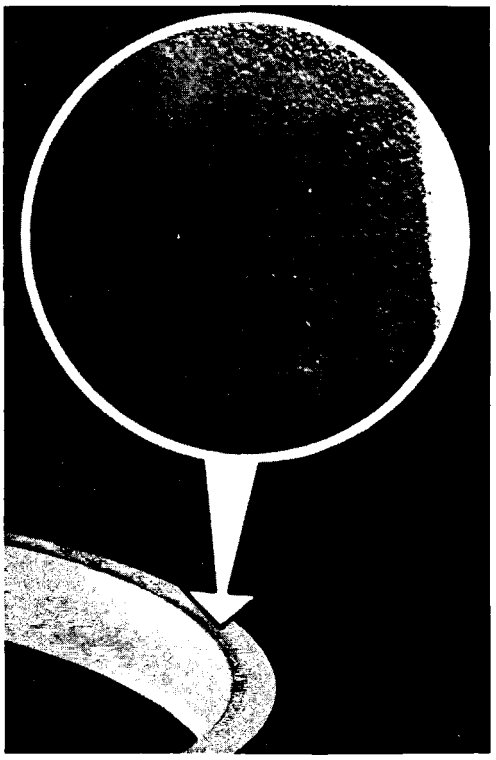


FIG.7 PORCELAIN. DETAIL OF SURFACE PREPARATION PRIOR TO JOINING WITH ARALDITE .

FIG.8 ARRANGEMENT OF CENTERING JIG SHOWING TWO GROUPS OF TWO PORCELAINS IN POSITION FOR JOINING

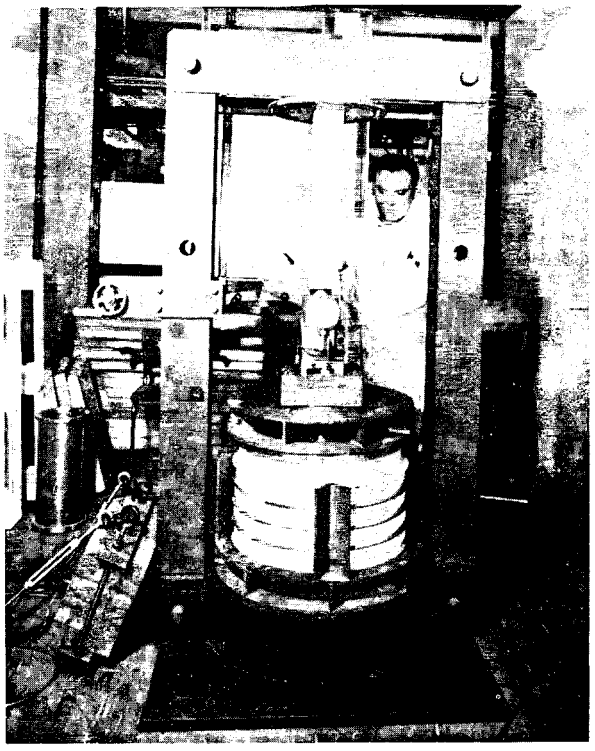


FIG.8a IDEM 8, BUT WITH LOAD OF 15 TONS APPLIED

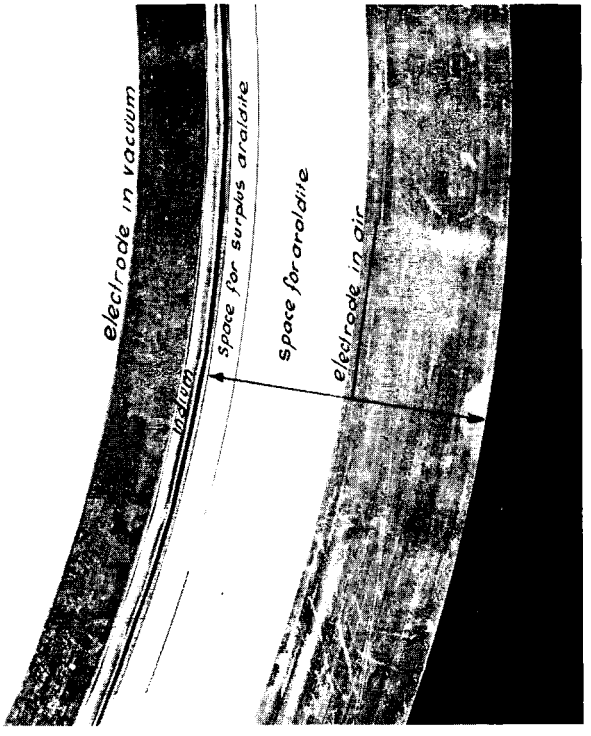


FIG.9 VIEW OF TWO ST.ST. RINGS SHOWING INDIUM JOINT

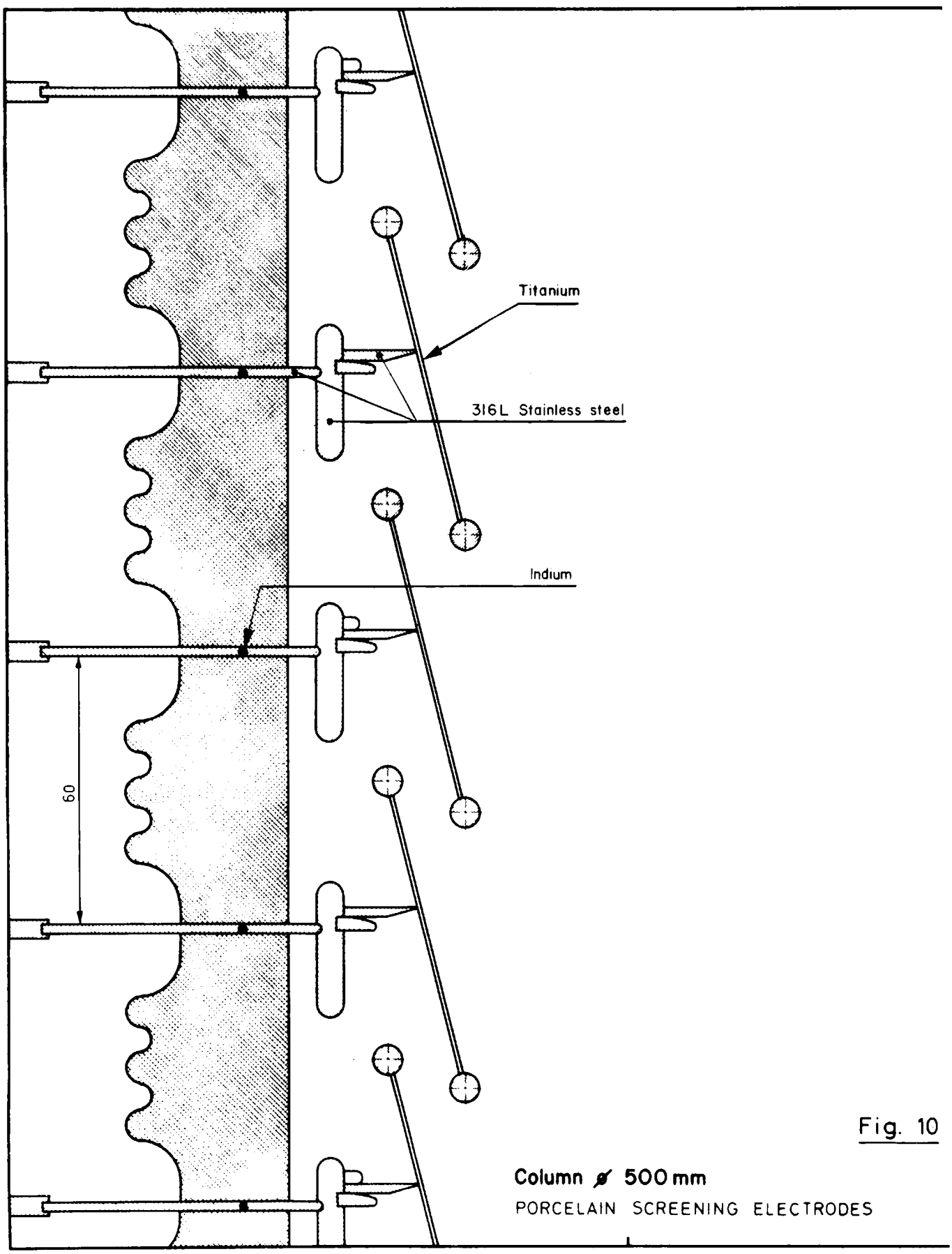


Fig. 10

Column ⌀ 500 mm

PORCELAIN SCREENING ELECTRODES

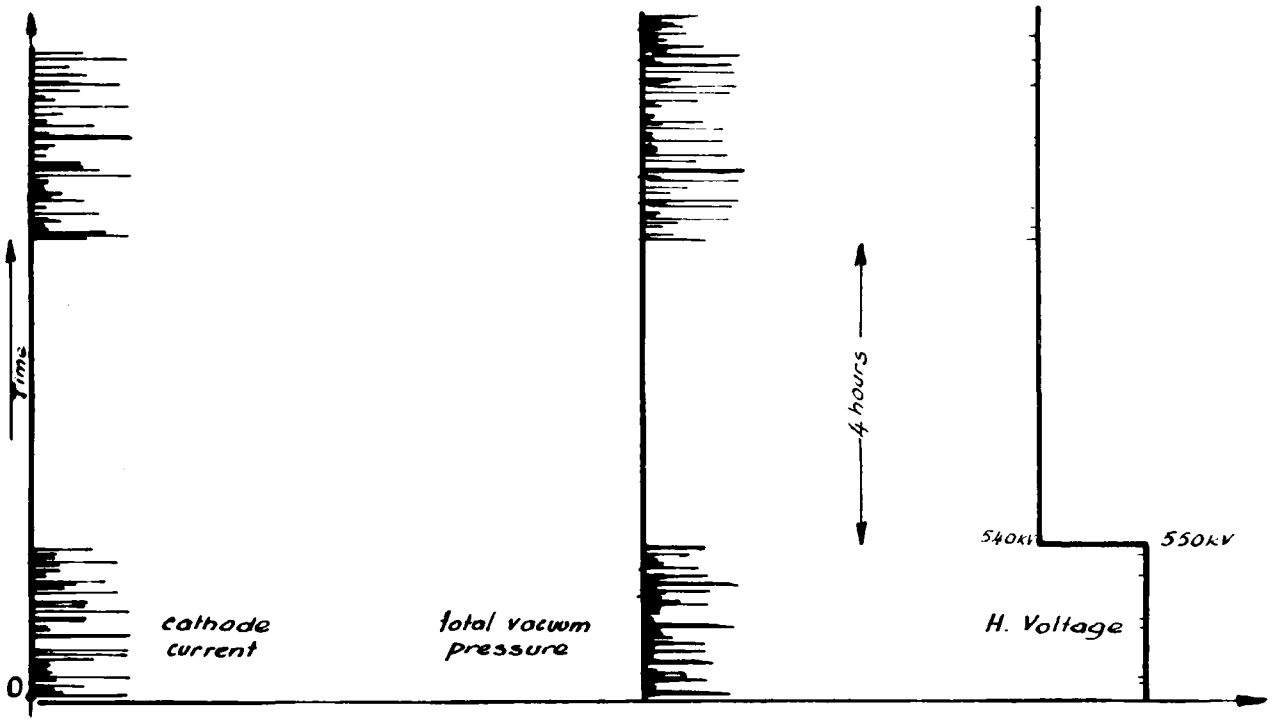


Fig. 11 Example of rate of conditioning loss measurement

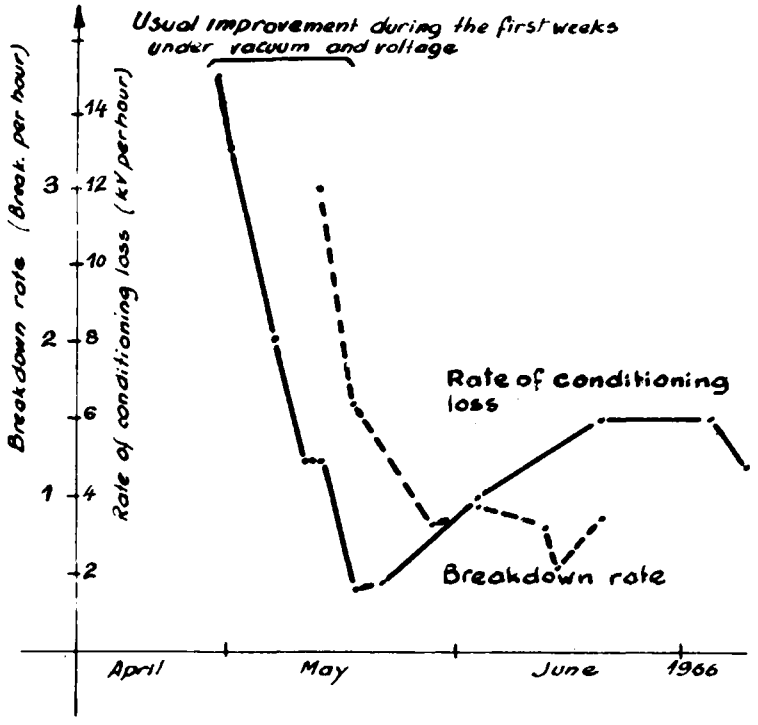


Fig. 13 Breakdown rate and rate of conditioning loss from april 66

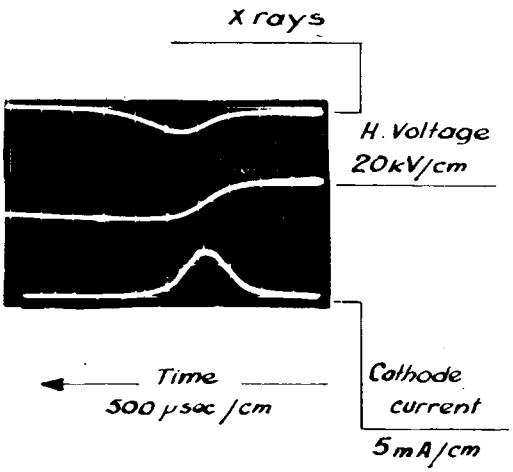


Fig. 12 Typical oscillogram of micro discharges

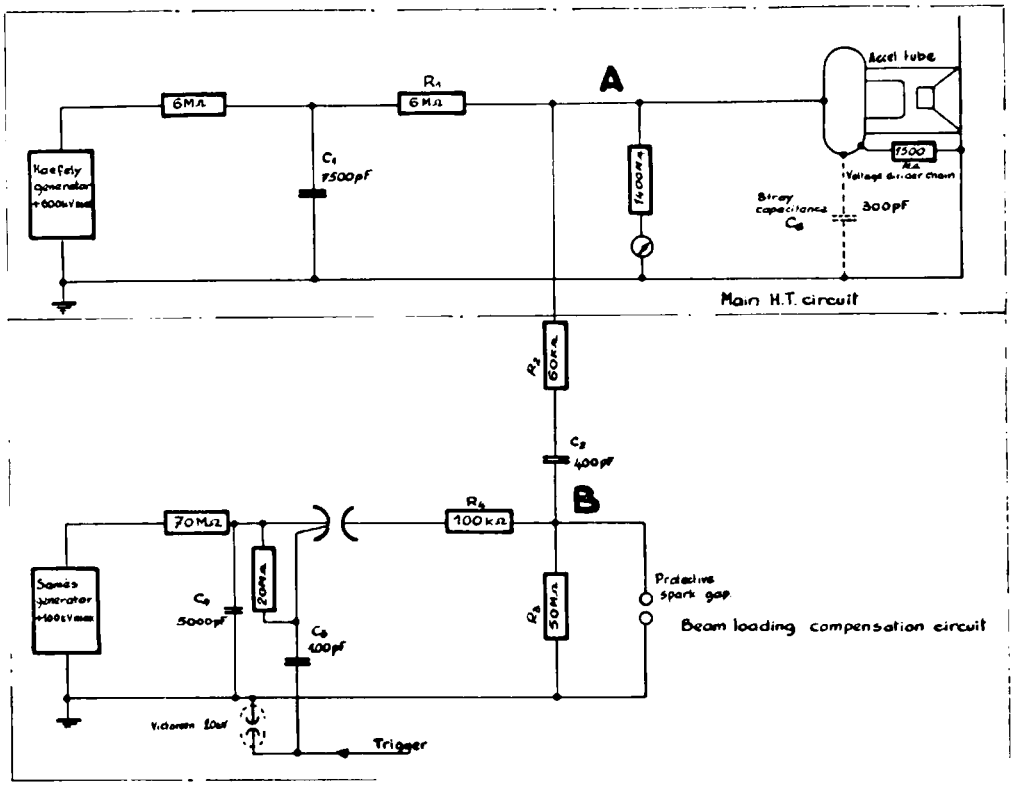


Fig. 14. Main H. T. circuit and beam loading compensation circuit.

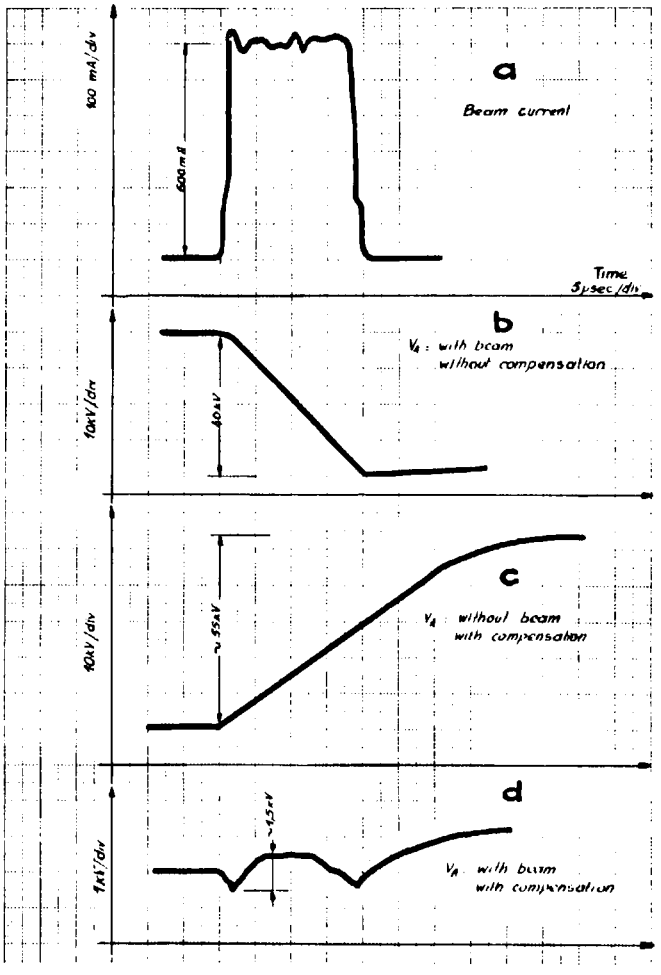


Fig. 15. Beam loading compensation--oscillograms.