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PROPOSAL FOR A HIGHER ENERGY PREINJECTOR FOR THE CERN P.S. +

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ABSTRACT

A paper on the : "Preliminary Study of a Higher Energy Preinjector for the CERN PS" was presented at the 1968 Brookhaven Conference, in which the expected improvements in the Linac beam to follow such a change were discussed. The continuation of the study produced some interesting results which are the subject of the present paper. These include high voltage tests (to 1.2 MV) on the CERN high gradient accelerator tube, ion optical calculations and proposals for the design of the HT generator.

We conclude that it seems feasible, taking a reasonable technological risk, to construct a pressurized 500 mA preinjector with a final energy of 1.4 MeV. Details of the layout of such a preinjector are included.

Arguments for a Higher Energy Preinjector

Over the past ten years the intensity of the CERN Linac has been increased by a factor of ten. When looking for the reasons of this large increase, one must state that all of them lie in the preinjector region : at first (chronologically) modifications in the preinjector focusing system and then the installation of the DP ion source and the short column were responsible for this rise of the linac beam. The modifications in the linac itself were mostly intended to cope with the increased intensities (RF beam loading compensation) in order to maintain the beam energy spread within tolerable limits.

Today the CERN preinjector is capable of delivering > 500 mA comprised in normalized transverse emittances of ∿ 4π mm mrad. This beam cannot be handled efficiently by the linac, in particular its front end; so some modifications are needed in this part of the linac if one wishes to keep the current (in intensity and quality) the preinjector is offering.

It must be remembered that the linac acceptance (in all phase planes) drops with the current increase [1,2]. In the transverse phase planes one can minimize this drop by an appropriate increase of quadrupole gradients. In the case of the CERN Linac one can, in addition, change the focusing from ++-- to +-, bringing thus an increase of the acceptance of ∿50% [1,2,3]. Longitudinally, the possibilities for an acceptance increase counter-

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acting the space charge effects lie in an increase of the stable phase angle. Unfortunately a larger stable phase angle has to be accompanied with an increase in the accelerating field as well as with an additional increase in quadrupole gradients. All this is practically impossible at 500 keV - so, to cure the situation at the linac front end one has to start again with the preinjector, this time trying to raise its energy by an amount sufficient to permit the above modifications.

Preinjector Structure and Choice of Energy

Going to higher energy with an open air preinjector structure would require serious moditications to the present PS linac building. Anyhow, above 850 kV, the insulating distances in air become prohibitive. The technique of pressurized systems, so long in use on van de Graaff generators, therefore becomes attractive.

Balancing advantages to be gained at higher energies from beam optic considerations, against technological difficulties and available resources (budget, manpower, time), made us choose 1400 kV as injection energy. This corresponds to the injection into the 9th cell of the present PS linac. An energy of 1400 keV is a reasonable extrapolation on the accelerating tube side from the encouraging results obtained with 1200 kV tests on a CERN accelerating tube (without beam) carried out at the University of Lyon. The HT of 1400 kV can be obtained in a pressurized environment by a series arrangement of two 750 kV generators of a design already tested in operation on the Saclay 750 kV pressurized preinjector. The horizontal arrangement of the latter has also been adopted for our proposal.

General Description of the Proposed Preinjector

The important parameters of the preinjector are given in Table 1.

The main components are mounted horizontally on the extended axis of the present linac in a pressure vessel with 7 atm. of SF_6 (see Fig. 1 to which the numbers in brackets in the following text refer).

The ion source is a duoplasmatron of the CERN type[4] giving reliably 500 mA of beam current (during 100 μs) at 2 p.p.s with a current density of ∿ 200 mA/cm^2 in a normalized emittance ∿ 4π mm mrad. It is placed in the anode (19) of the accelerating tube. Associated electronics are mounted in the two parts of the high voltage terminal (2), one part being mechanically supported by the accelerating tube, the other by the HT generator. Power is fed to the terminal equipment from a 3 kVA 400 Hz generator (17). Telemetering and controls go digitally over infra-red light channels [5] between ground and the HT-terminal, permitting a liaison to the PS control computer (IBM 1800). A closed liquid circuit with a heat-exchanger transfers the heat developed in the source to the surrounding SF_6 gas. A light metal container with hydrogen (3000 l NTP) mounted beside the source permits with the present gas consumption[6] 3000 hours of source operation before replacement.

The accelerating tube (3) is an extrapolation of the present CERN design[*] [7] making use of the excellent high voltage properties of titanium alloy to permit higher electric gradients in the tube than is normal with stainless steel or aluminium electrodes. The accelerating electrodes are shaped to allow for a high pumping conductance in the tube. The number of ceramic rings in the tube has been increased to eighteen, giving a total length of 120 cm, a longitudinal field at the tube wall of 11.7 kV/cm and a voltage per section of 78 kV. The CERN gluing technique is preserved, i.e. an indium ring prevents any outgassing at the araldite joint reaching the interior of the tube. The anode (19) and the cathode (21) are reentrant in order to permit a lower gradient at the tube walls. The ion source is mounted in the anode and a focusing quadrupole triplet in the cathode. The electrodes (20) assure the desired potential law of acceleration, in our case a Pierce structure to $\sim$ 700 kV followed by a constant gradient section to 1400 kV (E_{max} = 76 kV/cm). The anti-corona rings (22) at the outside of the tube have a diameter equal to the HT terminal and those close to the terminal have an oval section in order to reduce their surface gradient. Eight series of 120 kV spark gaps protect the sections against over-voltages. The voltage distribution along the tube is controlled by carbon resistors of the CERN design[8] or a liquid resistor of the Saclay type.

The high voltage generator (1) and its electrode are mechanically supported by four Makrolon rods (11) in cantilever fixed on the base plate (5) of the pressure vessel. Output voltage is nominally + 1.4 MV with a long term stability of 10^{-3}. The DC load current is 500 μA, whereof 100 μA for the measurement resistor. Peak current capability of the generator should be at least 5 mA. The Saclay preinjector [9] utilizes a cascade generator of 750 kV using selenium rectifiers and barium titanate capacitors. Our proposal is based on two similar generators in series; one fed with 2000 Hz at ground level and available for fine regulation, the other from a 2000 Hz generator (16) placed in an intermediate electrode at 0.7 MV. A motor at ground (14) drives this generator over an insulated shaft (15) and over a second shaft the 400 Hz generator at 1400 kV. A protective resistor (13) is electrically in series between the HT generator and the HT terminal.

Beam loading compensation is needed if one has to keep the HT terminal voltage within the required limits of $\pm 10^{-3}$. Since the capacitance to ground of the HT terminal is only about 700 pF, the terminal voltage would, if nothing is done, fall linearly during the beam pulse, attaining a droop of 110 kV at the end of the pulse. A cylindrical electrode (7) is therefore introduced between the HT terminal and ground permitting one

* Recently commercialized by a HT firm in view of manufacturing several accelerating tubes for the Heavy Ion Accelerator at Heidelberg.

to introduce an opposite voltage which will cancel the effects of the original droop. In reality we set the compensating voltage proportional to the discharge current, i.e. the beam current, since the latter is more readily measured with the help of a current transformer.

The pressure vessel consists of a central part (4) and two end plates (5,6). The principal electrical fields inside the vessel, indicated in Table 1, have led us to adopt in agreement with several commercial accelerators (Fig. 3) SF_6 at 7 atm. as insulating gas. A gas treatment plant should permit us to execute a complete working cycle, opening-closing, in about 1 hour. This condition, imposed in order to reduce dead time at interventions in case of failures, requires gas pipes of large dimensions adapted to big sized compressors and a well-studied heat exchange system for reducing the thermal shock in the preinjector during the expansion and compression of the gas. The opening of the pressure vessel can be executed in different ways (Fig. 2) if access is required to the accelerating tube, HT terminal equipment or HT generator.

The vacuum pump (9) should have a speed in excess of 1000 l/s for air. Several types have been tried or considered : mercury diffusion, turbomolecular, cryogenic and ion pumps. The final choice will depend on the outcome of future tests.

Preinjector Beam Optics

The acceleration of intense beams up to energies of $\sim$ 1.5 MeV cannot be done properly without a focusing scheme[10] which can be either concentrated at discrete positions or distributed along the beam path. The latter solution, a Pierce accelerating structure, has advantages in maintaining a quasi-uniform charge distribution across the beam. The axial electric field in a Pierce structure depends on the accelerated current density and increases with the potential (Fig. 4)

$$E \propto j^{\frac{1}{2}} \; V^{\frac{1}{2}}$$

j .. accelerated current density
V .. potential

The current densities at the exit of the CERN DP ion source are of the order of 200 mA/cm^2. Such densities would require prohibitive axial fields towards the end of acceleration with a Pierce structure. So, one can choose either a Pierce geometry constructed for a lower current density (non-matched) or introduce a "hybrid" acceleration scheme consisting of a matched Pierce geometry up to a certain energy and followed by a constant field acceleration. These solutions are analysed in what follows.

In addition, one has to check the behaviour of a Pierce structure under realistic conditions. This means that the structure calculated for a constant, uniform and zero emittance beam must be analysed in view of effects of non-uniform charge distributions, finite emittances and beam density fluctuations.

The analysis of the items described above is effected numerically by a computer program[11]; the results are grouped in diagrams from which one draws the following conclusions :

1. Due to a finite emittance and non-uniform beam charge density, the best matching of a Pierce geometry is obtained when designing it for a density 10-15% higher than the average beam density. In this case, the variation of the beam radius is minimum (Fig. 5).
2. Pierce and hybrid geometry are compared by imposing a maximum axial field of 76 kV/cm. The latter structure is preferable (Fig. 6)
3. Hybrid solutions having Pierce structures up to different energies are compared in Fig. 7. The Pierce structure is very efficient at low energies, less above 700 keV.
4. Non uniform beams become more uniform in course of acceleration (Fig. 8).
5. A beam accelerated up to 1400 kV with a hybrid structure does not represent difficulties for successive focusing. Fig. 9 shows the evolution of the beam envelope, where the focusing after the acceleration is achieved by a triplet having the same magnetic characteristics as the present CERN preinjector triplet, only its length being increased by the factor $\beta_{1400\ kV}/\beta_{520\ kV} = 1.65$.

Generally, a hybrid structure presents a flexible and satisfactory solution from the beam optical point of view. Flexible due to the possibility of stopping the Pierce geometry once the maximum permitted field is reached; satisfactory due to the fact that small mismatches do not alter significantly the accelerated beam quality.

High Voltage Tests of the Accelerating Tube (Berthe Project)

Due to the proposed combination of high gradients and high accelerating voltage, the accelerator tube was a part of the project which required a detailed experimental study (Fig. 10). This research was carried out in cooperation with the Institute of Nuclear Physics, IPN, at the University of Lyon. Considerable assistance during the tests was provided by the IPN staff. A test hall[12] (Fig. 11) to house the experiment and a 1500 kV generator with programmed rate of voltage rise was put at our disposal. This equipment is needed at IPN for their heavy ion linear accelerator project[13]. The maximum voltage was until now limited to about 1200 kV by the small distance between the generator and the wall of the building. An 18-section accelerator tube of conventional CERN design contained a movable cathode and anode or the intermediate electrodes to be tested (Figs. 12, 13, 14). For tests above 850 kV the accelerating tube was placed in an envelope containing SF_6 at atmospheric pressure (Figs. 15 and 16). The detailed results of the test of which a summary is given here, can be found in separate reports[14,15].

High voltage hold-off in vacuum for two titanium alloy electrodes as function of distance was measured with the set-up shown on Fig. 12 and the result is given on Fig.17. The distance is given for the condition of a cathode current of < 0.1 μA. The upper curve, measured under very clean vacuum conditions, shows that the hold-off ranges from 130 to 200 kV/cm according to electrode distance. This indicates that a subdivided high gradient accelerating tube is feasible provided that the "total voltage effect"[16] does not prove to be detrimental. The anode-cathode test using voltages up to 850 kV for the air structure shown in Fig. 11 ran for 50 actual tests days and was for lack of time interrupted in November 1969 to permit tests at higher voltages on a realistic multigap model. It will be completed for voltages to 1200 kV at a later time.

The high voltage hold-off for a group of five electrodes, similar to the ones to be used in the final tube (Fig. 13) could be expected to give difficulties due to certain geometrical factors in the electrode design. However, the extreme tapering of the Pierce electrodes towards the beam hole did not have any adverse effect in spite of very high local fields, and enabled the equipotentials of the Pierce field to be defined very accurately. Neither did the suspension of the electrodes by three rods instead of the more conventional metal cone, with perforated holes for pumping, create any difficulties, i.e. electron loading. On the contrary, this design might have been vital for the performance of the accelerator tube, since it provides a very high pumping conductance. It is known that accelerating tubes with small pumping conductance need a long recovery time after a breakdown (up to several minutes). Further, any small microdischarge, due to local out-gassing, might easily develop into a real breakdown. The fact that no problems occurred with electron loading (N.B. without beam) confirms the technique of titanium alloy electrodes in a very clean vacuum, i.e. without hydrocarbons from out-gassing of glued joints or pumping system.

The Pierce structure tested carried the max. available 1200 kV without difficulty, with a cathode current of less than 0.01 μA and a low breakdown rate, this after a rapid conditioning (50 kV/h above 1000 kV). More extreme conditions, created by moving the anode and cathode closer together to obtain fields of 80 kV/cm in the two outermost gaps did not adversely affect the hold-off.

Endurance tests on the accelerating structure was carried out at 1150 kV in order to ensure that no breakdowns occured between the generator and the building wall at a rate of 16 to 24 hours per day during 40 actual test days, with the following results :

Breakdown rate 3/h
Direct current at cathode : $\leq$ 0.01 μA
Radiation at 10 m distance : $\leq$ 0.1 mR/h
Deconditioning rate : 2 to 10 kV/h

Hold-off at the wall of the accelerating tube was also satisfactory and the current between the titanium shields was negligible.

To sum up, the high voltage tests of the accelerating tube model has made the design of a high voltage high-gradient accelerating structure look feasible, provided that tests with a proton beam confirm the above results. The use of large turbomolecular pumps in this connection has proved satisfactory.

Conclusion

Efficient use of the presently available beam of $\sim$ 500 mA from the PS preinjector calls for modifications in the PS linac. However, many of these would be impracticable if not impossible at 500 keV. Going to 800 keV the practical limit of an open air structure still does not allow all the improvements envisaged in the linac. Our choice therefore lies in a pressurized preinjector with an energy well above 1 MeV.

A compromise between advantages to be gained and technological difficulties seems to situate the energy in the region of 1.5 MeV. This region has been investigated and very conclusive HT tests up to 1.2 MV have been carried out on an accelerating tube.

Tanking a reasonable risk, it seems feasible to construct a 1.4 MeV pressurized preinjector making use of a series connection of two 750 kV generators of a design already in operational use. The results should be a substantial improvement of the PS linac beam quality as well as of its intensity bringing it up from the present operational value of 130 mA to more than 200 mA.

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Abstract sent to MPS and SI Scientific Staff

Table 1

Main Parameters of the Proposed Preinjector

Beam Parameters	
Final energy	1.4 MeV (β_p = 0.0546)
Beam current	500 mA
Total emittance at 1.4 MeV (normalized)	∿ 4 π mm mrad
Stability in energy	2.10^{-3}
Source	
Type	Duoplasmatron
Beam current	> 500 mA
Pulse length	> 100 μs
Proton percentage	∿ 85%
Current density at the extraction electrode	∿ 200 mA/cm^2
Normalized emittance	< 4 π mm mrad
Consumption	∿ 1 l/h (NTP)
Supply	3000 l/h (NTP)
Repetition rate	Max. 2 p.p.s
Power of electronics	400 Hz, 3 kVA generator
Type of controls	Opto-electronic
Accelerating Tube	
Optics	Hybrid structure (Pierce + const. field)
Max. accelerating field	76 kV/cm
Longitudinal field along the wall of the tube	∿ 12 kV/cm
Number of ceramic rings	∿ 18
Type of gluing	araldite + indium joints
Electrode material	titanium
Distribution of electrode potentials	CERN carbon type resistors or liquid resistor of Saclay type
Mechanical load on the tube (terminal flange, source and associated equip.)	about 350 kg
HT Generator	
Working voltage	1.4 MV
Stability in time	1.10^{-3}
DC current	500 μA
Peak current	about 5 mA
Type	Greinacher-series, 2 x 750 kV
Number of stages	2 x 15
Supply frequency	2000 Hz
Efficiency	0.87
HT compensation	pulsed generator 110 kV
Pressure Vessel and Gas	
Longitudinal field (HT generator and accel. tube)	< 12 kV/cm
Radial field between HT terminal and compensating electrode	$E_{surf.\ anode}$ = 103 kV/cm $E_{surf.\ cathode}$ = 69 kV/cm
Gas	SF_6
Volume of pressure vessel	∿ 16 m^3
Time for opening and closing	∿ 60 min.
Pumping System	
Speed	> 1000 l/s
Pressure limit with H_2	2.10^{-4} mm Hg
Type of pump foreseen	choice between turbo-molecular, cryogenic, ion pump, mercury

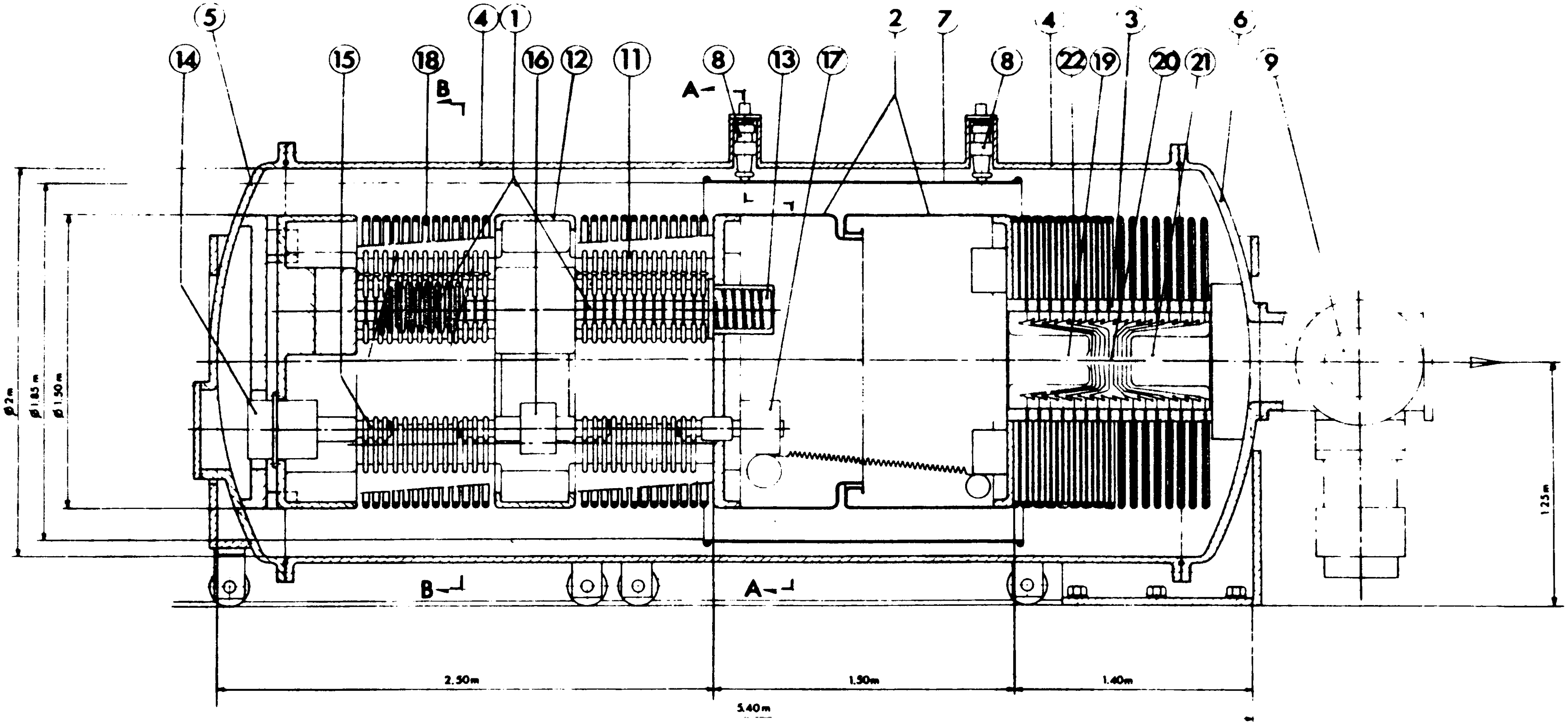

Fig. 1 LONGITUDINAL SECTION OF 1,4 MeV PREINJECTOR

1	HT generator	9	Pumping system	16	2000 Hz generator
2	HT electrode	10	Roots pumps	17	400 Hz generator
3	Accelerating tube	11	Makrolon insulating rods	18	Equipotential rings
4	Central cylinder	12	Intermediate electrode	19	Anode with ion source
5 6	Base plates	13	Protective resistor	20	Accelerating electrodes
7	Capacitive screen	14	Motor	21	Cathode with focusing triplet
8	Insulator	15	Insulating shaft	22	Equipotential rings

Fig. 2

OPENING OF PREINJECTOR. ACCESS TO COMPONENTS

1 HT generator
2 HT electrode
3 Accelerating tube
4 Central cylinder
5 6 Base plate

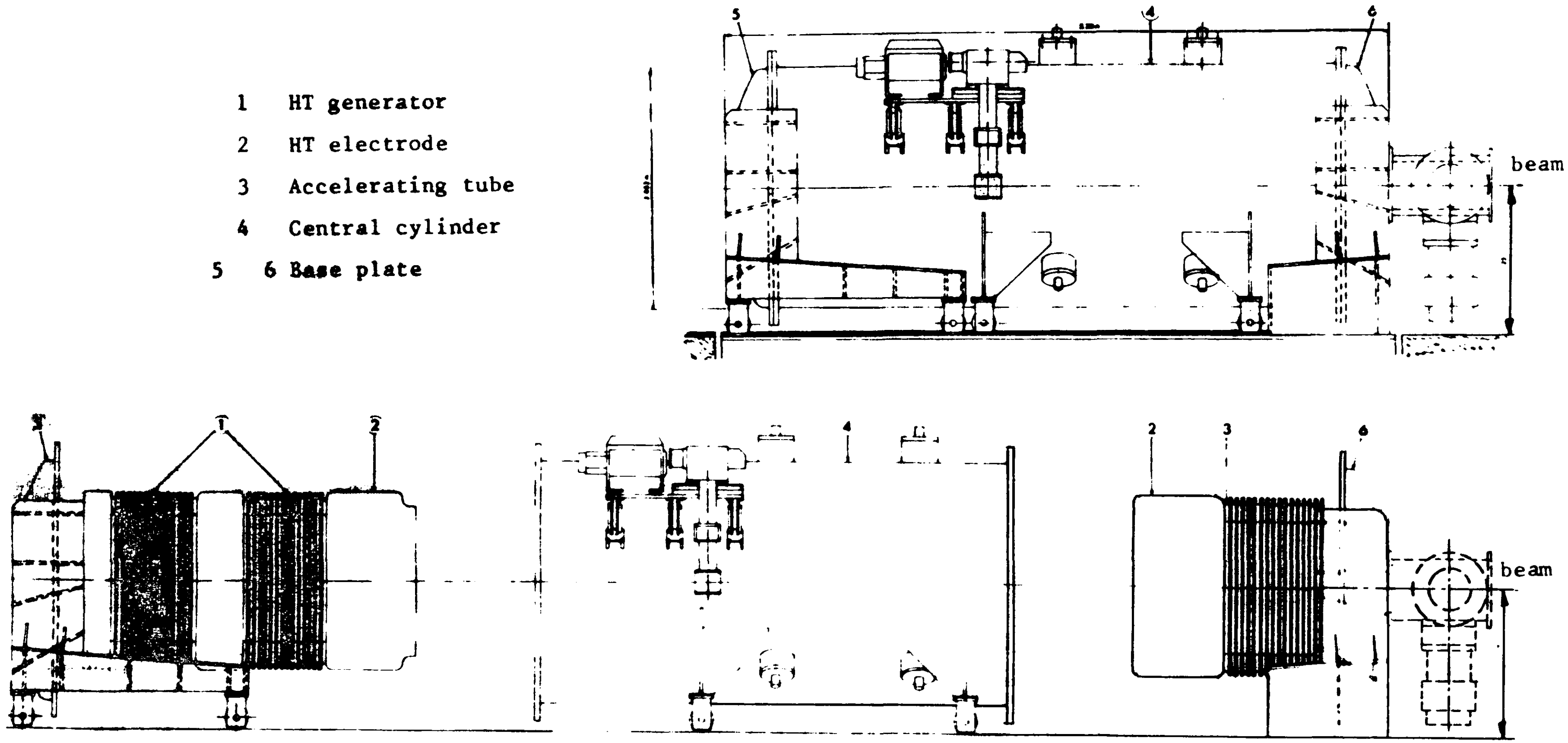

FIG. 3: Mean and maximum radial fields in SF 6 of Dynamitrons and CERN project

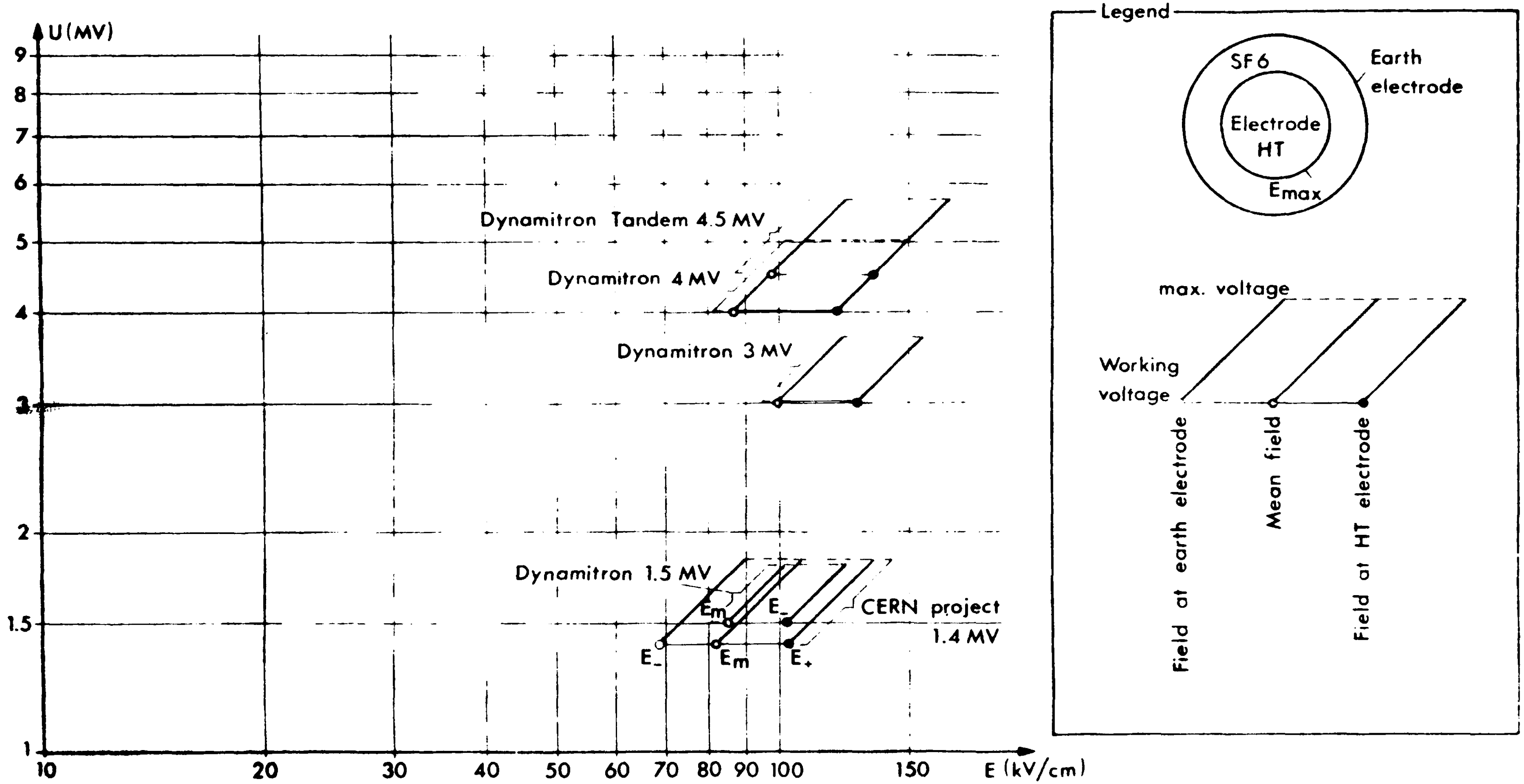

FIG. 4

Axial electric field in a Pierce structure

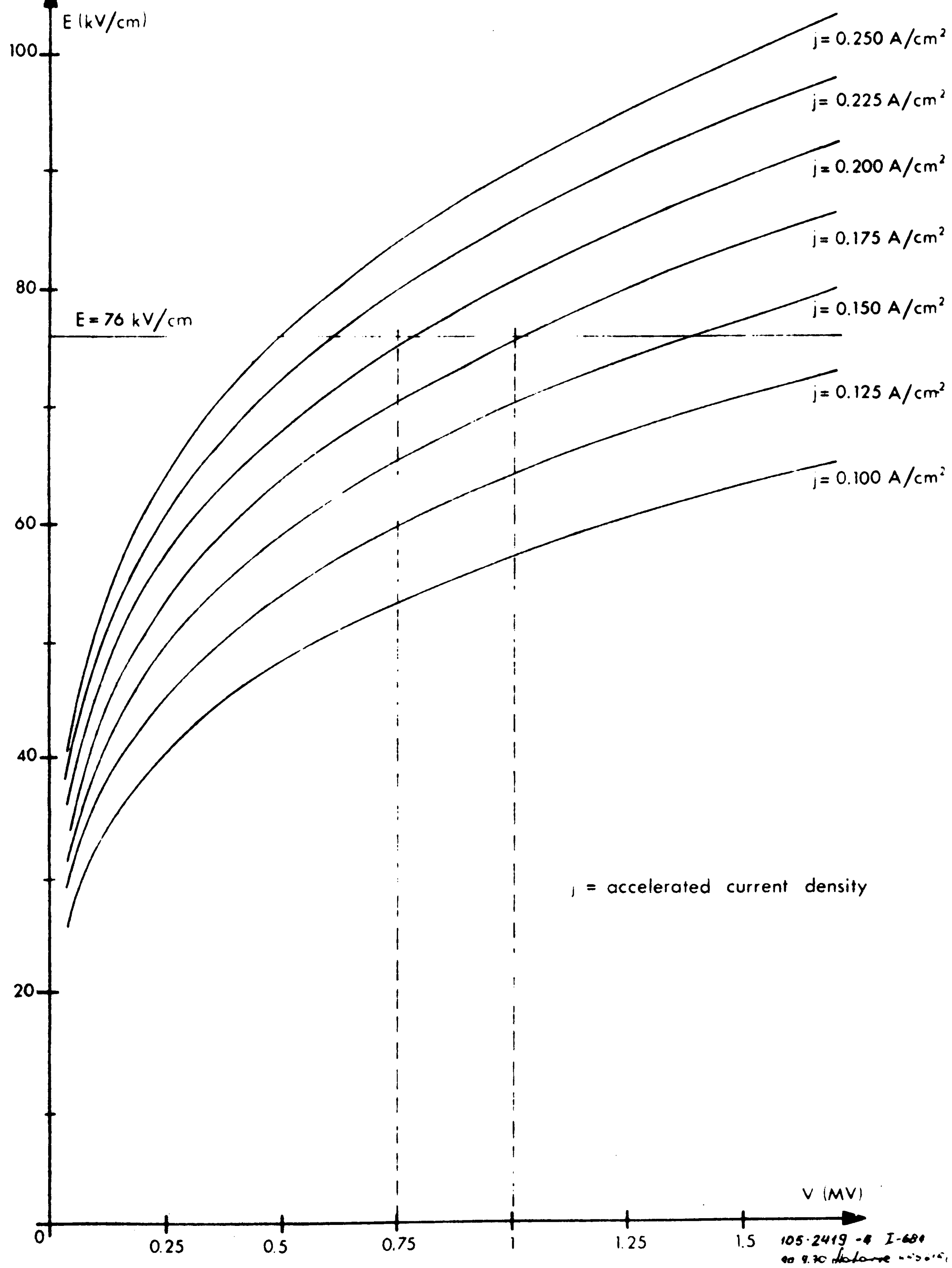

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Fig. 5

VARIATION OF THE BEAM RADIUS DURING ACCELERATION IN A PIERCE STRUCTURE

Beam current : 0.5 A

Initial normalized emittance : 3.7 mm mrad

Initial density distribution in a 4 dimensional phase space :

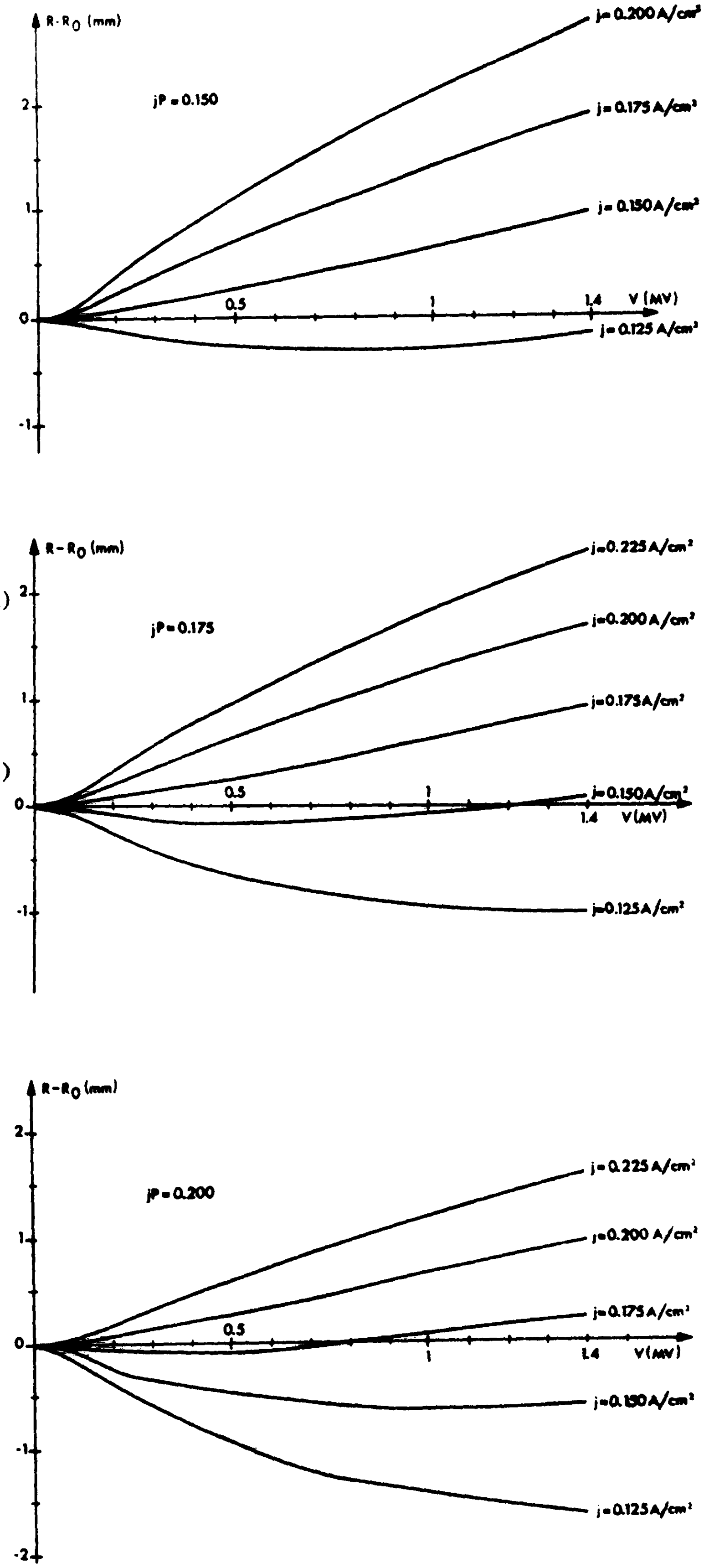
Gaussian $\sigma = \sqrt{2}$

σR_0 ... initial standard deviation (at 40 keV)

R_0 ... beam radius at 40 keV; (mm)

j ... density of the accelerated current

jP ... nominal density(for the design of Pierce structure)



COMPARISON BETWEEN PIERCE AND HYBRID STRUCTURES

E_{max} = 76 kV/cm

Beam current : 0.5 A

Initial normalized emittance :
3.7 πmm mrad

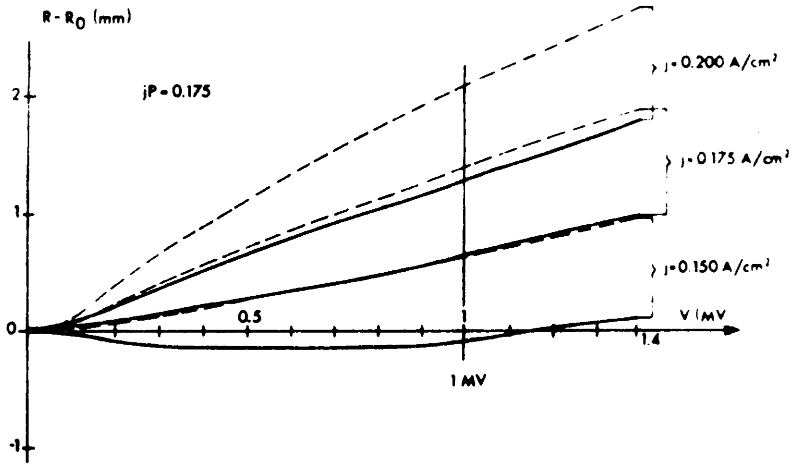
Initial density distribution in a 4 dimensional phase space :
Gaussian $\sigma = \sqrt{2}$

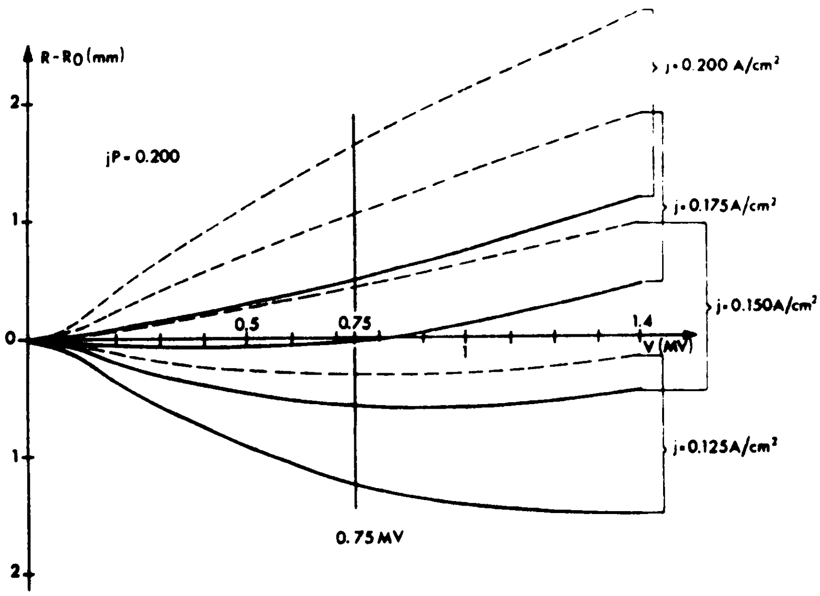
σR_o ... initial standard deviation (at 40 keV)

R_o ... beam radius at 40 keV

j ... density of the accelerated current

jP ... nominal density (for the design of Pierce structure)





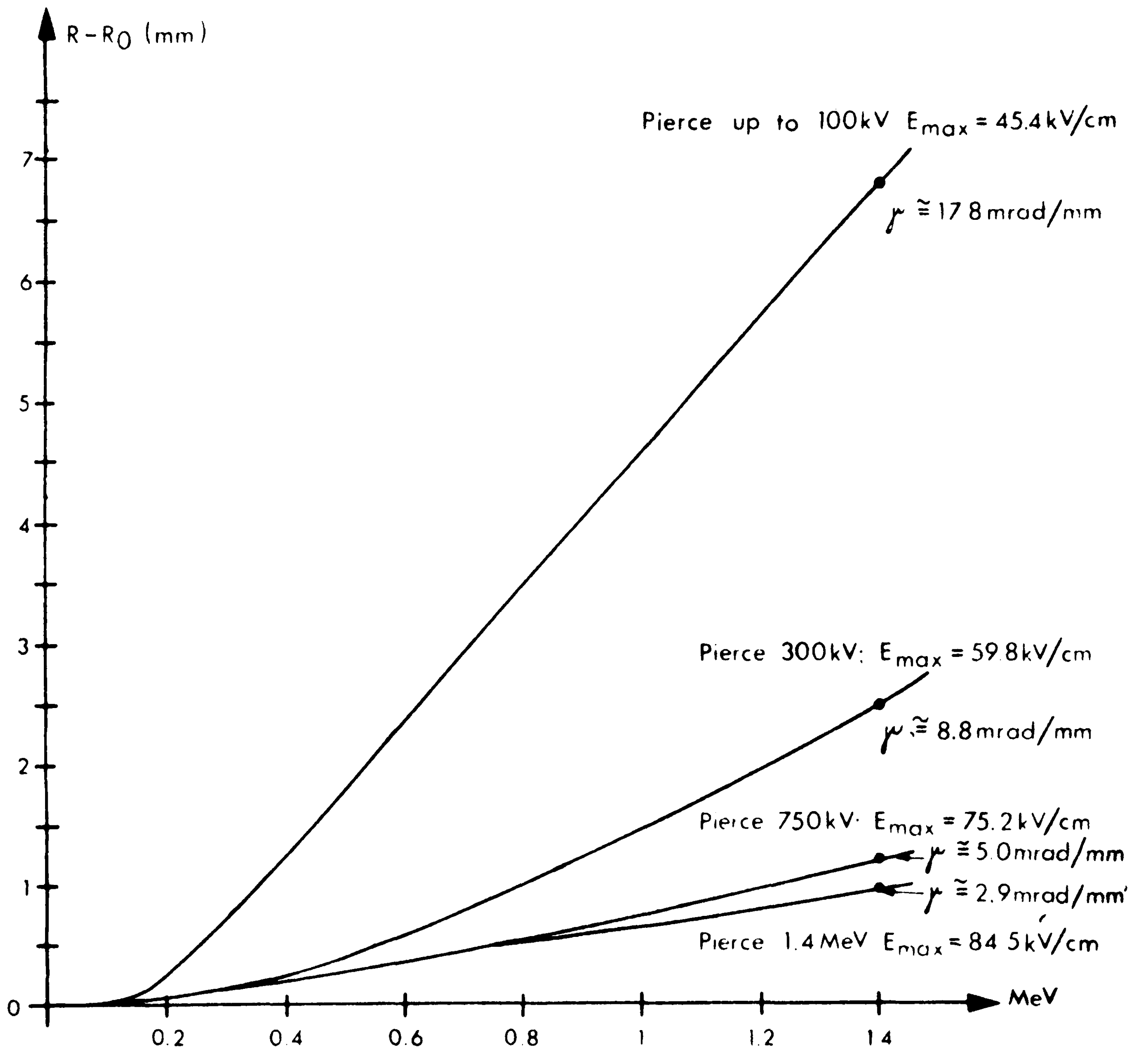
--------- Pierce structure (calculated for a current density of 0.150 A/cm^2 corresponding to E_{max} = 76 kV/cm)

________ Hybrid structure : a) Pierce geometry up to 1 MeV with jP = 0.175 A/cm^2

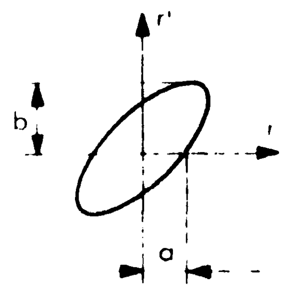
b) Pierce geometry up to 750 keV with jP = 0.200 A/cm^2

FIG. 7

Increase in beam radius during acceleration in hybrid structures



$\gamma = \frac{b}{a}$



$I = 0.5\ A$

$j = 0.200\ A/cm^2$

$R_0 = 8.9\ mm$

$jP = 0.200\ A/cm^2$

BEAM DENSITY UNIFORMIZATION DURING ACCELERATION

FOR DIFFERENT INITIAL GAUSSIAN DISTRIBUTIONS

Hybrid structure, jP = 0.200 A/cm^2 , j = 0.175 A/cm^2

Beam current : 0.5 A

Initial normalized
emittance : 3.7 mm mrad

Initial density distribution
in a 4 dimensional phase space :

Gaussian

σR_o ... initial standard deviation (at 40 keV)

R_o ... beam radius at 40 keV

j ... density of the accelerated current

jP ... nominal density (for the design of Pierce structure)

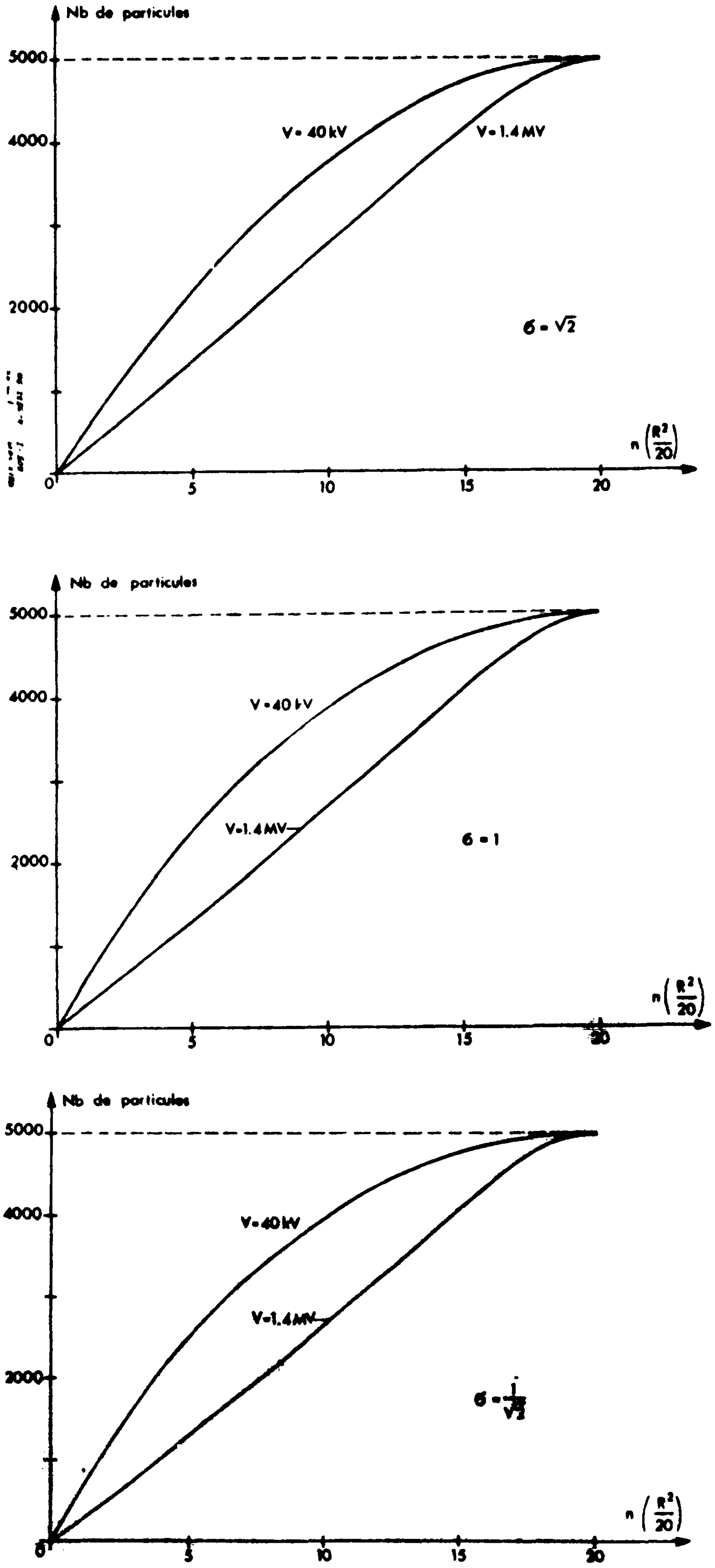
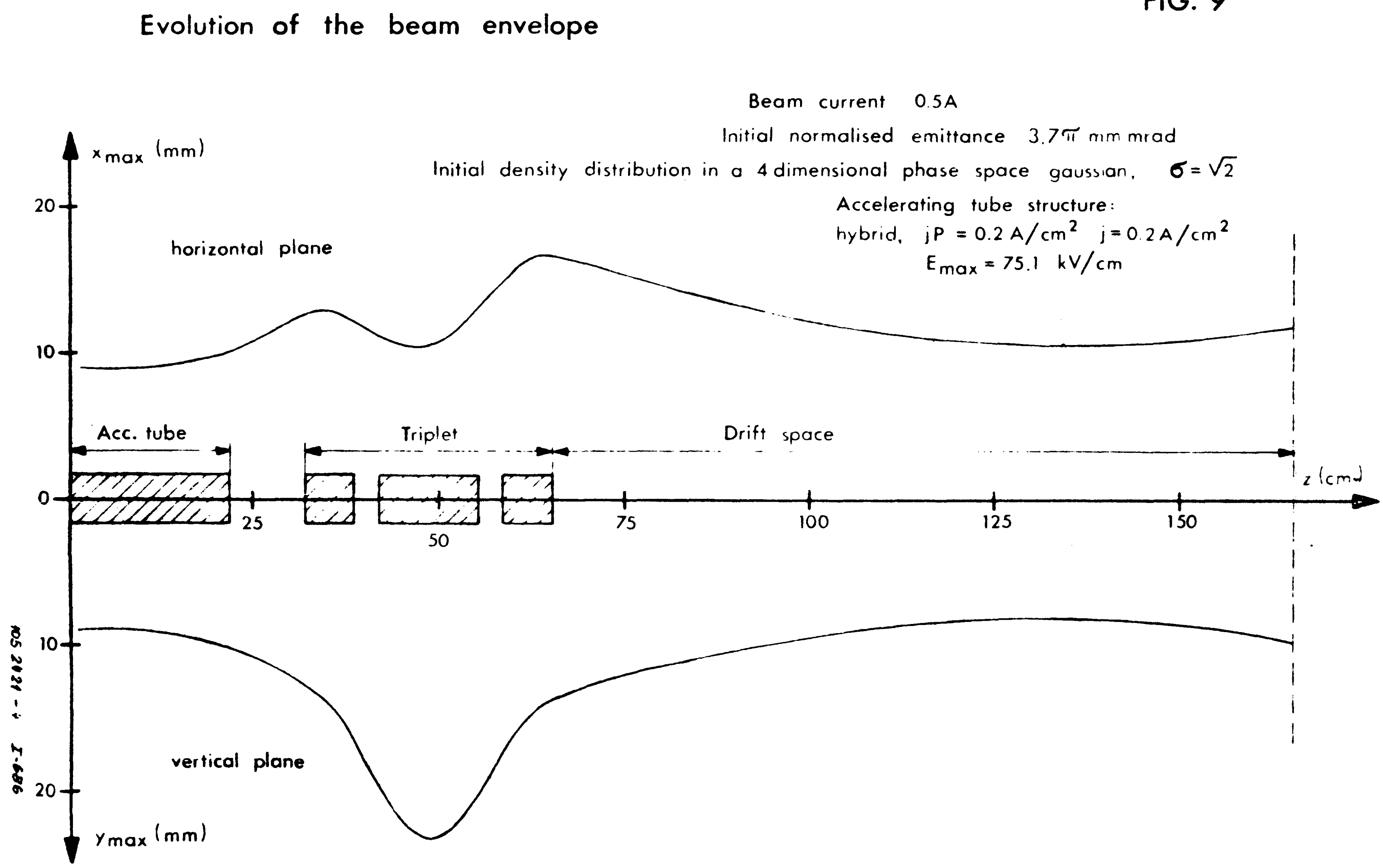


FIG. 9



Evolution of the beam envelope
Beam current 0.5A
Initial normalised emittance 3.7π mm mrad
Initial density distribution in a 4 dimensional phase space gaussian, σ = √2
Accelerating tube structure:
hybrid, jP = 0.2 A/cm² j = 0.2 A/cm²
Emax = 75.1 kV/cm
xmax (mm)
horizontal plane
Acc. tube
Triplet
Drift space
z (cm)
vertical plane
ymax (mm)
20
10
0
10
20
25
50
75
100
125
150
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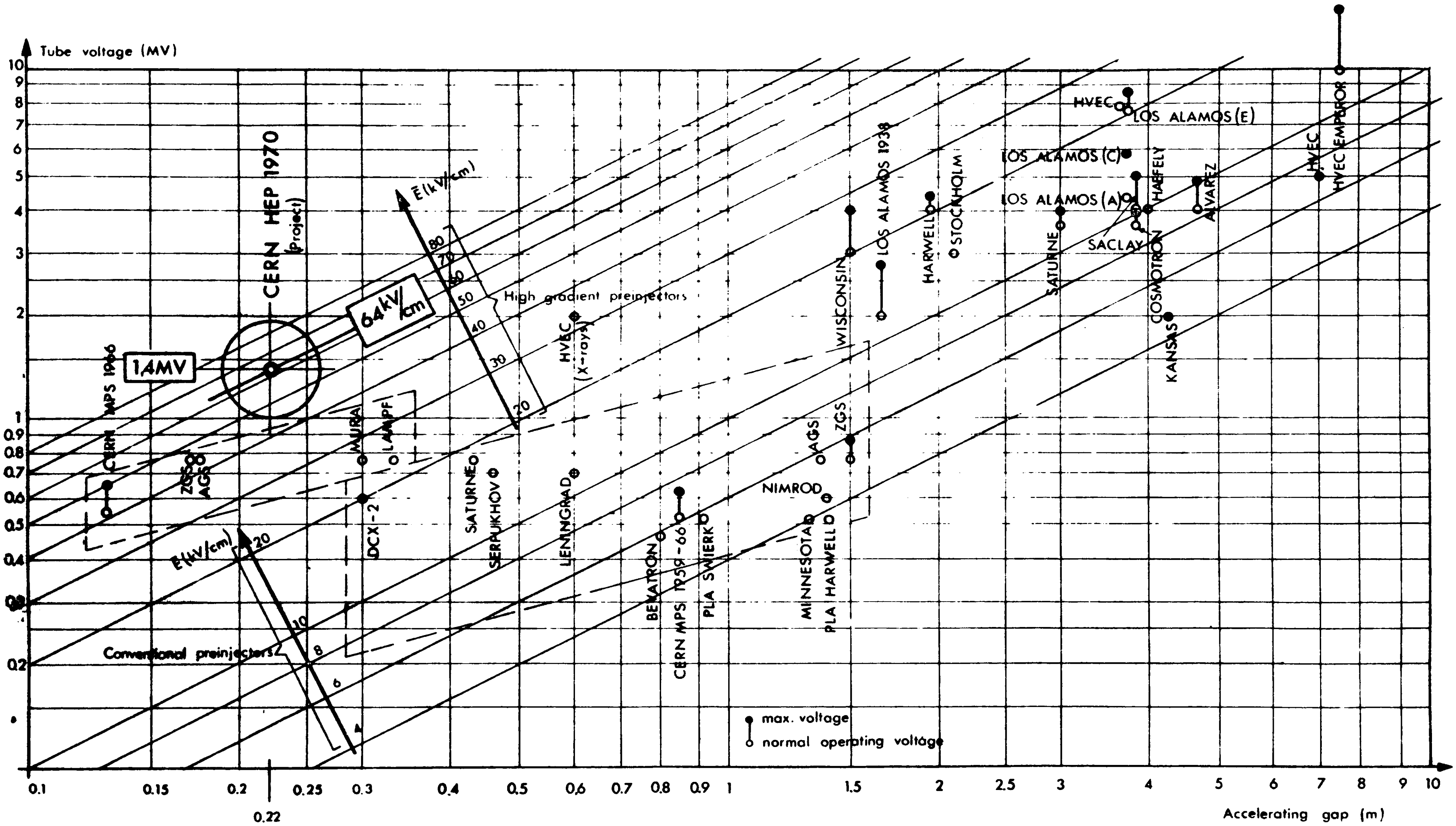

Voltage, gap and accelerating gradient of some tubes

FIG. 10

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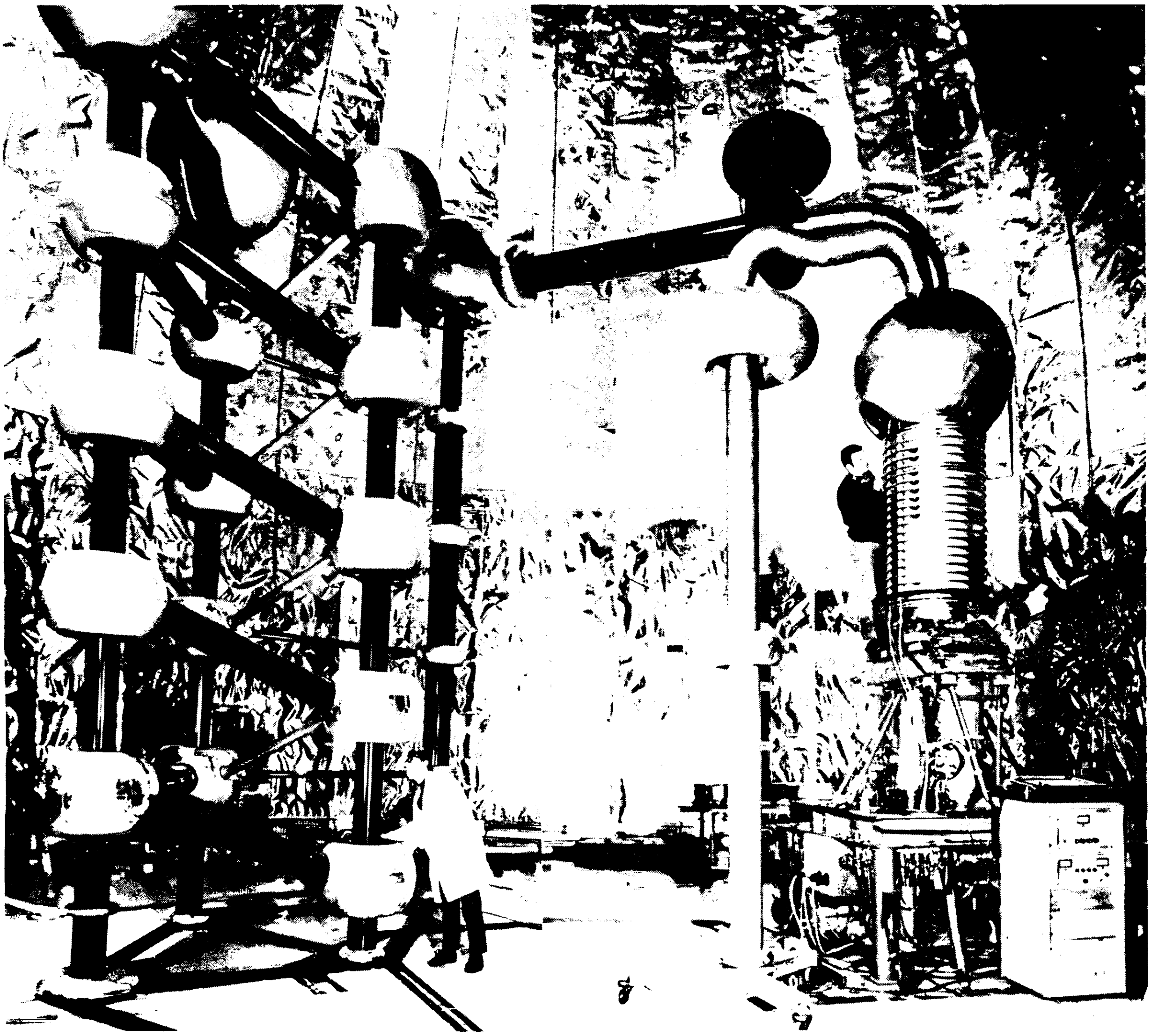
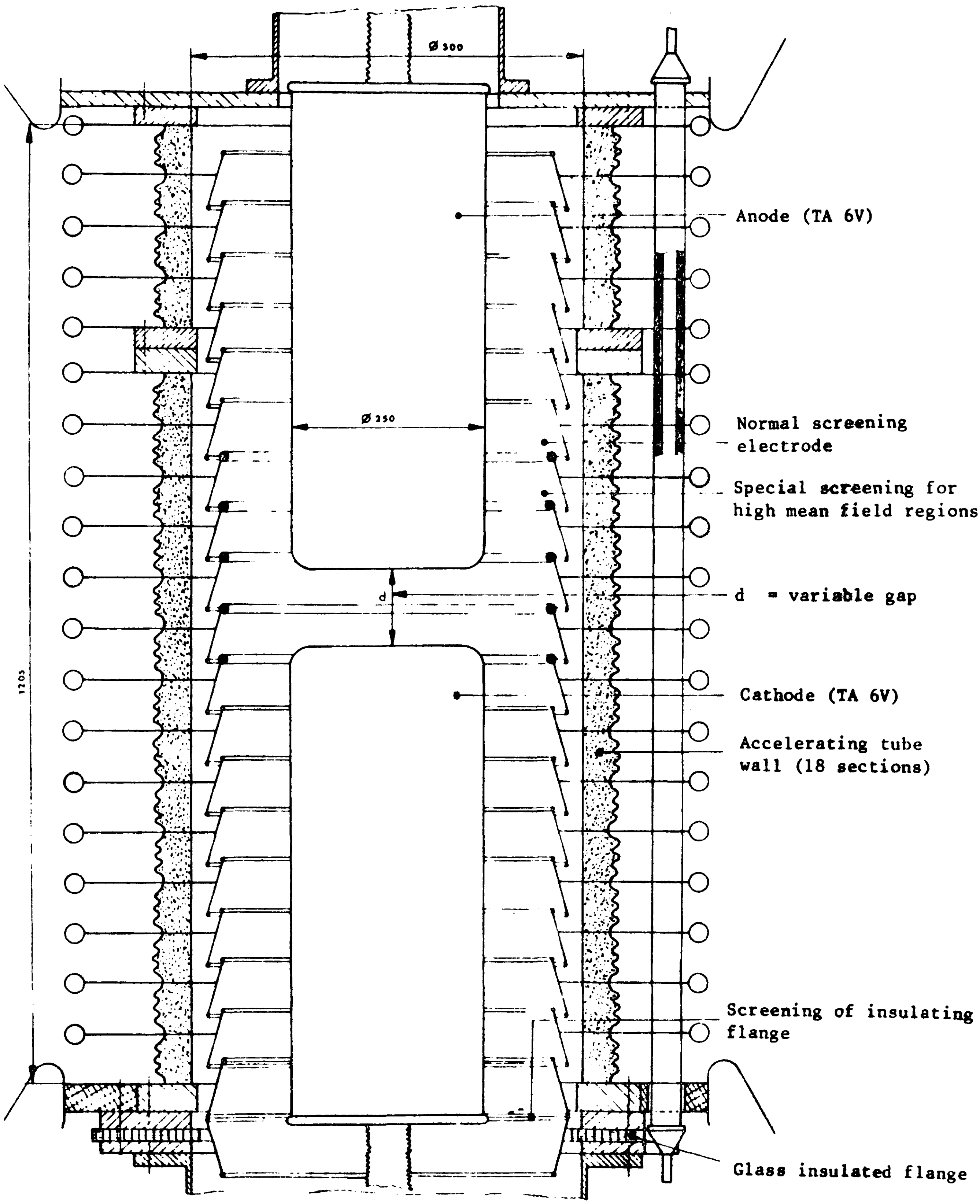
BERTHE TEST - HT GENERATOR AND ACCELERATING TUBE
WITHOUT INSULATING GAS (850 kV max)



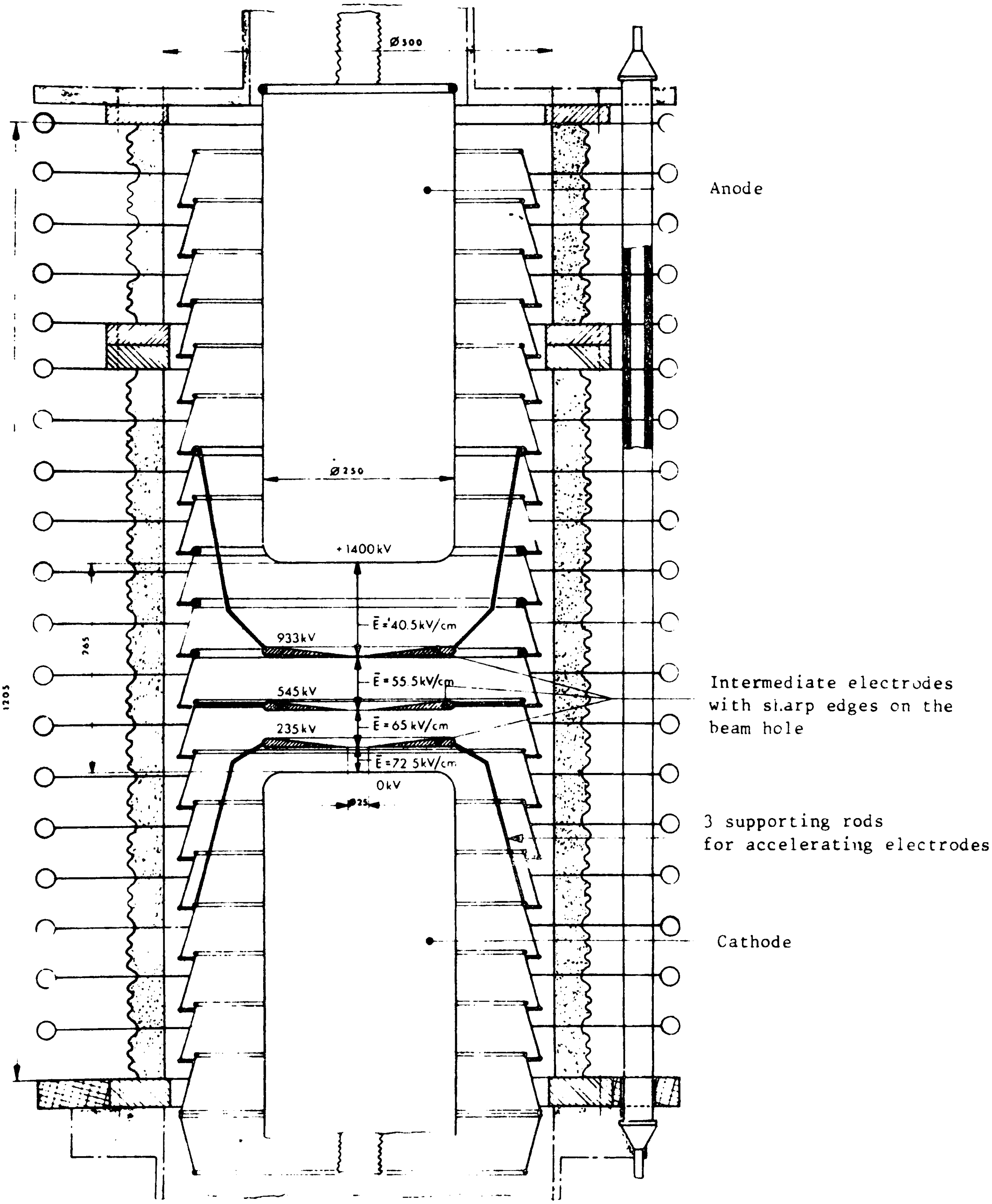
1 Cascade 1,5 MV generator (Haefely)
2 Protective resistor
3 Resistive measuring divider
4 Accelerating tube in air (tests limited at 850 kV)
5 Liquid resistive divider
6 Leads for resistive liquid
7 Pumping system
8 Residual gas analysor

BERTHE TESTS - EXPERIMENTAL LAYOUT FOR TESTING HT HOLD-OFF BETWEEN TITANIUM ALLOY ELECTRODES IN FUNCTION OF GAP SPACING

(U_{max} = 1,4 MV)



BERTHE TEST - 1,4 MV TEST PROTOTYPE OF
PIERCE TYPE ACCELERATING STRUCTURE . jP = 0,150 A/cm^2



PIERCE ELECTRODE

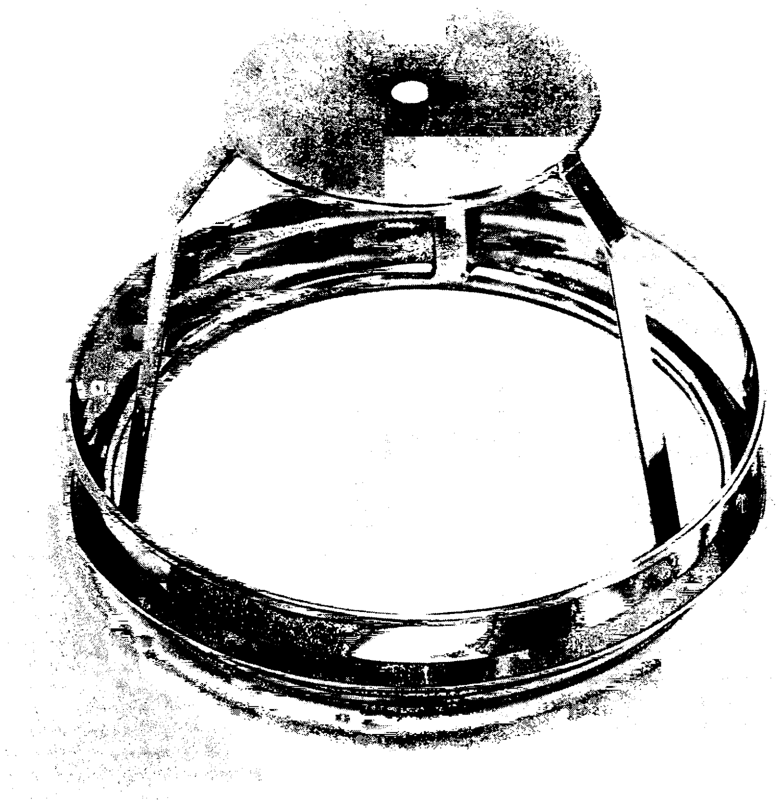
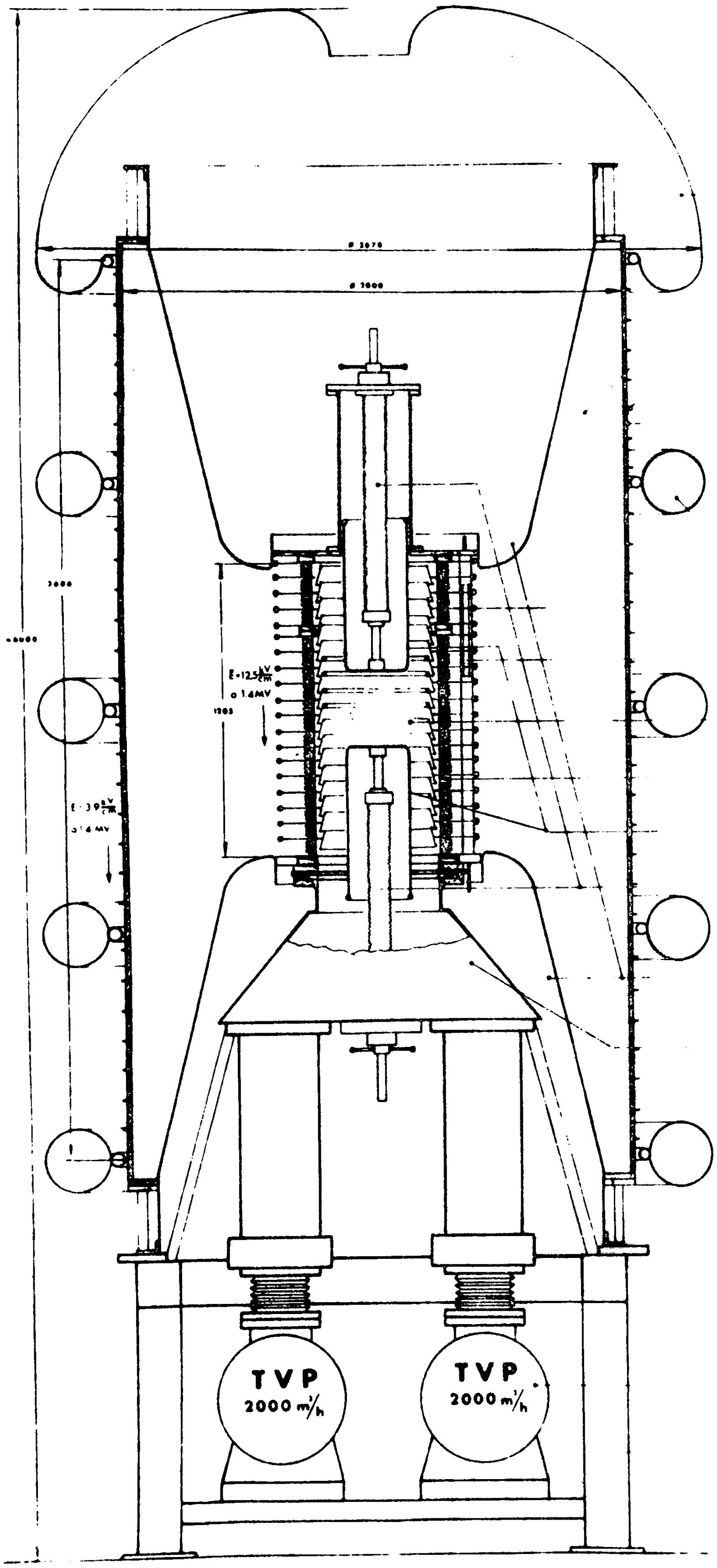


Fig. 15

BERTHE TESTS - EXPERIMENTAL LAYOUT



15 Upper HT electrode

12 Insulating gas at atm, pressure (SF_6)

11 Resistive divider

10 Insulating envelope

14 Anticorona ringsin air

6 Anticorona ringsin SF_6

5 Liquid resistance divider

4 Screening electrodes (Ti alloy)

1 Accelerating tube(18 sections)

2 Adjustable titanium electrodes

3 Adjusting screen

13 Conical electrodes

7 Vacuum tank

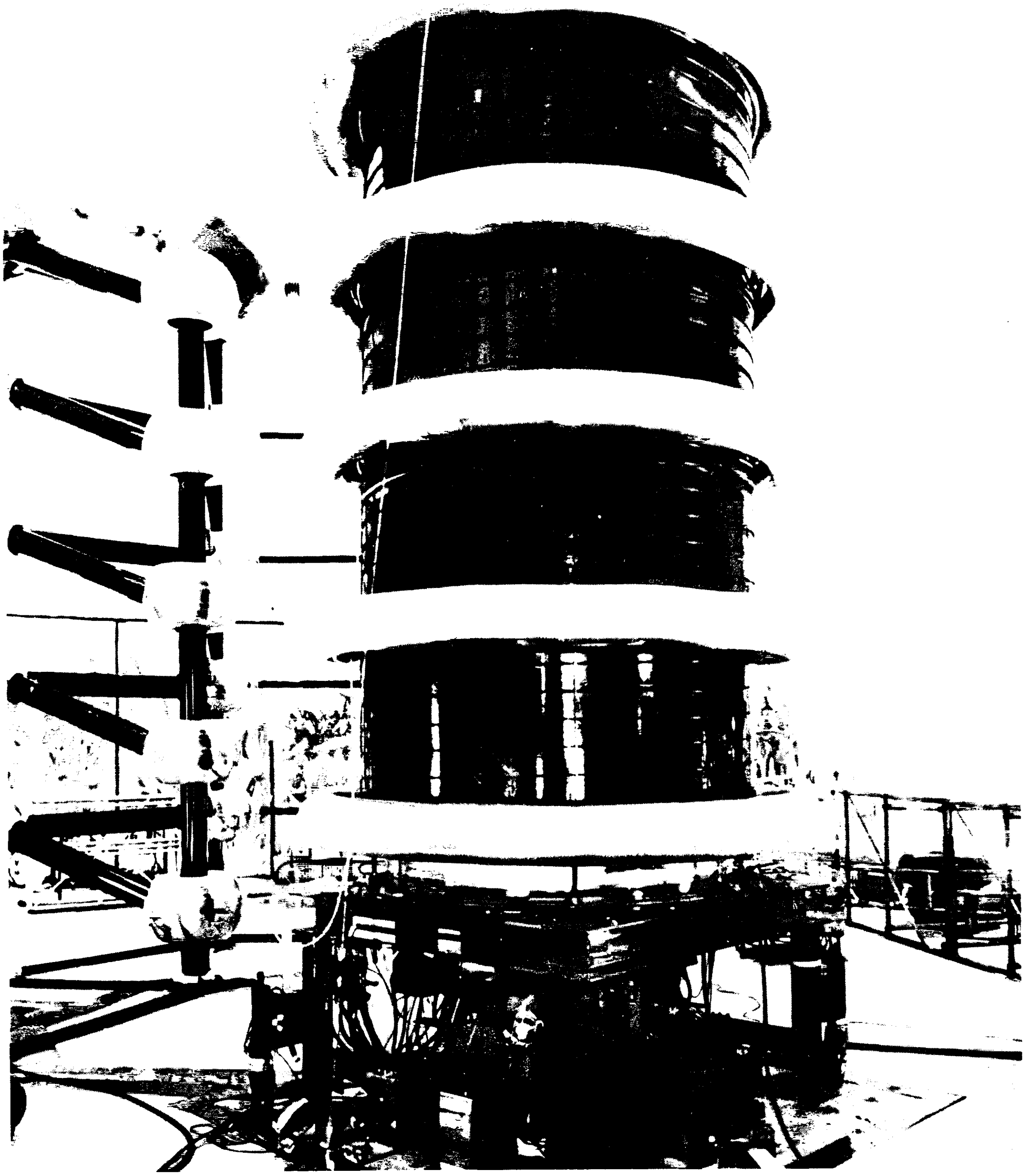
8 Turbomolecular pumps

9 Supporting chassis

Fig. 16

"ESSAI BERTHE"

EXPERIMENTAL LAYOUT FULLY ASSEMBLED



1 Insulating cylinder
2 Upper HT electrode
3 Anticorona rings
4 Resistive divider
5 Lower aluminium cone
6 Supporting chassis
7 Pumping system