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PROGRESS REPORT ON THE CPS ELECTROSTATIC SEPTUM PROTOTYPE

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1. Introduction

The first deflector in a slow ejection (SE) scheme must have a septum which is as thin as possible. By septum we mean the material partition between the active region where the deflection takes place and the field free region; by extension this will also mean the whole apparatus. In the present state of the technology, for the gaps required to eject beams from alternating gradient synchrotrons and for the same useful deflection, in an electrostatic field one can use a thinner septum than in a magnetostatic field.

The first proposal to use an electrostatic septum (ES) for the ejection in a synchrotron was made at NAL for the 200 GeV accelerator [1,2]: this method had already been used for some years in cyclotrons.

Brookhaven also has plans for using an ES in the ejection of the AGS and in 1969 some interest arose at CERN for installing an ES in the CPS for SE 16. It was decided then to construct a prototype and to test it in SE 62 in order to finalize the specifications for the ES that will be an essential part of SE 16 after the improvement programme has increased the intensity of the CPS to the 10^{13} ppp range.

The ES prototype was constructed late in 1969 and was installed in SS 64 at the end of January 1970 to take part in a PS machine development on SE 62. During this first test period, the ES performed satisfactorily in the absence of a proton beam, but serious difficulties were encountered with the beam on. It was nevertheless possible to eject the beam at a reduced intensity of 3×10^{11} ppp and a record of 95 % ± 2 % in the extraction efficiency was established without a complete optimization of the ejection process.

In the following PS Machine Development (MD) periods methods for reducing the influence of the PS beam on the ES high voltage behaviour were found. Since June 1970 the ES prototype has been installed in SS 45 for testing the ejection SQUARE and its high voltage performance has been progressively improved and assessed during a dozen of MD periods.

2. Description of the electrostatic septum prototype

The prototype has been designed according to provisional specifications having the following main characteristics:

Length: maximum possible in a short straight section;
the corresponding equivalent field length is 0.8 to 0.9 m

Septum foil thickness: ≤ 0.1 mm

Septum apparent thickness: as small as possible
(in any case < 0.2 mm)

Position of the septum: adjustable between 35 and 73 mm from axis with angle and position reproducible to better than 0.1 mrad and 0.1 mm respectively

Position of the HT electrode (cathode): adjustable between 45 and 78 mm

Working field: ≥ 120 kV/cm for a gap of 1 to 2 cm

Anode aperture: the beam aperture of the anode must be such that there is no interference with the circulating beam when the ES is not used.

In Fig. 1 is shown a cross-section of the ES as installed in SS 45 in June 1970. The stainless steel vacuum tank internal diameter is 400 mm. It contains a U-shaped anode on which the 0.1 mm stainless steel septum foil is stretched by two rows of bolts. This anode is supported by two alumina insulators bolted to micrometric screw adjustable supports which are isolated from the vacuum by stainless steel bellows. The anode is connected to ground through a 230 ohm resistance made of Kanthal wire wound around the insulators and whose function is to absorb the energy stored in the cable connected to the ES when a spark occurs. The anode has an aperture of 150 x 70 mm^2 for the circulating beam. The cathode, which is 830 mm long and is the only electrode at a high voltage, is made from a light alloy (PRE 30 = 97 % Al + 3 % Mg) coated with a 6 to 10 μm alumina layer by anodization in a chromic acid bath. This oxide layer is then sealed in boiling water following the technology developped in connection with electrostatic separators at CERN [3,4].
The cathode is supported by two alumina insulators fitted to adjustable supports similar to the anode supports. An alumina bushing is used for connecting the cathode to a negative 300 kV generator through a 2.7 MΩ shielded protection resistor.

In Fig. 2 is shown a plane view of the ES as installed in SS 45. The anode is 930 mm long but the septum foil itself is a little shorter, 910 mm, to allow for the ends of the anode to support transversal screens whose functions will be discussed in the next section. These screens, together with the extension of the standard PS vacuum chamber into the ES tank close to the screens, were introduced during the first few months of tests in SS 64. They have very much increased the impedance for pumping the ES at both ends by the standard PS stations and they have made it necessary to install on the ES tank itself a 400 l/s ion pump to keep the pressure below 10^{-6} torr.

The septum of the anode must in principle be vanishingly thin and perfectly flat. For the following reasons we have so far used in the ES prototype a 0.1 mm stainless steel foil, streteched as uniformly as possible on the U-shaped anode frame:

- a good and reliable high voltage behaviour as discussed in section 4
- the need to construct and install the ES prototype in a short time
- the fact that a septum apparent thickness much less than 0.2 mm was not essential for the first tests with the present PS intensity. In fact there was so little pressure applied to minimize the septum thickness that operating the slow ejection with a thin (relatively) magnetic septum was considered satisfactory and perhaps preferable to complicating the ejection scheme with an additional component, namely the ES used as the first ejection element.

The foil is stretched on two calibrated steel rods resting in accurately machined triangular grooves that define the septum plane to ± 0.01 mm. After stretching the foil all its points lie to within ± 0.025 mm of an ideal plane so that the apparent thickness of the septum before it has been submitted to sparking is about 0.15 mm.

The position of the cathode, the position and angle of the septum are remotely and accurately controlled from the PS main control room and so, of course, is the high voltage applied to the cathode.

3. High voltage performance of the ES prototype

The conditioning of the ES takes place in the HT laboratory prior to its installation in the PS. The process is usually accomplished in three steps:

1) With the electrodes set at a large gap (4 cm) the voltage is progressively applied by automatically controlling the voltage so as to keep the current constant at a low value of about 10 μA. A significant outgassing of the metal surfaces takes place under the influence of the electric field and the maximum voltage of the generator, 300 kV, is usually reached in a dozen of hours.

2) The gap is set at its operation value, say 1 or 2 cm, and the conditioning at constant current is resumed. This second step is accomplished in a much shorter time.

3) The ES is then tested under its operational conditions for one or two weeks at a voltage that can reach as much as 90 % of its fully conditioned voltage limit.

3.1 Initial performance of the ES in SS 64

After the first assembly the ES reached a conditioned voltage limit of 280 kV across a 2 cm gap and was able to stay at 200 kV for 160 hours with only 6 sparks. It was then installed in SS 64 at the end of January 1970.

As soon as the first tests started it became apparent that the high voltage behaviour of the ES was strongly perturbed by the circulating proton beam. Whereas the ES could stand 160 kV across 10 mm without current when the beam was off, large current pulses up to several hundreds of microamps or sparks would appear when the beam was accelerated, eventually tripping out the generator.

Several possible parameters were varied in order to find the cause of this behaviour: intensity of the beam, energy at which the beam was killed and the method used for it, positions of the septum and the beam, voltage applied to the septum. The outcome of this study indicated that the current pulse increased with the beam intensity (Fig. 3), with the time during which it was circulating and quite naturally with the voltage applied to the ES (Fig. 4). The position of the beam relative to the septum did not matter very much so that it seemed likely that the origin of the current was the ionization of the residual gas by the proton beam.

During this first MD period the ES could, however, be used successfully for slow ejection by limiting the PS intensity to 3×10^{11} protons per pulse. In this condition the current pulse was only 50 μA for 110 kV across the 26 mm gap required and without refining the optimization an efficiency of 95 ± 2 % was achieved according to the losses measured in the relevant straight sections. This was already a significant advance compared to the previous situation, but a reliable ES performance under the full PS intensity was still to be achieved [5].

The high voltage supply which has been used with the ES is a 300 kV SAMES generator whose insulation is provided by hydrogen at about 20 atmospheres. The 2.7 MΩ shielded protection resistor is insulated by compressed freon. Both the generator and the resistor had to be placed close to the ES and are thus submitted to radiation, especially when protons are lost on the ES. Ionization of the insulating gas under radiation causes current pulses to appear in the HT supply, even when it is not connected to the ES. The current pulse induced in the HT supply is shown in Fig. 5 as a function of the voltage for two values of the AIC 64 readings corresponding to about 10^{11} and 6×10^{11} protons interacting in the ES which was for this test set at an angle with respect to the beam. The current pulse induced in the HT supply can exceed 100 μA but in working conditions for testing SE 62 the losses on the ES are smaller than 10^{11} protons per pulse so that the corresponding current accounts for only a fraction of the observed pulse. Nevertheless, the problem of a more appropriate HT supply has to be considered.

3.2 Improvements to the ES in SS 64

The assumption that the current pulse created in the ES by the circulating beam is caused by the ionization of the residual gas by the protons does not alone account quantitatively for the magnitude of the current observed. With a vacuum around 10^{-6} torr and a proton beam of 10^{12} the ion current thus created is only about half a microamp per metre of vacuum chamber. Furthermore, it is unlikely that the electric field in the ES can drain the ions created in the PS chamber over more than a short distance, since these ions are created with a very small energy (< 0.1 eV) and are driven in a short time (a few tens of μs) to the chamber walls by the potential (a few volts) created by the proton beam [7].

Since the current pulse is a function of both the lifetime of the proton beam and the voltage applied to the ES, some kind of multiplication process has to take place locally in the ES to account for currents in the hundreds of microamps range. When positive ions impinge on a surface a variety of phenomena may result [8,9]. The most relevant to our problem is secondary electron emission which is dependent on the energy and nature of the incident ions, the angle of impact, the nature and state of purity of the target surface. These ions have an energy corresponding to the potential of the cathode, i.e. 100 to 200 keV for singly-charged ions, and their nature is determined by the materials of the PS vacuum system and the pumping stations used. The composition of the residual gas in the PS depends on which straight section is considered since the conventional oil diffusion pumps have been replaced only in a fraction of the ring by the new ion pumps and furthermore some sectors are influenced by the proximity of highly outgassing equipments like internal targets, ejection magnets, fast kickers, etc. One can nevertheless surmise that the composition of the residual gas, in nitrogen equivalent partial pressures, is given approximately in table I [10], column1 for SS 45 and column 2 for SS 64.

Gas	Oil diffusion pumps SS 30 $p = 2.3 \times 10^{-6}$ torr	Ion pumps SS 17 $p = 2.3 \times 10^{-7}$ torr
H_2	14 %	48 %
H_2O	61	24
N_2	12	6.5
O_2	3	1.6
Ar	0.3	0.9
CO	2.2	10
CO_2	0.5	0.7
C_nH_n	7	8.3
	similar conditions in SS 45	similar conditions in SS 64

Table I

A large amount of information is available on the emission of electrons from metal surfaces by bombardment with charged particles. At the ion energies likely to be encountered in the ES the secondary electrons are emitted mostly by the kinetic ejection process, but none of the proposed theories of this mechanism has been generally successful [9]. There are indeed important variations in the experimental values of γ (secondary electron emission coefficient, i.e. number of electrons emitted per incident ion) when relevant parameters mentioned earlier are changed (for instance kind of the ions, metal and surface coverage of the electrode, angle of incidence and energy of the ions, etc...) and the theories still account imperfectly for all the experimental data because ofthe necessary simplifying assumptions. It can be said qualitatively that at higher ion energies the secondary electron yield and the cross-section for the ionization of an atom by the impact of an ion have a similar dependance on the velocity of the incident ion, that is to say they reach a maximum in the region of tens of keV and subsequently decrease with increasing energy. As the velocity of the incident ion increases, more secondary electrons are formed deeper within the target and have a smaller chance of leaving the target. The maximum value of γ is reached at a higher energy with increasing mass of the incident ion and corresponds to an optimum velocity.

The published values of γ for secondary electron emission from metal surfaces under bombardment with high energy ions (10^4 to 10^6 eV) are generally in the range 1 to 15. This is not sufficient to account for the enhancement factor of up to more than two orders of magnitude that we observe in our ES. Furthermore, it is very difficult to assess a correct value of γ because of all the uncertainty in the values of the relevant parameters defining the conditions existing in the ES for secondary electron emission. However, the three following remarks will lead us to some extent towards the required values for γ:

1) The incidence of the ions on the cathode surface is not necessarily at right angles but may be at grazing incidence and in this condition the secondary electrons have a shorter path to reach the surface. The variation of the yield with α (the angle between the ion trajectory and the normal to the surface) would then follow a sec α law.

2) The secondary electron emission may be enhanced with certain adsorbed layers or surface coverages since the diffusion

length of these electrons is orders of magnitude larger in insulators than in metals. The thin oxide coating of the ES cathode may give rise to such an effect but there is a dearth of information directly relevant to this problem and further tests in the PS, with other electrodes, will be made to check this point. Then the possible drawback of a higher secondary electron emission from oxide-coated cathodes will have to be weighed against their better high voltage behaviour.

3) At equal ion velocities the secondary electron yield is proportional to the mass of the bombarding molecular ion, that is to say the molecular ions break up into their constituent particles at the electrode surface and each of them produces its own kinetic emission of secondary electrons. Referring to table I, this effect is to be expected for most of the residual gas components, especially for heavier molecules. With the voltage applied to the ES cathode the light incident ions have an energy well above that for maximum secondary electron emission, but the constituent atoms of molecular ions, having each a fraction of the total energy, have a higher electron yield so that the total electron emission may be considerably enhanced. In the range considered for the energy E_i of the incident ions the functional dependence of γ is approximately $E_i^{-\frac{1}{2}}$.

At the present state of the study no satisfactory quantitative explanation has yet been worked out for the large values of the pulsed current induced in the ES by the proton beam. It is indeed difficult to account for the large enhancement factor, at least two orders of magnitude, of the primary ionization current of the residual gas. However, the assumption that this primary ionization current is the origin of the observed large current pulse seems valid since we could drastically reduce the latter by carefully screening the cathode against the ions created in the PS vacuum chamber.

The screening has been designed so that the ions in the PS chamber cannot see the cathode and furthermore so that there exists a significant impedance for the flow of gas from the PS vacuum chamber and anode beam passage to the inside of the ES tank itself. This is obtained, as shown in Figs. 1 and 2, by using tubular screens positioned close to the plane screens. Out of the way of the ejected beam the plane screens are thick and in the way they are thin and made with 0.02 mm aluminium foil stretched on a frame.

The influence of the PS circulating beam on the ES was drastically reduced after the installation of these screens but for this it is necessary that the thin Al screen be placed almost in contact with the septum foil so as to prevent ions from leaking through the small passage to the cathode. A first test with only the thin screens placed not so closely to the septum did not give a significant improvement. With the final set of screens the current pulse at a voltage of 150 kV over a 2 cm gap was reduced to a few microamps at a PS intensity of 13×10^{11} ppp in the case of no beam losses on the septum. When we adjusted the beam so as to get losses on the septum, we obtained the expected current drain due to the gas ionization in the HT supply only and no sparking in the ES. The decoupling of the ES from the proton beam seemed satisfactory and we could keep 150 kV over a 2 cm gap during 120 hours with only two sparks in a normal PS run without slow ejection, when the septum was positioned so as not to intercept the proton beam.

A test was also performed at a higher pressure in the PS in order to simulate a larger beam intensity from the view-point of the residual gas ionization. Air was bled into the vacuum chamber through a needle valve in order to raise from 1×10^{-6} torr to 1×10^{-5} torr the pressure read on an ionization gauge. Under these conditions we could still observe sparks in the ES at 150 kV across 25 mm with a beam of 13×10^{11} ppp. This is an indication that for the future PS intensity we should work at a pressure in the 10^{-7} torr region and/or design a still more efficient screening which is also possible.

3.3 Performance of the ES in SS 45 and test of ejection SQUARE

The ES prototype was overhauled in May and then installed in SS 45 for MD tests of the ejection SQUARE running at $Q_r = 6\ ^1/_3$. With this type of SE one hoped to achieve an efficient sharing operation with a target and since this was new to the PS, a series of MD tests was devoted to this problem, with the ES working at its maximum performance under direct shot conditions.

From June until the PS shut-down in November ejection tests were performed during a dozen of MD periods and the performance of the ES was progressively improved and assessed without having to limit the present beam intensity. Operating conditions were set at 170 to 200 kV across a 1 cm gap with a low sparking rate, but it should be stressed that these tests lasted only for six hours each time. We still had the expected current drain due to gas ionization in the HT supply and we are now taking steps to suppress this current by using a protection resistor insulated by a special epoxy resin.

At the end of this series of MD periods, sharing with a target was finally obtained with a very good efficiency, but the efficiency of the ejection itself was still lower than theoretically possible. The losses were about 12 % of the PS beam, with about 4 % lost on the ES and 8 % on the ejector magnet. The ES was taken apart and examined for possible damages that could increase its apparent thickness and account for some of the unexplained losses. After these periods of testing at a high performance level which had required thorough conditioning with many thousands of sparks the stainless steel septum foil was no longer as flat as originally and its apparent thickness had doubled, increasing from 0.15 to about 0.3 mm. Since the jump at the ES was set at 7 mm, this can account for the 4 % lost there. It is more difficult to explain why the losses are so high on the ejector magnet in SS 62, since the hole created by the ES in front of this magnet is large enough and is at the right position. A part of it could, however, be attributed to the following fact: The septum foil had somewhat bulged out over the last centimeter of its length at the exit end, due to some local overheating so that the divergence of a fraction of the ejected beam had been increased by multiple Coulomb scattering. In the future a molybdenum foil, which has given good results in a small test model, will be used for mounting the ES in order to eliminate this weak point.

4. Continuation of the work and conclusion

The experience gained with the ES prototype, though limited, is quite encouraging and we proceed with the project of installing an ES during the next PS shut-down, very likely in SS 83, for the slow ejection SE 16. It seems reasonable to assume a working field in excess of 120 kV/cm in this ES for a gap of about 1 cm, even with the improved PS intensity, but there is still much work ahead to meet all the specifications.

The next steps during 1971 are :

1) Installing a new ES in SS 45 to proceed with the tests of ejection SQUARE. This requires an ES working at high performance for short periods.

2) Installing a new ES in SS 43 where it will be used for the normal SE 62, in order to gain experience in the routine operation of this equipment and assess the corresponding long time performance level as well as the required maintenance. With the present installation it is almost impossible to use a direct shot ejection because the position of the magnetic septum lens in SS 63 is unfortunately limited to 75 mm instead of the required 84 mm from the axis, so that a large gap with a low field will be required in the ES.

3) Carrying out with the ES prototype installed in SS 66 all the required HT tests that could not be performed because the

prototype was used for testing ejection SQUARE. The purpose of these tests will be to improve the screening to the degree required for the future PS intensity, to try and understand the nature of the current pulse induced in the ES by the proton beam and why it takes such a long time, about 200 ms, to start after injection. The behaviour of wire septa must also be tested in the PS because another type of cathode or special ion collecting electrodes may then be required for them and their performance must be compared to that of foil septa under operational conditions for long periods, since they are likely to be more easily damaged by sparks.

4) Constructing and installing on the ES tanks special narrow miniscanners which are required for the best setting up of the slow ejection. These miniscanners will be of the "clean vacuum" type in order not to perturb the ES performance or the improved quality of the PS vacuum.

5) Developping radiation-resistant protection resistors for the HT supplies and installing the latter in such a way as to suppres the current pulse induced in them by the proton losses.

6) Detailed engineering of the final ES for slow ejection SE 16, with all the required control and monitoring equipment, keeping in mind the need for easy and fast maintenance on the ES which will become radioactive.

5. Acknowledgements

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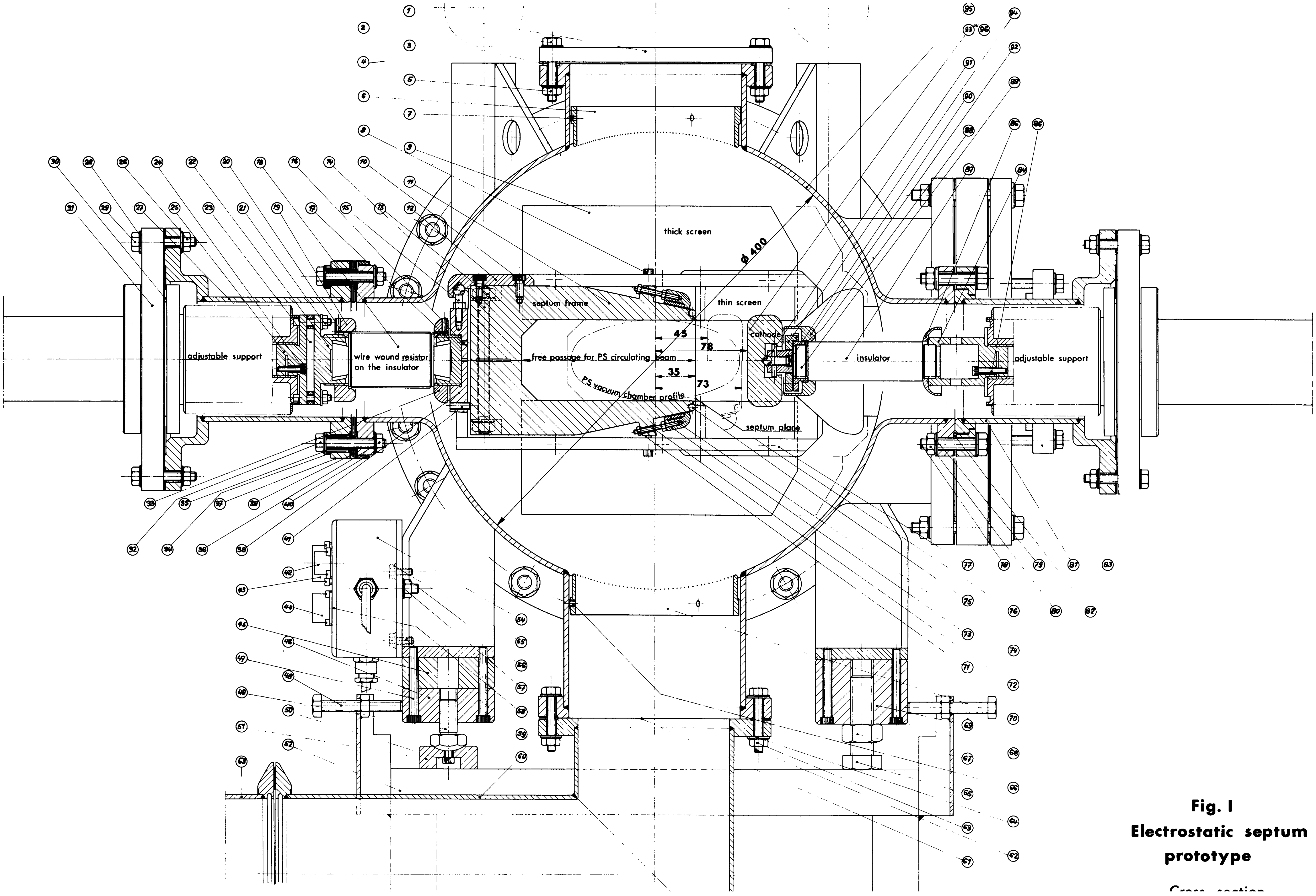


Fig. 1
Electrostatic septum prototype

Cross section

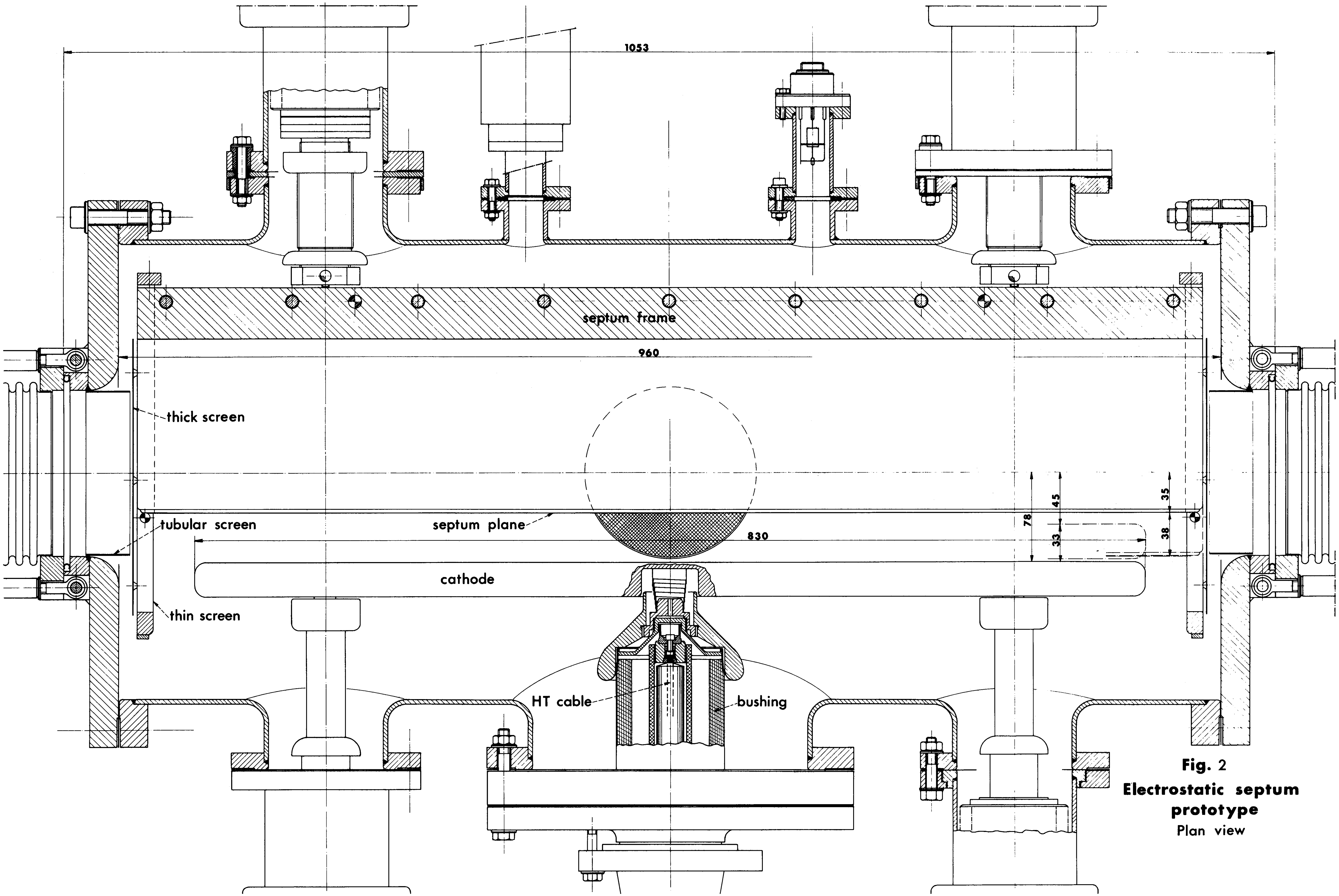


Fig. 2
Electrostatic septum prototype
Plan view

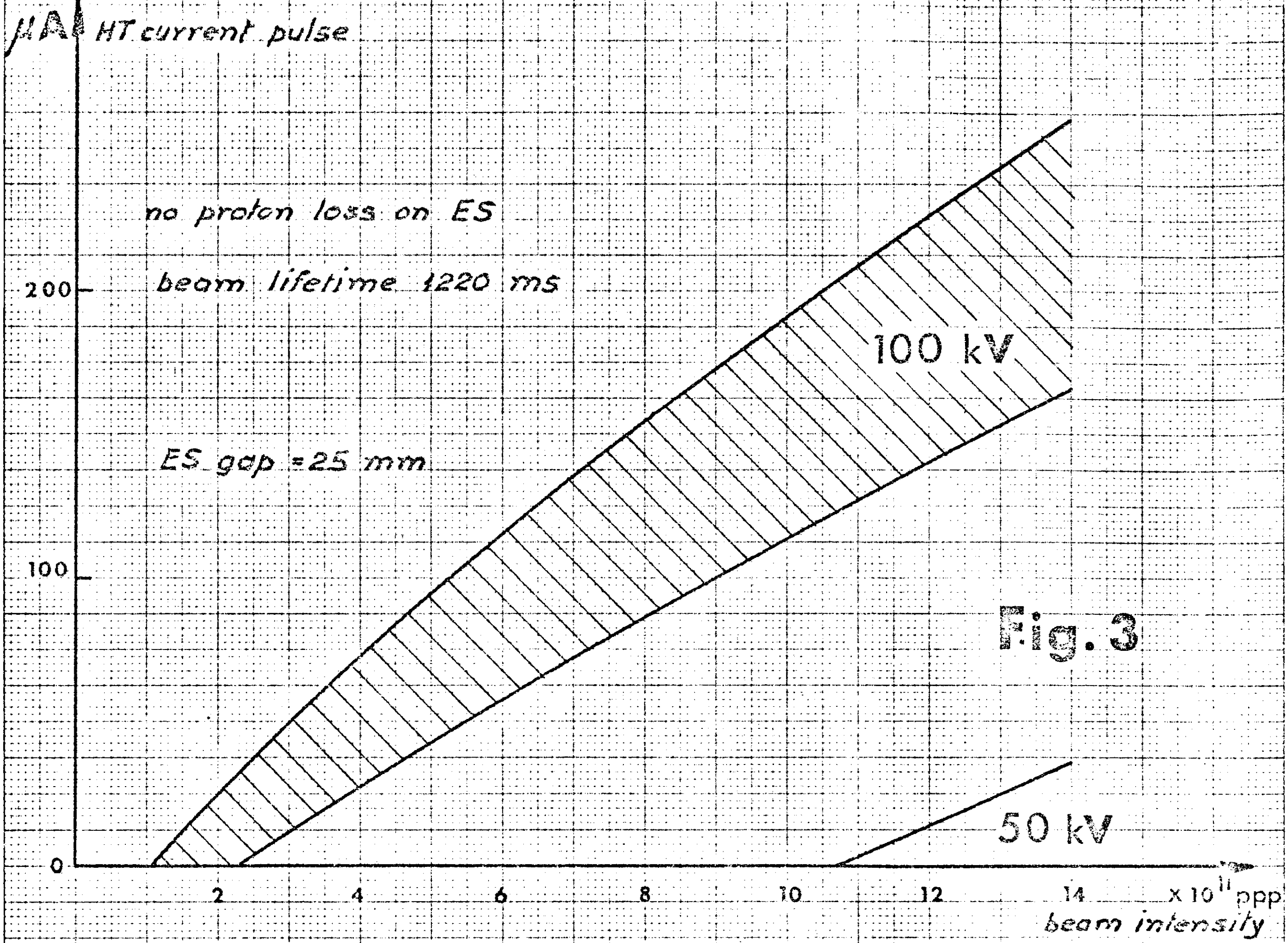

μA HT current pulse
no proton loss on ES
beam lifetime 1220 ms
ES gap = 25 mm
200
100
0
100 kV
50 kV
2
4
6
8
10
12
14
x 10^11 ppp
beam intensity

Fig. 3

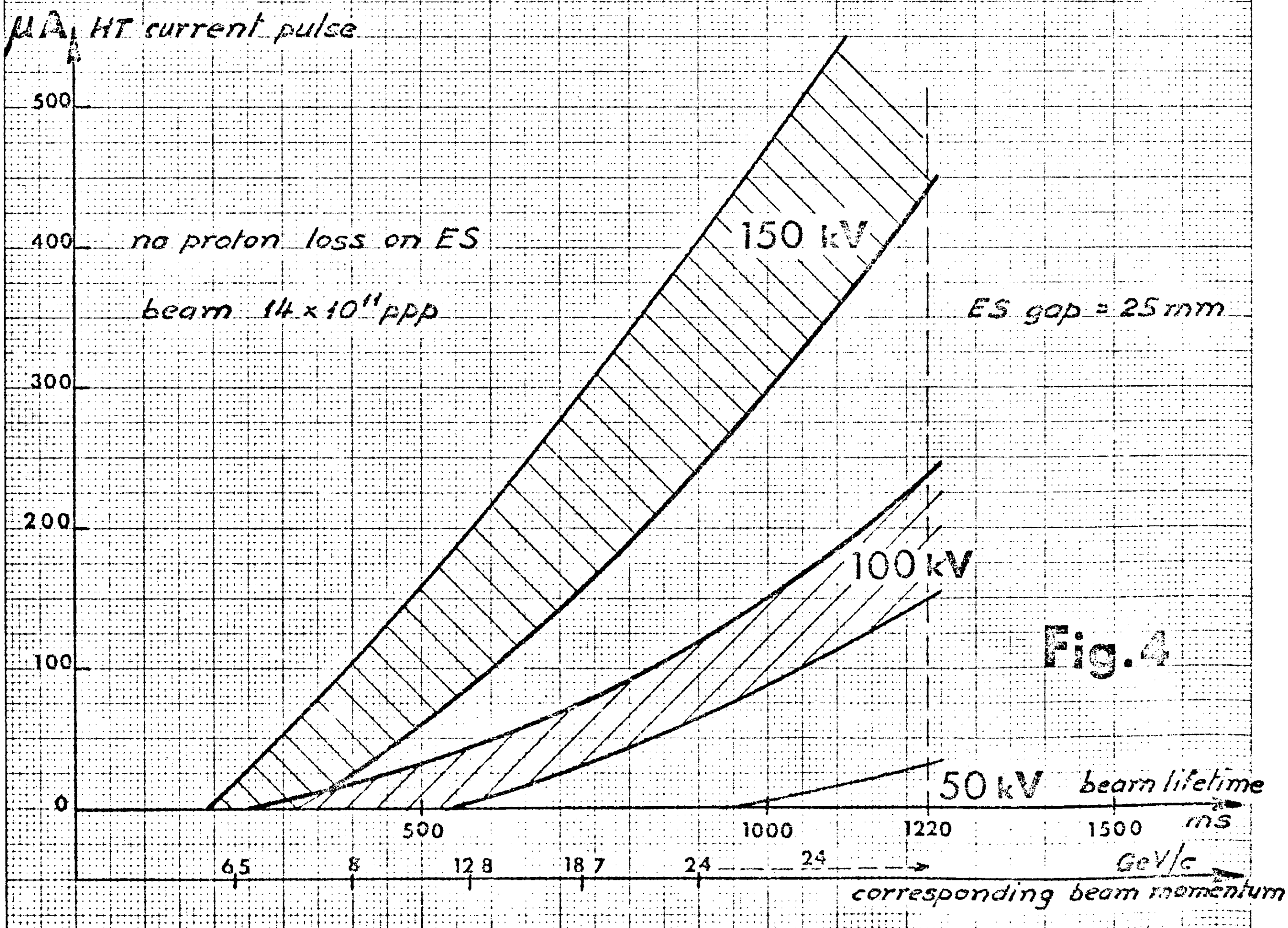
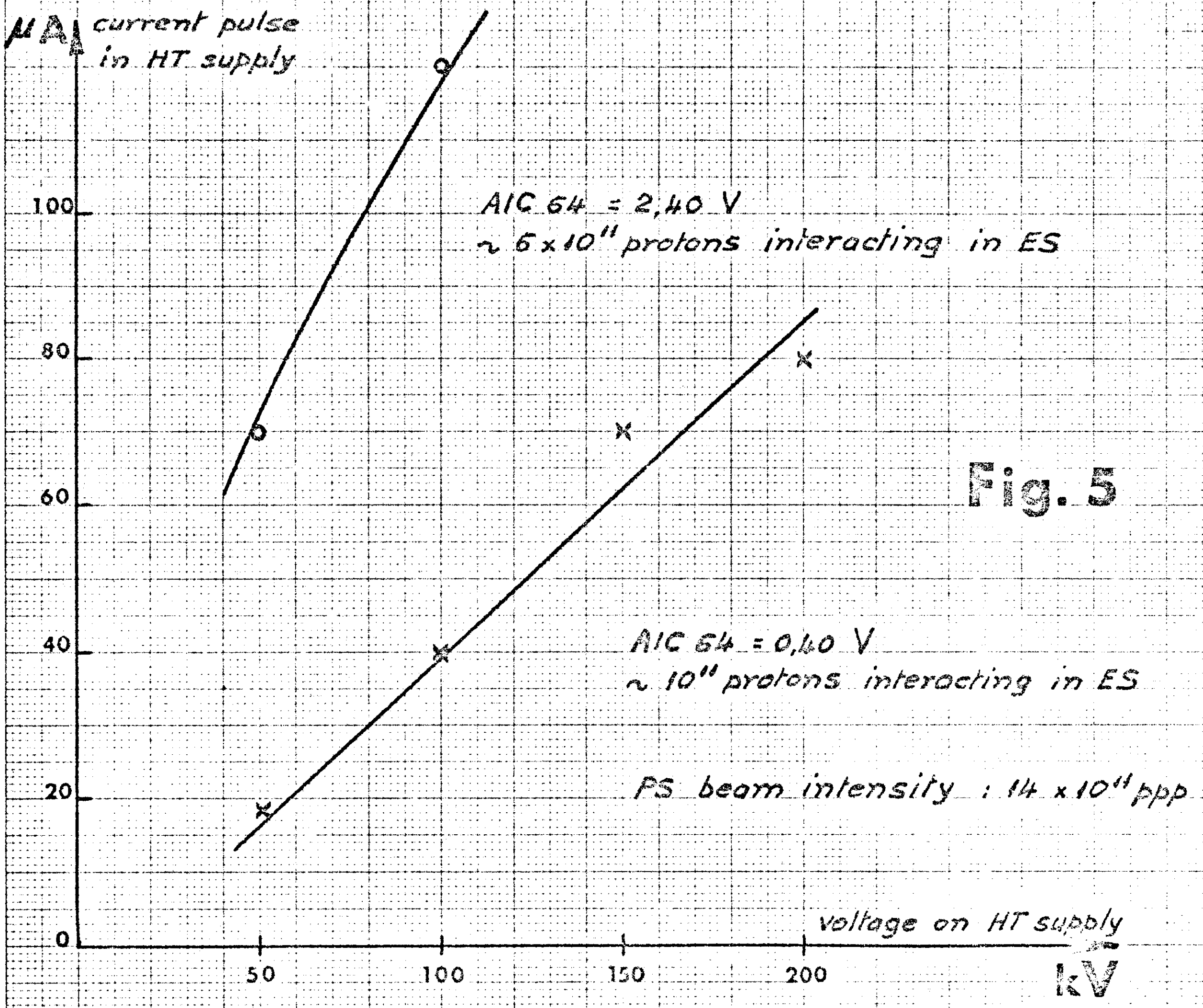

μA HT current pulse
no proton loss on ES
beam 14 x 10^11 ppp
ES gap = 25 mm
500
400
300
200
100
0
150 kV
100 kV
50 kV
beam lifetime
ms
500
1000
1220
1500
6.5
8
12.8
18.7
24
24
GeV/c
corresponding beam momentum

Fig. 4



μA
current pulse
in HT supply
100
80
60
40
20
0
AIC 64 = 2,40 V
~ 6 x 10" protons interacting in ES
AIC 64 = 0,40 V
~ 10" protons interacting in ES
PS beam intensity : 14 x 10" ppp
voltage on HT supply
50
100
150
200
kV

Fig. 5