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PROPOSAL OF A NEW KICKER SYSTEM FOR FAST EJECTION TOWARDS THE ISR AND THE WEST HALL

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1. Summary

A new coherent kicker system for fast ejection towards the ISR and the West Hall is described and proposed to be installed in the CPS in 1972 and 1973. The system is conceived as a sequence of two 0.47 m long full aperture kicker modules per short straight section. For the first stage, coinciding with the beginning of the Booster operation, 2-3 straight sections would be required, a fourth section to be added at the second stage corresponding to multiturn injection into the CPS at 800 MeV Booster energy.

In order to obtain such a system, capable of ejecting with equal efficiency from ss 16, 58 and 74, it is foreseen to place the kicker modules in the required number of F-sections 81 (long ss), 89, 97, 5 and 13.

In order to avoid inconvenient degassing and formation procedures, a ceramic vacuum chamber with a useful CPS F-section aperture of 150 x 52 mm^2 is foreseen, the rest of the magnet delay line elements like ferrites, capacitor plates and terminating resistors being immersed in insulating oil.

The maximum magnet voltage is 50 kV, the corresponding PFN-voltage 100 kV. At this voltage 6 modules in 3 ss will give a 23 mm displacement in a D-section at 28 $\frac{GeV}{c}$, which is more than required for the first stage Booster operation.

With 8 modules the displacement is 31 mm (at 28 $\frac{GeV}{c}$) corresponding to a beam size assuming a filled PS vacuum chamber at 800 MeV by multiturn injection from the Booster.

Two switching systems will be investigated :

i) 120 kV maximum operating voltage deuterium thyratrons with non linear pulse sharpening lines for the current (and voltage) rise and a 60 kV maximum operating voltage tail-clipper of the kicker 97 type or laser-triggered spark gaps for the pulse falling part. In both cases, rise (fall)-times inferior to 15 ns have been obtained. A second 120 kV thyratron to be used for PFN termination and energy evacuation from the system.

ii) Low voltage, full scale model measurements having shown that incoming current or voltage pulses with rise-times slowed down to 50 ns - i.e. to figures that can well be obtained with deuterium thyratrons - resulted in an only 15 ns longer field rise-time in the kicker, it is intended to design the new system so as to use deuterium thyratrons only for switching, tail clipping and PFN termination.

This elegant solution would permit the elimination of the only spark gap, the tail clipper; it would also have the advantage of a smaller magnetic field overshoot and of a more uniform flat top than solution i).

All kicker modules shall be designed for a theoretical 85 ns magnetic field rise-time. A 90 ns interval between the 2 °/o and 98 °/o of the magnetic field flat top value had been measured on a low voltage model, designed for a theoretical 85 ns rise-time of the magnetic field.

The proposed kicker system should be able

i) to eject any number of bunches between 1 and 20, once per second,

ii) to double or triple pulse within 100 ms interval the same or different number of bunches, at one PS momentum, and

iii) to perform operation ii), but at different PS momenta during one machine cycle.

As to the 2 turn-, 10 bunch ejection towards the ISR a second slow rising low voltage kicker with a 1 μs rise-time should be added to the proposed system between 1973 and 1975.

It is proposed to build a 2 module-kicker prototype for mid 1969 and start the series production only after successful high voltage life tests of all components, clarification and confirmation of all relevant parameters and successful performance under conditions i) ... iii).

2. The new kicker system; guide lines and requirements

The first fast ejected beam for the ISR will be needed at the beginning of 1970, the 97-kicker to provide for high energy ejection of an actual size PS beam.

By mid 1971 the West Hall will come into operation requiring more refined fast ejection facilities to be again met by the improved 97-kicker ("straight flush" facilities).

By mid 1972 the Booster should become operational with a possible increase of the PS beam size. The first stage of the new kicker system should then be installed in the PS to satisfy both the ISR ejection requirements - which can be assumed to be rather straightforward at that stage - and the West Hall ones which, as explained later, can be summarized as "straight flush II" requirements.

By mid 1973 the full PS intensity should be accelerated in only 10 bunches, with a considerably enlarged beam size. At this stage the new kicker system should be fully installed and provide enough kick at 28 $\frac{\text{GeV}}{\text{c}}$ for a beam, assumed to fill the PS vacuum chamber at 800 MeV injection energy.

In 1975 two turn ejection towards the ISR may be required. A separate additional slow(1 μs)rise-time,low voltage kicker magnet should then be installed in the PS.

In proposing the new kicker system the first and obvious guide line is reliability plus straightforwardness for complex requirements. The new kickers can no more be considered as an important part, but only as a part of a system providing protons for experimental areas; they will form an integral part of a new machine, the ISR.

The approach to the design of the new system should be "horizontal" and "eclectic" : horizontal in the sense that the kicker voltage, current and filling time can be reduced by adopting a modular system, spreading over several straight sections of the PS, thus buying reliability for more machine space. An "eclectic" kicker system should as far as possible use solutions and components which have already proved their reliability and successful operation in similar systems in and outside CERN, such as deuterium thyratrons (Brookhaven National Laboratory, ISR and SI Divisions), resonant power supplies (SI Division), the multi-gap tail clipper (97-kicker) a.s.o.

The guiding principles, in connection with the proposed new kicker system, can be summarized as follows :

i) Voltage limitation

When designing kicker magnets for beam deflections and momenta and with apertures as for the CPS, a reasonable magnet voltage limit seems to exist, beyond which difficulties and expenditures grow very fast with increased voltage.

The proposed maximum 50 kV magnet voltage - the normal operation voltage would lie between 40 and 45 kV - should be safely below the "trouble threshold" of 70 ... 80 kV (according to the experience with the full aperture kicker 66).

ii) The magnet active parts shall not be placed inside the PS vacuum system. Both the test experience with the FAK 66 and the running experience with the first kicker 97 have shown how inconvenient outgassing and vacuum forming procedures are.

It is therefore proposed to increase the aperture of the new kicker magnets, use a non degassing ceramic vacuum chamber as part of the PS vacuum system and immerse the rest of the magnet parts in oil or a similar insulation of predictable and reliable minimum dielectric strength, available at any time without special formation process.

iii) Only passive elements such as the magnet, terminating resistors and cables shall be installed in the PS ring.

Switching elements with their electronics to be installed in a permanently accessible building about 100 m from the kicker modules. This is of particular importance for the thyratrons, tail clipping spark gaps and power supplies.

iv) High voltage mechanical switches for bunch variation should be replaced by electronic devices, especially since switching within one machine pulse and from pulse to pulse is required. There is no evidence yet that mechanical switches will successfully withstand millions of pulses without contact erosion and break-downs.

v) Spark gaps should, whenever possible, be replaced by high voltage deuterium thyratrons.

Although satisfactory performance had been obtained with the 97-kicker main 60 kV spark gaps and with the 30 kV tail clipper, where jitters of 12 ns had been obtained, and although a 15 ns jitter for 90 °/o of all pulses could be reached with the two 110 kV spark gaps of the FAK, it is felt that deuterium thyratrons should be used wherever this is allowed due to their inherent slower rise-time. There is now sufficient evidence that they are jitter-free devices, jitters of 1 - 2 ns having been measured after 10^7 pulses. Thyratrons have also the advantage of regular, non erratic firing, simpler triggering systems and no danger of erosion or contamination.

vi) The project feasibility should be fully demonstrated and proved before starting the manufacturing of the new kicker system.

This is an essential requirement, necessary in order to save money, time and to allow a correct planning of the PS and ISR experimental programme.

A modular system meets this requirement, since the performance of the complete system can be verified by constructing and testing a 2 module-prototype. This prototype being itself demountable, can have its parameters changed and adjusted until the required performance is reached. Only then shall the series manufacturing start.

By doing so, one avoids the FAK situation, where the magnet performance was only known after the completion of the entire project.

The requirements to be met by the new kicker system could be stated as follows :

ISR requirements

i) 20 bunch ejection up to 28 $\frac{\text{GeV}}{\text{c}}$ with a required magnetic field rise of 95 ns.

ii) 10 bunch ejection up to 28 $\frac{\text{GeV}}{\text{c}}$ with a required magnetic field rise and fall time of 95 ns.

iii) Two turn, 10 bunch ejection up to 28 $\frac{\text{GeV}}{c}$; for the first 10 bunches, requirements as under ii), for the rest a slow, 1 μs rise time is sufficient with no requirements as to the fall time.

West Hall requirements

These are the more complex ones. A tentative list of requirements is indicated below. The final ones will, of course, have to be discussed with the users in due time.

i) Ejection of any number of bunches between 1 and 20 at one PS momentum up to 28 $\frac{\text{GeV}}{c}$ once every second; required kicker field rise and fall time of 95 ns.

ii) Double and triple pulsing within 100 ms interval of equal number of bunches at one PS momentum up to 28 $\frac{\text{GeV}}{c}$, once every second.

iii) Double and triple pulsing within 100 ms interval of different number of bunches at one PS momentum up to 28 $\frac{\text{GeV}}{c}$, once every second.

iv) Ejecting up to three times, different number of bunches at different PS momenta (flat tops), this to be repeated once per second.

v) Same as iv), but with double or triple pulsing within 100 ms at one of the (longest) PS flat tops.

A certain preselection and sequencing of these possibilities from pulse to pulse should also be envisaged.

It will be explained in some detail how to achieve these ejection facilities with the new kicker system.

3. Parameters, electrical scheme and components of the new kicker system

The kicker system parameters are determined by the following factors :

i) First stage : Booster Synchrotron becomes operational. At an assumed 1.2 x 33 π μmrad beam emittance at 800 MeV, a beam displacement of 22 mm in a D-section, corresponding to a 1.5 mrad kick in F, at 28 $\frac{\text{GeV}}{c}$ is required.

ii) Final stage : Multiturn injection from the Booster into the PS at 800 MeV, PS vacuum chamber practically filled at this energy. A 31 mm beam displacement at 28 $\frac{\text{GeV}}{c}$ in D is then required, corresponding to a 2.1 mrad kick in F.

iii) Available PS short straight section length amounts to 1.08 m, yielding some 0.94 m for the magnet active parts.

iv) Maximum safe operating voltage of 100 kV D.C. has been assumed for 120 kV deuterium thyratrons.

v) The PS F-section 150 x 52 mm^2 aperture to be available within a 4 mm thick vacuum chamber of the kicker magnet.

Based on these requirements and limitations, the proposed kicker system parameters are as follows :

Table I

Item	Value	Remark
Useful ferrite aperture (mm^2)	170 x 64	
Useful vacuum chamber aperture (mm^2)	150 x 52	
Module length ℓ_m (m)	0.47	
Number of modules per short straight section	2	
Kick per module at 28 $\frac{GeV}{c}$ ξ_m (mrad)	0.26	
Magnetic field B (G)	525	
Magnetic field in ferrite B_f(G)	750	
Number of ferrites per module	14	
Computed magnetic field rise-time T_r (ns)	85	
Expected magnetic field rise-time 2 °/o - 98 °/o (ns)	< 95	
Module inductance L_m (μH)	1.56	
Module capacitance C_m (nF)	4.6	
Module impedance Z (Ω)	18.5	
Module current I_m (kA)	2.7	
Magnet voltage at 28 $\frac{GeV}{c}$ U_m(kV)	50	
Pulse forming network voltage at 28 $\frac{GeV}{c}$ U_{pfn} (kV)	100	
Required number of modules	8	see also para. 4, page 21

Figs. 1 and 2 show the electrical schemes of the proposed two variants, always for 2 modules or 1 short straight section.

According to Fig. 1 a resonant 130 kV maximum charging voltage power supply as proposed and developed by A. Brückner (1) is envisaged. It consists of the high voltage transformer Tr excited by the discharge of the low voltage capacitor bank(s) C_{ch} via SCR1 ... SCRn. The charging voltage of C_{ch} is regulated to a few $^{o}/oo$. The PFN is connected to the high voltage winding of the transformer which charges the network to a constant voltage during an interval of a few ms. The 100 kV d.c., 9.25 Ω, 2 μs pulse forming network for two modules is being charged via a 1 ... 2 kΩ protective resistor. The PFN will be made of lumped ℓ and c elements with air or oil insulation. Adjustable elements will be foreseen in order to obtain a smooth flat top within ± 1 ... ± 2 % and to correct for its droop.

The PFN to be discharged via one "English Electric" deuterium thyratron of the CX 1171 (small arc diameter) or CX 1176 (larger arc diameter) type with a nominal voltage of 120 kV. If necessary, a higher 160 kV nominal voltage thyratron of the 1193 type could be envisaged.

An 80 ns to 15 ... 10 ns pulse sharpening line (PSL), as proposed by A. Brückner (2) and consisting of capacitors and saturable ferrite core inductances is connected to the thyratron. The PSL has the required impedance of 9.25 Ω (of two modules in parallel) once the ferrite cores are saturated.

The PSL is connected to four outgoing, about 100 m long, attenuation free, 50 kV, 37 Ω cables with the magnet. In this same point, a 50 kV, 9.25 Ω, 10 ... 15 ns fall time tail clipper of the 97 kicker type is also connected to the 4 cables.

At the other end of the PFN, a second 120 kV nominal voltage deuterium thyratron for energy evacuation terminates the line with its 9.25 Ω resistor, according to an established programme. There are no special requirements as to the current rise time in this thyratron.

The 4 cables connect the PSL and the tail clipper to the approximately 100 m further away magnet modules in the PS ring. Each module is fed from two 37 Ω cables via cross-connectors (see Fig. 12) in order to connect the magnet before a particular run for a "positive" or "negative" kick without having to charge any other high voltage load or to invert the power supply or deuterium thyratron connections.

As will be explained later, this point is of particular importance for reliable and safe ejection towards different experimental areas.

The 18.5 Ω modules consisting of 14 C type ferrite cores and of 28 oil insulated capacitor plates, alternatively connected to the two conductors, are terminated with 18.5 Ω resistor discs. A ceramic chamber is connected to the PS vacuum chamber, the rest of the magnet parts being immersed in oil.

Fig. 2 shows the scheme of the second and preferred variant : Low voltage measurements on a kicker module model having shown (see para. 5, page 23) that the incoming current or voltage pulse could be slowed down to 50 ns while loosing only 15 ns in the magnetic field rise and fall time, the second variant is based on the use of deuterium thyratrons only for switching, energy evacuation and tail clipping.

In order to obtain the required 50 ns rise time current pulse, two CX 1176 or CX 1193 thyratrons, one per module, are connected to the PFN. For energy evacuation and PFN termination, one - preferably CX 1176 tube - is foreseen. Tail clipping to be performed with two (one per each module) 80 kV nominal voltage CX 1168 or CX 1175 thyratrons. For the rest, these scheme is identical with Fig. 1.

Fig. 3 shows the proposed location of the various kicker magnet components referring to 2 modules.

The following equipment should be installed in a central ejection building some 100 m from the kicker magnet : The 130 kV power supply, occupying 1 ... 1.5 standard racks plus the 50 kVA H.V. transformer. If air insulation is used for the PFN, four standard racks would be required. A preferred solution would consist of placing the PFN into an oil tank, directly connected to the H.V. connection of the power supply transformer Tr.

The two (for variant 1) or five (for variant 2) deuterium thyratrons to be mounted in a coaxial arrangement and insulated and cooled with oil. The switching on thyratrons have their grid pulses, filament heating and deuterium pressure voltages supplied through 130 kV insulating transformers. A common oil system should be envisaged for all deuterium thyratrons and their H.V. insulating transformers. Although the thyratrons could preferably be mounted on the PFN oil tank, they should have a separate oil system, in order to quickly inspect or exchange any tube without having to evacuate the oil from the PFN tank. This solution is supposed in Fig. 3. If a PSL and a tail clipper is used (for variant 1), they should be connected to the cathode of the switching thyratron in such a way that the tube and the clipper can be easily disconnected, inspected or exchanged.

The PSL would again be immersed in oil.

It is hoped that the four about 100 m long, no semi-conducting layer containing 37 Ω cables can be made for the required 50-60 kV voltage without filling them with SF_6. However, the 120 kV SF_6 filled cables used with the full aperture kicker have proved to be very reliable so that, if required, a solution is always in hand also for the new kicker system.

The attenuation of these cables for a 100 ns rise time pulse and a 2 μs travelling time, corresponding to 200 m of one way cable length, resulted in a 5 ... 10 ns increase in the rise-time.

The kicker system components shall now be described in more details :

3.1 The Power Supply and the Pulse Forming Network

The power supply will consist of one or several rectifiers for charging one or more metal paper capacitor banks of ≈ 3 kWs L ≈ 450 V , of the electronics for regulating the charging voltage(s) within a few $^{0}/oo$, for timing and sequencing the discharges and for the regulation of the H.V. transformer bias excitation current, in order to make full use of the peak to peak magnetic flux charge in the iron core during discharge. The capacitor bank(s) is discharged through a number of silicon controlled rectifiers (SCR). As it is intended to have a multi-pulsing system capable of charging the PFN 3... 4 times per second within 100 ms intervals, this at the same and at different voltage levels, the following three schemes shown in Fig. 4 are envisaged :

i) The number of low voltage capacitor banks C_{1ch} ... C_{nch} and of their charging rectifier sets is equal to the maximum number of pulses per PS cycle; every capacitor bank is discharged through a separate SCR bank.

ii) Same as i), but with a low voltage contactor S_1 ... S_n for every capacitor bank and a common SCR bank; the contactors would switch with no tension applied to them.

iii) One capacitor bank C_{ch} is charged according to a programmed reference voltage cycle 3 ... 4 times per second and discharged through an SCR bank. For this solution a 100 $^{0}/o$ spare unit consisting of the rectifier plus capacitor C_{sp} and SCR bank would be foreseen, the spare system being automatically switched on in the case of failure of the main part.

The average power drawn from the mains, when pulsing two modules four times per second, would amount to 15 ... 20 kW.

Solution iii) is the preferred one.

If this solution is adopted, the power supply for 2 modules would require the space of 1 1/2 standard racks plus the H.V. transformer (about 1 m^3). For every additional low voltage capacitor bank half of a standard rack would have to be added.

The PFN for two modules with air insulation would require 4 - 5 standard racks of epoxy cast barium-titanate H.V. capacitors. By placing them into an oil container, the required space could at least be halved.

In order to obtain $\pm$ 1 °/o ... $\pm$ 2 °/o flat top error of the magnetic field and compensate its droop towards the end, a lumped line of non-identical elements can be used and a tuning system for the PFN inductances foreseen.

3.2 The switching elements, deuterium thyratrons, pulse steepening lines and tail clipper

As already stated, the design of the new kicker system is based on the use of "English Electric" deuterium thyratrons as the main switching elements. These tubes are produced in 40 kV element stages, a recent development being a 3 stage - 120 kV nominal voltage type. Tubes for voltages above 40 kV should be oil immersed for insulation and cooling. The "120 kV" thyratron has, according to the manufacturer, been tested up to 100 kV $_{D.C.}$ If required, a 4-stage "160 kV" tube can also be manufactured which would be able to withstand 120 kV $_{D.C.}$. "English Electric produces a smaller 3 cm arc diameter and a larger 6 cm arc diameter type, the latter with a double current carrying capacity.

Although it is intended to mount all deuterium thyratrons in coaxial oil containing cylinders, their matching to the PFN or magnet module characteristic impedances $\frac{R_z}{2}$ resp. R_z is not possible.

The tube will represent an inductance L_t in the system. Placed in a matched system with an impedance R_z, a time constant $\tau_t = \frac{L_t}{R_z}$ (ns) is obtained, which together with the inherent time for ionisation build up limits and determines the rate of current rise in the tube.

From the geometrical dimensions of the 120 kV thyratrons, one computes $L_t \approx 110$ nH for the larger arc diameter and $L_t \approx 180$ nH for the smaller arc diameter type.

With one tube per magnet module the corresponding time constants are 12 ns and 19 ns, limiting the current rise to 36 and 67 ns. H. O'Hanlon and J.P. Zanasco(3) have determined the current and voltage rise times by discharging a 80 kV nominal-voltage 2 stage smaller arc diameter CX 1168 thyratron of "English Electric" into a 14 Ω matched resistor. The charging voltage was 50 kV, the resistor voltage 25 kV, the current 1.8 kA; measurements were performed for different reservoir voltages U_r (V) regulating the deuterium pressure in the tube. Fig. 5 shows two oscillograms and the computed $\frac{dI}{dt}\left[\frac{kA}{\mu s}\right]$ and voltage rise times T_r (ns) in function of U_r (V). Based on these results curves for small and large arc diameter 80 kV and 120 kV thyratrons had been computed. The larger arc diameter, 120 kV thyratron CX 1176 would give satisfactory performance as the main switching element at a reservoir voltage of $U_r \geq 5.9$ V, this for variant 2 on Fig. 2.

The large arc diameter, 80 kV CX 1175 thyratron would perform satisfactorily as tail clipper at a reservoir voltage of $U_r \geq 5.4$ V. The smaller arc diameter tubes seem to be marginal in both cases.

It is foreseen to check these computations by adequate measurements of small and large arc diameter 80 kV, 120 kV and 160 kV nominal voltage deuterium thyratrons. These tests will also show what nominal tube voltage is required for a 100 kV PFN switching voltage and for a 50 kV tail clipper voltage at the relatively high reservoir voltage U_r. Life tests carried out with the 80 kV thyratron have resulted in a ± 1 ... ± 2 ns pulse jitter after 7.10^6 pulses. The total anode drift had been measured to less than 5 ns. We nevertheless propose to use a pulse to pulse drift correction with a 1 ns sensitivity, the maximum correction amounting to 5 ns per pulse. The drift correcting system has recently been successfully tested.

These deuterium thyratron performances are superior to any results obtained with spark gaps for similar voltages.

In order to obtain such low jitter and drift figures, the cathode heater voltage should be stabilized to ± 5 $^{o}/oo$, the reservoir voltage continuously adjustable and stabilized to $1^{o}/oo$. The 50 ... 100 ns rise-time, 500 ... 1000 V grid trigger pulse amplitude should be reproducible from pulse to pulse within 1 $^{o}/o$.

As indicated in Figs. 1 and 2, all thyratrons in the proposed two kicker magnet schemes are in the preferred position with positive anode potential towards ground. The energy evacuating and tail clipping thyratrons have their cathodes (heaters reservoir voltage, grid pulse) at ground potential; the main switching thyratrons work with the cathode at half (50 kV pulsed regime) the PFN charging potential. For these thyratrons, 130 kV $_{D.C.}$ insulated heater, reservoir and grid pulse transformers should be foreseen.

<u>It is essential that for any kick polarity the PFN potential and the potential of all deuterium thyratrons remain unchanged.</u> It is easy to see that at reversed PFN polarity two of the thyratrons - for switching on and for energy evacuation - would require transformers insulated for the full PFN voltage. The tail clipping thyratron would require transformers insulated for 50 kV impulse voltage.

For variant 1 the use of a non-linear, saturable inductance PSL for the pulse rise and of a tail clipper are envisaged, although it is expected to finally adopt variant 2 with deuterium thyratrons as the only switching elements.

The PSL would be dimensioned for a "slow", 80 ns current pulse rise. A single 9.25 Ω, 5.5 kA, 50 kV-PSL supplying two magnet modules could be foreseen, consisting of a multiplate capacitor with one set of plates being adjustable and with clophene as high dielectric strength insulation. 16 ... 18 parallel, 6.3/19 mm ∅, 25 mm long ferrite cores would form the series inductance between adjacent capacitors. The plate distance would amount to d = 6 mm, the active plate surface to 700 x(50 ... 100)mm^2, the number of segments to 40 and the total length of the PSL to 750 mm.

The PSL is shown in Fig. 6 a); Fig. 6 b) and 6 c) show the voltage oscillograms taken before and after a 30 kV, 6.25 Ω, 5 kA-PSL, built for the Booster synchrotron radial kicker magnets. The 30 kV, 80 ns rise-time incoming pulse of a CX 1154 type deuterium thyratron (osc. 6 b) is steepened to about 15 ns (Fig. 6 c).

As to the tail clipper, the 97 kicker type, developed by H. von Breugel and oth.$^{(4)}$ could, if necessary, be envisaged. A 30 kV tail clipper is shown in Fig. 7 a) and 7 b). It consists of a 3 electrode spark gap system (1-2-3) plus a floating triggatron (4) providing instantaneous ionisation in the whole gap and initiating the break-down between the central electrode 2 and the triggatron 4. Current rise-times of 15 ns, including a 5 ns jitter, had been obtained.

A parallel solution would consist of laser triggered tail clipping spark gaps. The feasibility of laser beam use for achieving very low jitter and fast break-down (within a few ns) firing of spark gaps being demonstrated $^{(5)}$, work is continuing in this direction with the aim of developing a system capable of simultaneous triggering with one laser beam of several (3-4) tail clipping spark gaps. The laser beam would be split and all gaps - in this case one would use one gap for two magnet modules - fired simultaneously. In order to achieve the correct actioning of the tail clippers on the magnets due to their location in different straight sections, cables with adequate delays could be inserted between the gaps and the magnet modules.

With our actual 20 kWs laser, it would be possible to trigger the spark gaps up to 5 times per second. It remains to be seen if flash tubes with acceptable life times can, under these conditions, be obtained.

Fig. 8 shows the relative timing of the various thyratron (and spark gap) triggers, assuming both the main switching thyratron S1 and the tail clipping one S2 to be connected to the magnet by ℓ (m) long cables with a single way pulse traversal delay of D_c (ns). Firing S1 at $t = 0$, the firing of S2 determines the magnet pulse length (bunch number). The energy evacuation thyratron S3 is always switched before S2 : as an example, for a 15 bunch field length S2 - S1 = 1.5 µs, while S3 should be fired at S3 - S1 = 0.5 µs.

4. The magnet

Fig. 9 shows the cross section of a proposed magnet module. It would consist of 14 identical elements, each with a C-shaped 264 x 290 mm^2, 23.5 mm thick ferrite core in accordance with Fig. 10. The ferrite aperture is 64 x 190 mm^2. The ferrites are on both sides screened by C-shaped aluminium plates, normally connected to the high voltage, left conductor. The opposite, earth potential plates are again C-shaped and placed at 18 mm distance around the ferrite cores. Inside the stress-free and electrostatically screened gap a 4 mm thick, 150 x 52 mm^2 useful aperture ceramic vacuum chamber is placed; the whole active part of the magnet to be immersed in insulating oil. The maximum 50 kV impulse stress appears at the right side between the rounded off left capacitor plates and the right hand, again rounded off earth conductor, the oil distance being 10 mm.

The right hand wall of the vacuum chamber is thus placed in a relatively low and uniformly distributed electrical stress region.

All plates and ferrite cores are easily demountable.

In the longitudinal direction, the 8 mm thick capacitor plates which screen the ferrite core, alternate with the 6 mm thick opposite and central plates at a 9.75 mm oil insulation distance for a maximum 50 kV pulse.

If the polarity change-over variant according to Fig. 12 a) can be adopted, the two terminating 18.5 Ω resistors can be firmly connected to the modules and mounted in the main magnet tank.

As to the ceramic vacuum chamber, an enquiry has been made and at least three technically satisfactory offers received from firms which have already made similar chambers, notably for the electron synchrotrons of DESY, Hamburg, and NINA, Daresbury. The most elaborate and technically best proposal was made by the Wade Co Ltd., Portadown (N. Ireland). This firm will first manufacture two about 1 m long chambers, one for the 2 module kicker prototype, the second to be mounted into the PS ring, in order to check its radiation resistance.

The vacuum chamber to be made by Wade is shown in Fig. 11. It will consist of two about 50 cm long, 4 mm thick high quality alumina elliptic chambers with a glass joint in the middle, which is in turn reinforced by a 25 mm wide glazed muff. At both ends the chamber will have two flat, precisely machined flanges of the standard PS dimensions, the indium ring grooves to be located in the standard metallic flanges to be connected to the ceramic chamber ones. The chamber will be tested at a 2.5 at differential pressure. The manufacturer will guarantee the inner 150 x 52 mm^2 useful aperture, the outer dimensions to be kept by machining the external chamber surface.

Special attention has to be paid to the problem of polarity change-over for the magnet modules. As stated before, the only reasonable place to change polarity is at the magnet modules. Polarity has to be changed when ejecting from ss 16 (or 1) - positive kick - or from ss 58 and 74 - negative kick.

There are two possibilities to change polarity, shown in Figs. 12 a) and 12 b).

In the first case, the connection between the two in opposite sense mounted kicker modules and the cables is simply reversed. By doing so, the left, under normal operating conditions,H.V. conductor assumes earth potential and forms a short-circuit around the ferrite core with the tank, also at earth potential. It will be verified on full-scale, low voltage models to what extent this condition influences the magnet inductance and rise-time. If the magnet parameters are changed in an inadmissible way, solution 12 b) will have to be adopted; in this case four identical connecting plugs to the modules will have to be foreseen, two plugs connected to two parallel 37 Ω cables and two plugs connected each to a 18.5 Ω terminating resistor. For one polarity the cables are connected to the mid point between the two modules, and the resistors to the ends. For polarity reversal the cable and resistor plugs have to be interchanged.

<u>Since very reliable high voltage and pulse current connections are required, it is strongly suggested not to reverse polarity during operation, i.e. from machine pulse to pulse.</u> The development of

reliable switches working once per second for 10^6 ... 10^7 pulses would require several years. To introduce switches of this kind which would still have to prove their reliability would mean to go against the simplicity and general reliability of the proposed kicker system.

It is therefore proposed that the kicker module polarities are set before and for a particular PS and ISR experimental programme. In the case of simultaneous or alternate (from pulse to pulse) ejections towards areas requiring positive and negative kicks, it is suggested to rather increase the number of kicker modules in the PS. With 10 modules in 5 straight sections or equivalent, 4 modules could eject a beam of the actual size from ss 58 and 74, and 6 modules an enlarged beam from ss 16 towards the West Hall and the ISR.

By no means should one try to economize one or two short sections in the PS against a complicated polarity change-over system.

The factors influencing the magnetic field rise-time in the kicker modules shall now be discussed.

The field rise-time increase may be due to

i) the series inductance of the capacitor plates resulting in a limiting charging current resonant frequency f_r

ii) the mutual inductance between ferrite cores, due to imperfect screening. The C-type cores can, of course, not be screened on their inner horizontal gap surfaces. A longitudinal inductive stray field coupling between all ferrites is thus introduced, having its maximum between adjacent ferrites.

Low voltage, full scale model measurements have demonstrated that the progressive slowing down of the current and voltage wave through the magnet is due to this coupling. Information has also been obtained on the influence of this phenomenon on the magnetic field rise-time as a function of the ferrite core screening and distancing. A theoretical examination to follow.

As to the inductance of the capacitor plates during charging, a simple approximate calculation shows that in our case the influence on the magnetic field rise-time can be neglected.

Let us, in accordance with Fig. 13, assume that the capacitor plate has a ferrite environment with $\mu = \infty$ on one side, and that the field created by the charging current is limited by the surrounding metallic box :

The charging currents are flowing radially outwards from the conductor. With the notations in accordance with Fig. 13 and assuming :

$$\ell = \ell_{min} \left(1 + k \cdot \frac{x}{x_o}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$d\Phi = dx \cdot \delta \cdot \frac{I\mu_o}{\ell_{min} \left(1 + \frac{kx}{x_o}\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$\Phi = \int_{\ell_{min}}^{\ell_{max}} d\,\Phi = \frac{x_o}{k\,\ell_{min}} \cdot I \cdot \delta \cdot \mu_o \cdot \ln \frac{\ell_{max}}{\ell_{min}} \quad \ldots\ldots \quad (3)$$

$$L = \frac{\Phi}{I} = \frac{x_o}{k\,\ell_{min}} \cdot \delta \cdot \mu_o \cdot \ln \frac{\ell_{max}}{\ell_{min}} \quad [\,H\,] \ \ldots\ldots \quad (4)$$

Introducing numerical values (see Fig. 13) $\ell_{max} = 1.2$ m, $\ell_{min} = 0.48$ m; $x_o = 0.22$ m, $k = 1.5$ and $\delta = 9.75 \cdot 10^{-3}$ m

$$L \approx 3.4 \text{ nH}$$

With a unit capacitance of 0.164 nF, the resonant frequency amounts to $f_r = 2.1 \cdot 10^8$ Hz corresponding to a rise-time of less than 1 ns.

This effect is thus not responsible for the slowing down of the voltage and current wave along the magnet. This has been confirmed on low voltage full scale kicker models, as shown in the next paragraph.

5. Low voltage model measurements

Two low voltage kicker module models had been built using 13 available ferrite cores from a Booster synchrotron kicker prototype. The ferrites had a 112 x 70 mm^2 aperture, thus different from the one proposed for the new kickers. The modified inductance has been taken into account. The parameters of the first model were :

$L = 0.8$ µH, $C = 10.9$ nF, $Z_o = 8.6\ \Omega$, $T_r = 95$ ns, $N = 13$ sections with 2 x 13 capacitor elements.

The module has been terminated with $R = Z = 8.6\Omega$ and subjected to low voltage pulses with a 12 ... 13 ns rise-time, as shown in Fig. 14.

The voltage (and current) behaviour along the module and the magnetic field rise and fall time were measured and recorded, the latter by means of a coaxial type, parallel transmission line field probe, terminated with a 75 Ω resistor. The following cases have been examined :

i) Ferrites unscreened, distance between adjacent cores 3 mm

ii) Ferrites unscreened, every second ferrite removed, distance between adjacent cores 31 mm

iii) Same as i), but with laterally fully screened ferrites

iv) Same as ii), but with laterally fully screened ferrites.

The results are shown in Fig. 15, after normalizing the measured field rise-time figures with respect to 170 ns, measured in case i) and assumed equal to 1.

Figs. 16 and 17 show the voltages measured along the magnet with all 13 ferrite cores and with only 7 ferrites left, i.e. with every second one removed. One sees how the incident 12 ... 13 ns rise-time voltage pulse is being slowed down to 120 ns and 85 ns respectively at the termination resistor end. Comparing the two oscillograms one can also see that the voltage pulse is always slowed down after a ferrite core. Measured at places where the ferrites had been removed - but with the capacitor plates in position - the voltage slope remained unchanged.

The capacitor plate series inductance or resonant frequency thus does not influence the voltage (and magnetic field) rise-time.

Based on these results, a second low voltage model had been built with parameters close to the final magnet ones as given in Table I, page 9. The 70 x 122 mm^2 aperture laterally fully screened ferrite cores were again used. The distance between adjacent ferrites was $\approx$ 10 mm, as proposed for the final magnet. The second model parameters were :

$L = 1.2\ \mu H$, $C = 6\ nF$, $Z_o = 14.2\ \Omega$, $T_r = 85\ ns$, $N = 13$,

the model length amounting to 0.52 m.

Fig. 18 shows the voltage pulse slow-down along the magnet from the incident 12 ... 13 ns to the 50 ns end value. Fig. 19 shows the differentiated magnetic field $\frac{d\Phi}{dt}$ at rise and fall.

Fig. 20 shows the situation when a 50 ns rise-time voltage pulse is applied to the magnet. It traverses the magnet without practically changing slope.

Fig. 21 shows the incident 50 ns voltage pulse applied to and measured directly accross a 14.2 Ω matching resistor.

Figs.22 a) and b) show the input voltage and $\frac{d\Phi}{dt}$ curves for the incident 12 ... 13 ns rise-time and for the 50 ns rise-time voltage pulse. In the first case the magnetic field rise-time, measured between the 2 $^{0}/o$ and 98 $^{0}/o$ of the flat top value amounts to 73 ns with a large 7 $^{0}/o$ overshoot. In the second case, T_{2-98} = 90 ns and the overshoot is less than 2 $^{0}/o$.

This result is of particular importance, as it indicates that by using 50 ns voltage and current pulse rise-time switches, very convenient field rise-times combined with low magnetic field flat top ripple can be obtained. Translated into practice, this means that deuterium thyratrons only can very probably be used for all switching operations as indicated in Fig. 2, for variant 2.

6. Future programme

In view of the above results and in order to obtain the maximum information, even before the construction of a high voltage prototype magnet, the following programme is suggested.

i) Construction of a third low voltage model with parameters in accordance with Table I. Ferrite cores have already been ordered.

Verification of magnetic field rise-time, determination of maximum permissible incident voltage (and current) pulse rise-time.

ii) Construction of a 130 kV resonant power supply with PFN and of a 2 module- high voltage kicker magnet prototype with ceramic vacuum chamber (already ordered). Low and high voltage pulse measurements, in order to verify and freeze relevant parameters; H.V. life test of magnet and vacuum chamber. Parallel to this :

iii) Determination of optimum "English Electric" deuterium thyratron type for our purpose. Determination of tube nominal voltage and of safe deuterium pressure regulating (reservoir) voltage U_r for the maximum PFN and clipping voltages and required rise-time.

iv) Life tests on chosen deuterium thyratrons and their auxiliaries; jitter and long term drift measurements for 10^6 ... 10^7 pulses.

v) Development of the switching electronics for multi-charging, multi-pulsing and sequencing operations.

vi) Prototype operation satisfactory; series construction of all power supplies, PFN, kicker modules with the necessary electronics and auxiliary equipment.

Acknowledgements

I would like to acknowledge the useful and animated technical discussions with Messrs. A. Brückner and D. Fiander, the helpful model measurements performed by the latter, as well as general discussions with Messrs. G. Plass and P.H. Standley.

A. Ašner

References :

(1) A. Brückner, J.F. Labeye : A resonant charging pulsed high voltage power supply
SI/Int. MAE/68-6, 27.6.1968

(2) A. Brückner : A non-linear step-pulse steepening delay line
CERN 68-25, Synchrotron Injector, 12.7.1968

(3) H. O'Hanlon, J.P. Zanasco : A high voltage thyratron switch for the fast inflector of the ISR
ISR-BT/67-55

(4) H. von Breugel, J. Goni, B. Kuiper : Pulse generators for delay line inflectors
NPA/Int. 65-28, 8.10.1965

(5) F. Deutsch : Development of a laser-triggered spark gap
CERN 67-33, Proton Synchrotron Machine Division, 28.12.1967

VARIANT 1

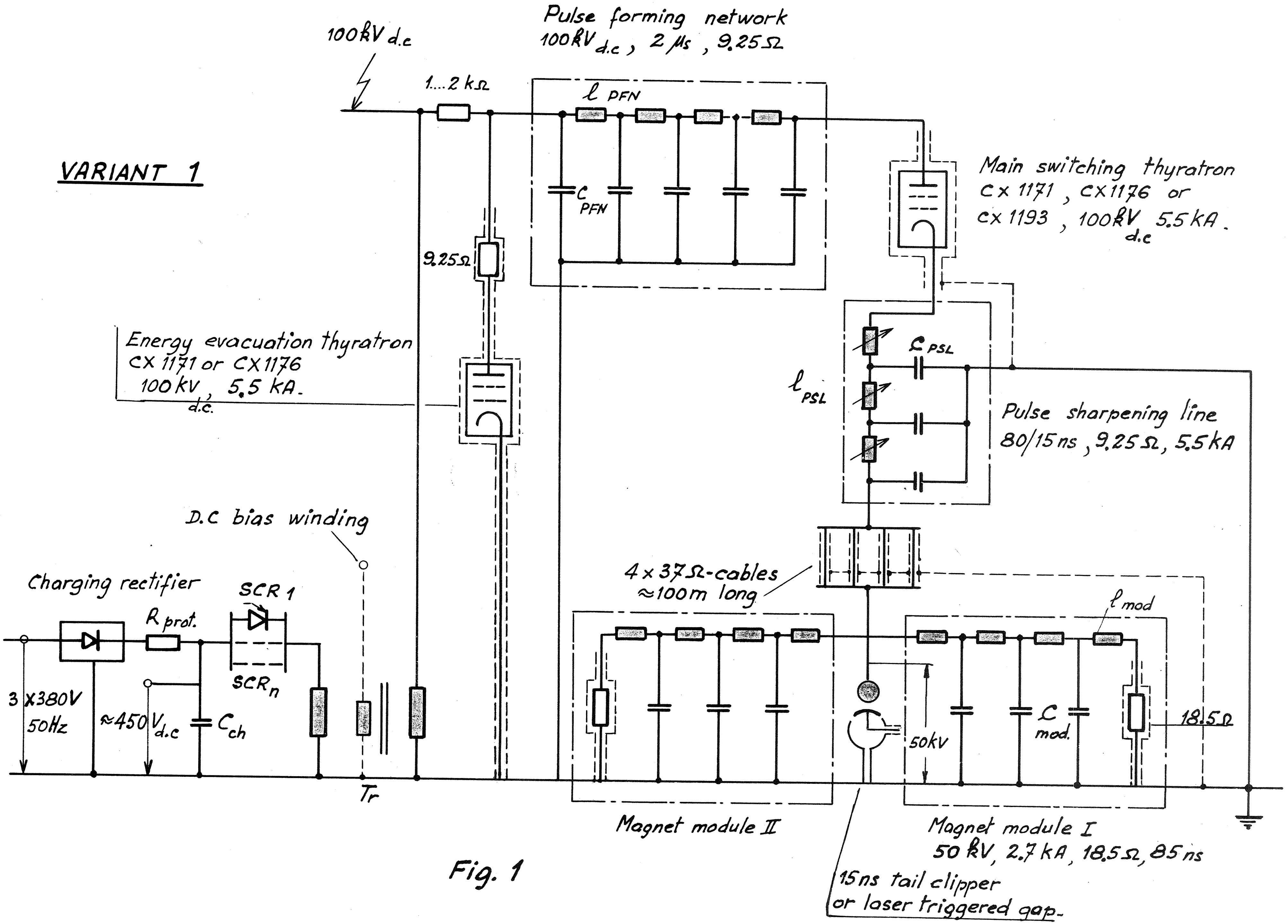


Fig. 1

VARIANT 2

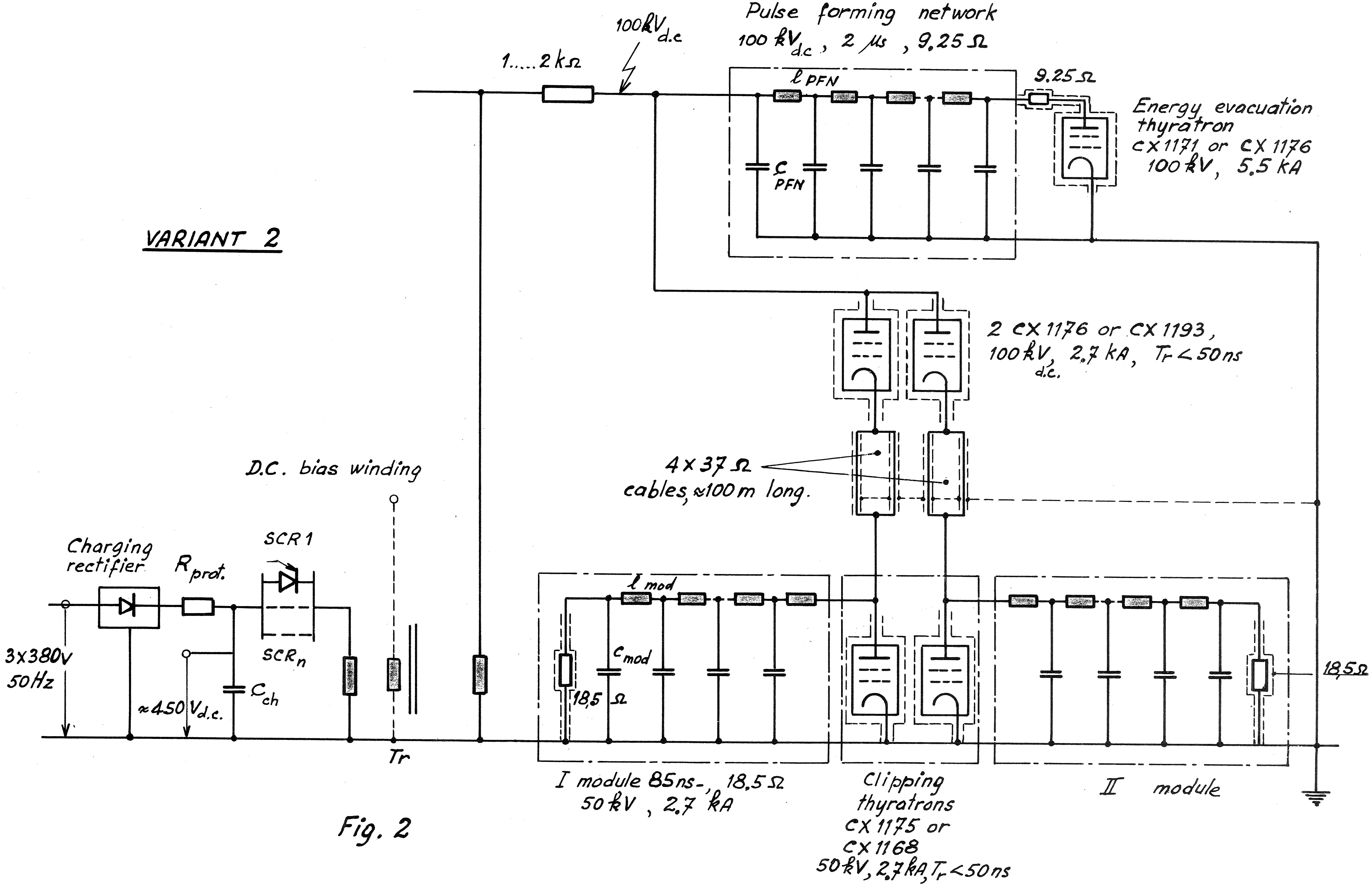


Fig. 2

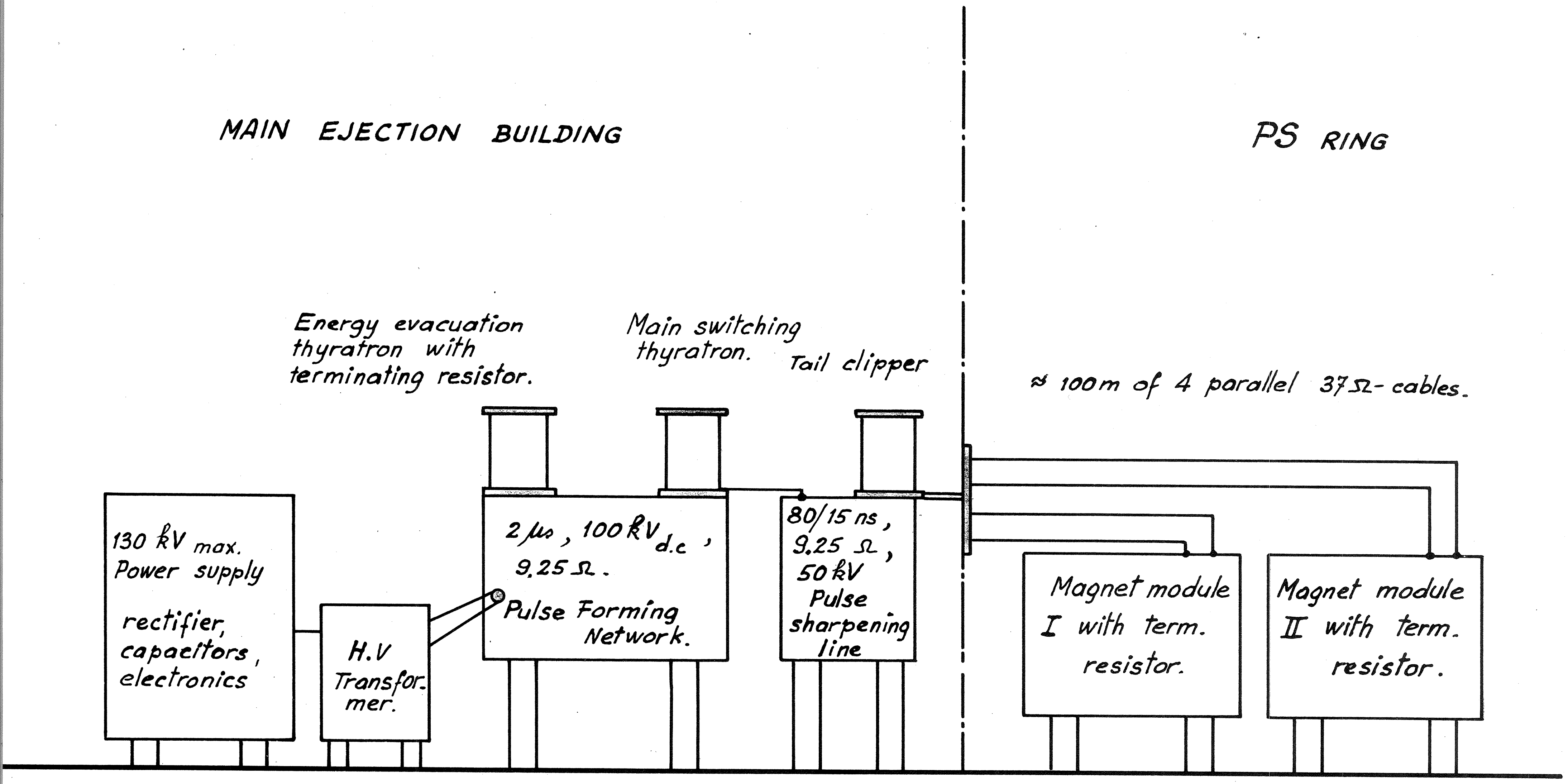

MAIN EJECTION BUILDING
PS RING
Energy evacuation thyratron with terminating resistor.
Main switching thyratron.
Tail clipper
≈ 100m of 4 parallel 37Ω-cables.
130 kV max. Power supply
rectifier, capacitors, electronics
H.V Transformer.
2 μs, 100 kV d.c, 9.25 Ω.
Pulse Forming Network.
80/15 ns, 9.25 Ω, 50 kV
Pulse sharpening line
Magnet module I with term. resistor.
Magnet module II with term. resistor.

Fig. 3a

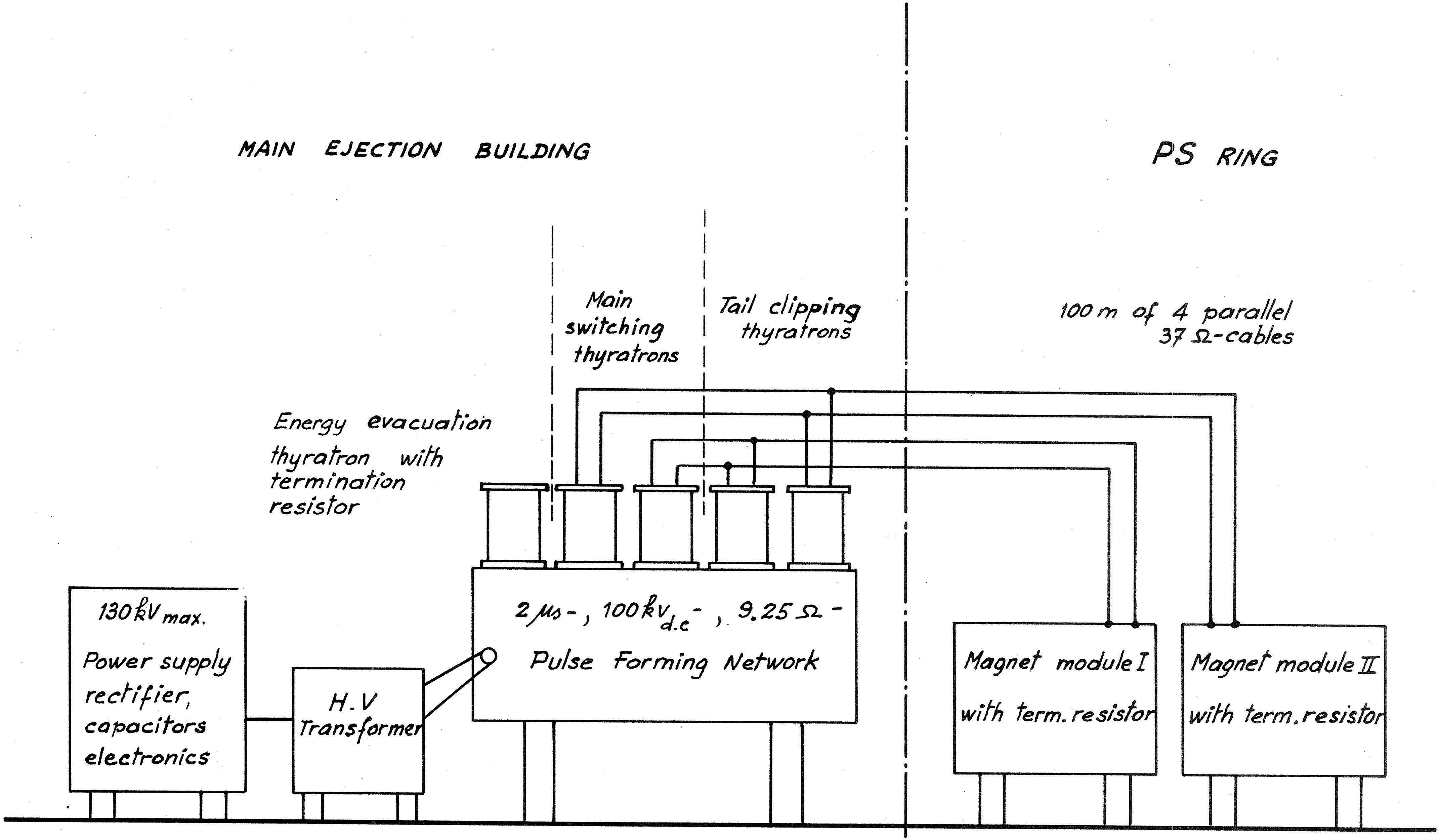
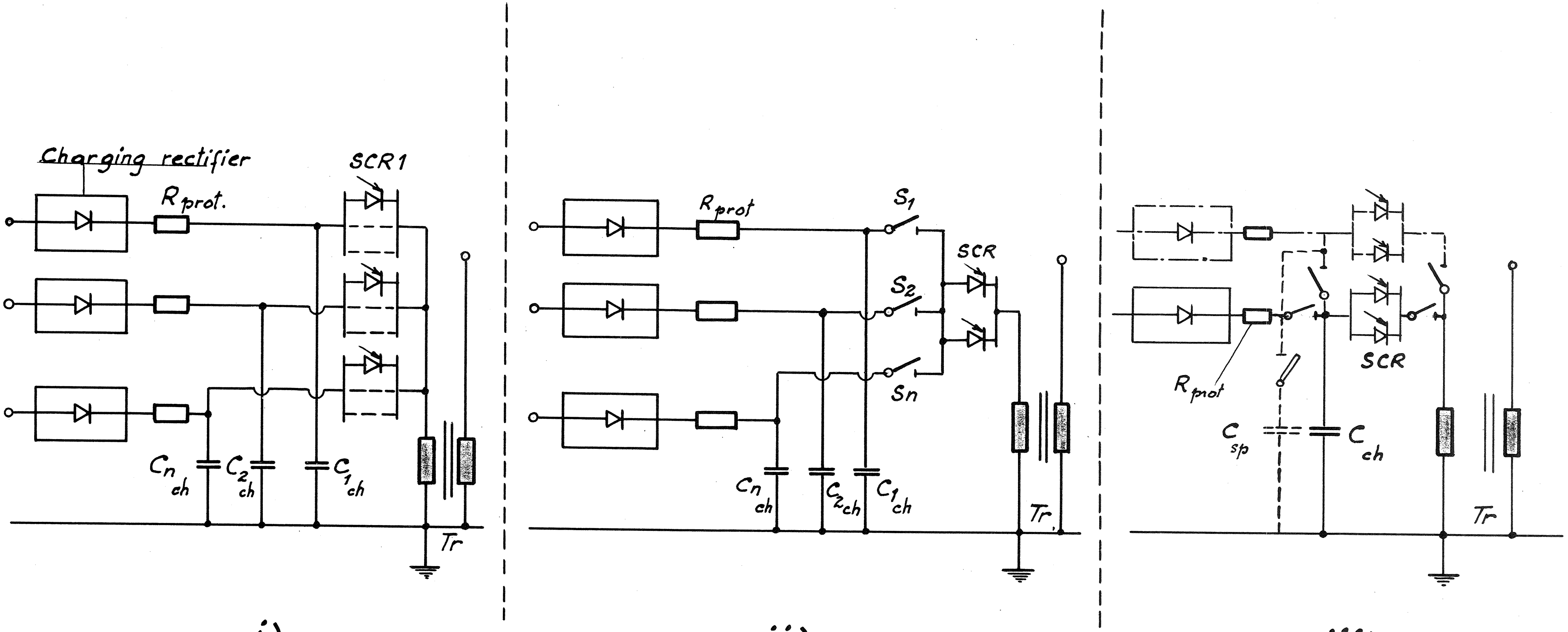

MAIN EJECTION BUILDING
PS RING
Main switching thyratrons
Tail clipping thyratrons
100 m of 4 parallel 37 Ω-cables
Energy evacuation thyratron with termination resistor
130 kV max.
Power supply rectifier, capacitors electronics
H.V Transformer
2 µs-, 100 kV d.c-, 9.25 Ω-
Pulse Forming Network
Magnet module I with term. resistor
Magnet module II with term. resistor

Fig 3 b


Charging rectifier
R prot.
SCR1
Cn ch
C2 ch
C1 ch
Tr
R prot
S1
S2
Sn
SCR
Cn ch
C2ch
C1 ch
Tr.
SCR
R prot
Csp
Cch
Tr

i)

ii)

iii)

Fig. 4

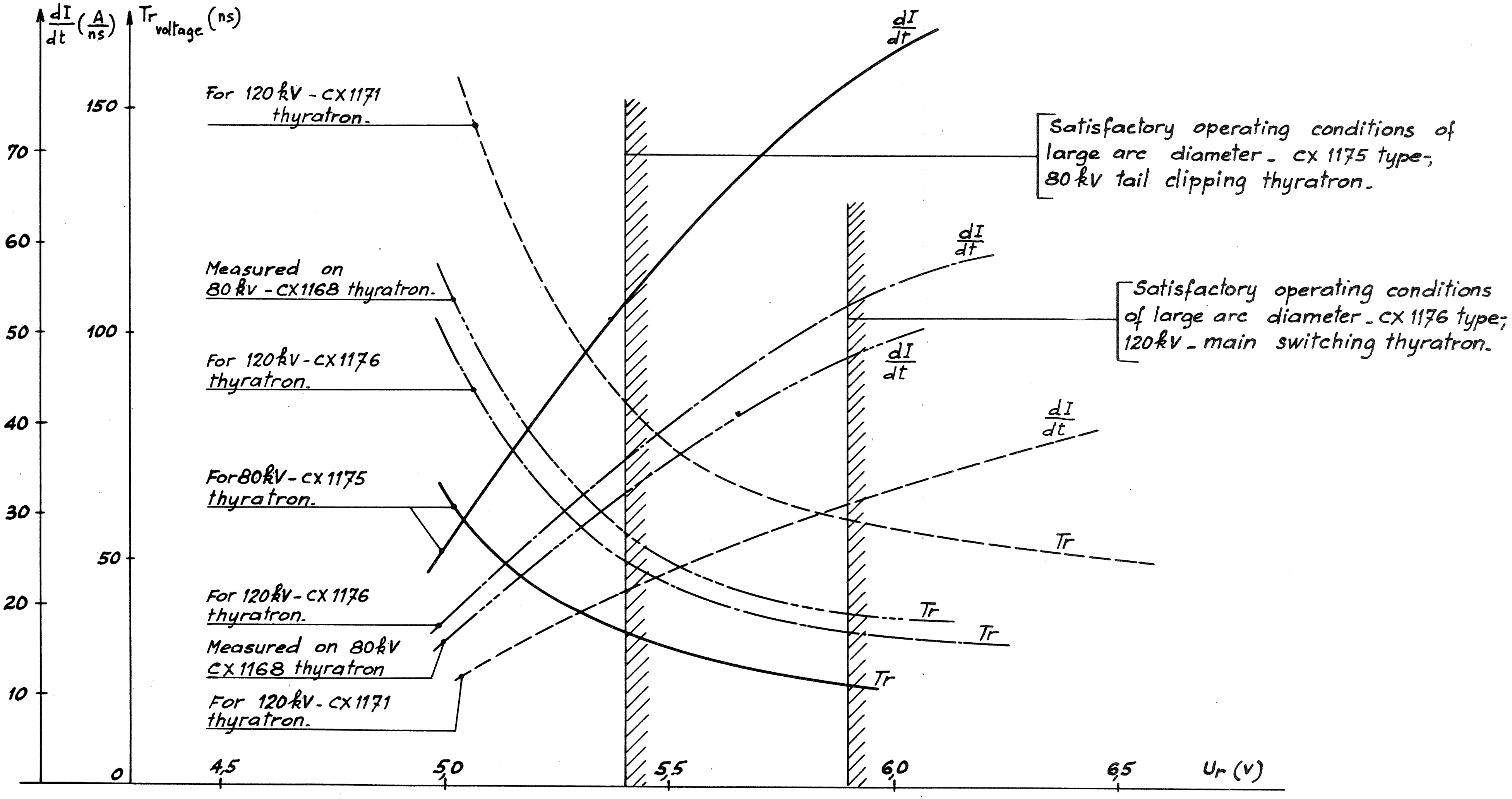
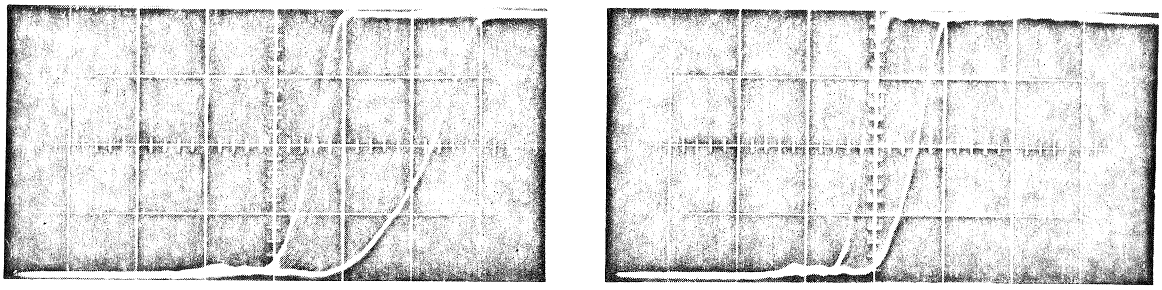

dI/dt (A/ns)
Tr voltage (ns)
70
60
50
40
30
20
10
150
100
50
0
4,5
5,0
5,5
6,0
6,5
Ur (v)
For 120 kV - CX 1171 thyratron.
Measured on 80 kV - CX 1168 thyratron.
For 120 kV - CX 1176 thyratron.
For 80 kV - CX 1175 thyratron.
For 120 kV - CX 1176 thyratron.
Measured on 80 kV CX 1168 thyratron
For 120 kV - CX 1171 thyratron.
Satisfactory operating conditions of large arc diameter - CX 1175 type; 80 kV tail clipping thyratron.
Satisfactory operating conditions of large arc diameter - CX 1176 type; 120 kV - main switching thyratron.
dI/dt
dI/dt
dI/dt
dI/dt
Tr
Tr
Tr
Tr

Fig. 5



H.V. 50kV. 50nsec./cm.
Reserv. 5→5,5V. 200 Pulses

a)

H.V. 50kV. 50nsec./cm.
Reserv. 5,5→6V. 200 Pulses

b)

Fig. 5

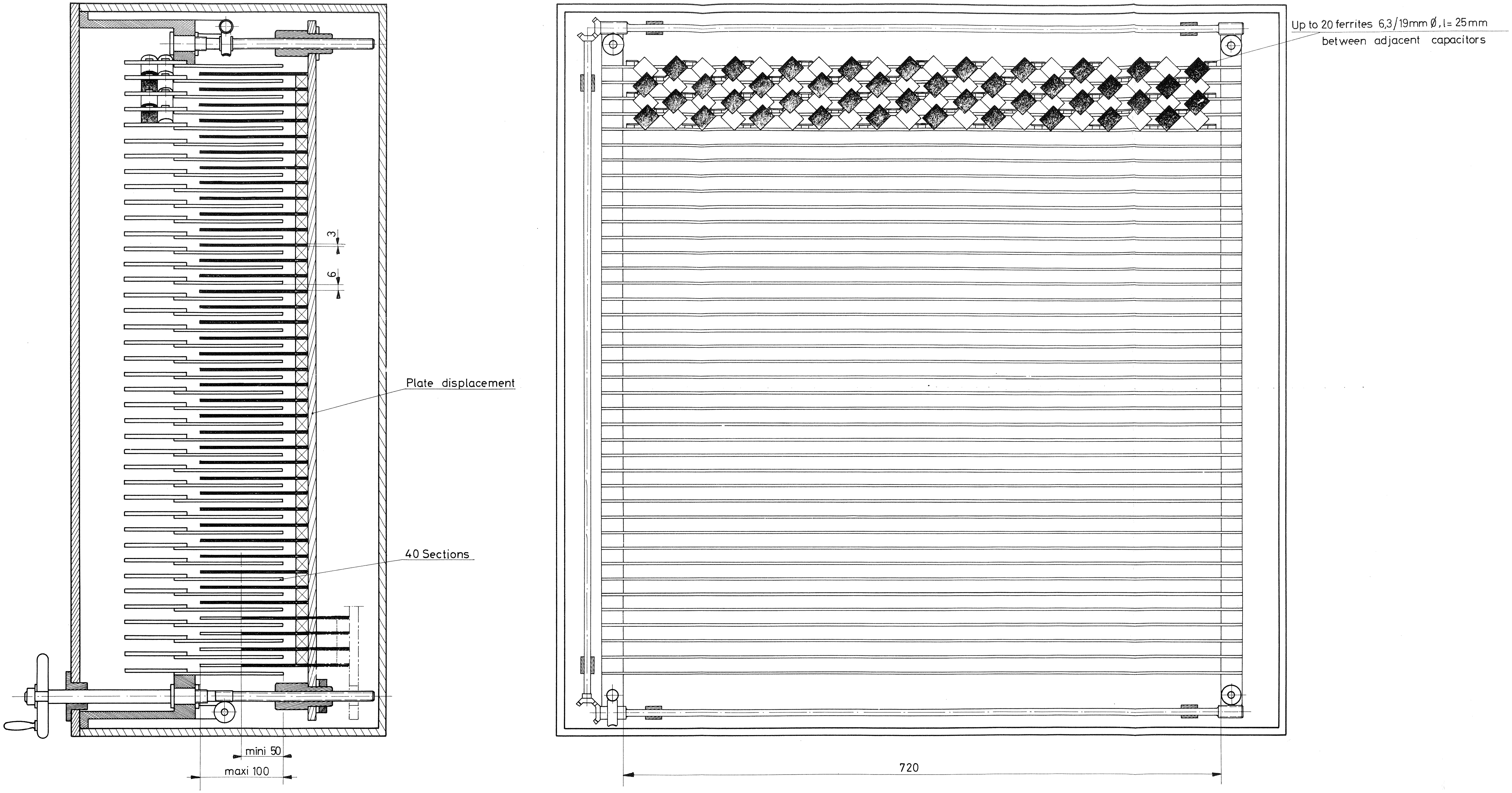


fig. 6 a

NOMBRE DE PIÈCES
DÉSIGNATION
POS.
MATIÈRE
OBSERVATIONS

NON LINEAR PULSE
SHARPENING LINE

ECHELLE
1/25
DESSINÉ
CONTRÔLÉ
VU
REMPLACE
REMPLACÉ PAR
RÉDUCTION

CERN
ORGANISATION EUROPÉENNE POUR
LA RECHERCHE NUCLÉAIRE - GENÈVE
M.P.S.

3
2
1

Incoming 80 ns - rise time pulse
of 30 kV amplitude (20 ns/cm)

b)

30 kV pulse after the sharpening
line: rise time reduced to ≈ 15 ns
(upper oscillogram 20 ns/cm)
lower oscillogram 50 ns/cm

c)

Fig. 6

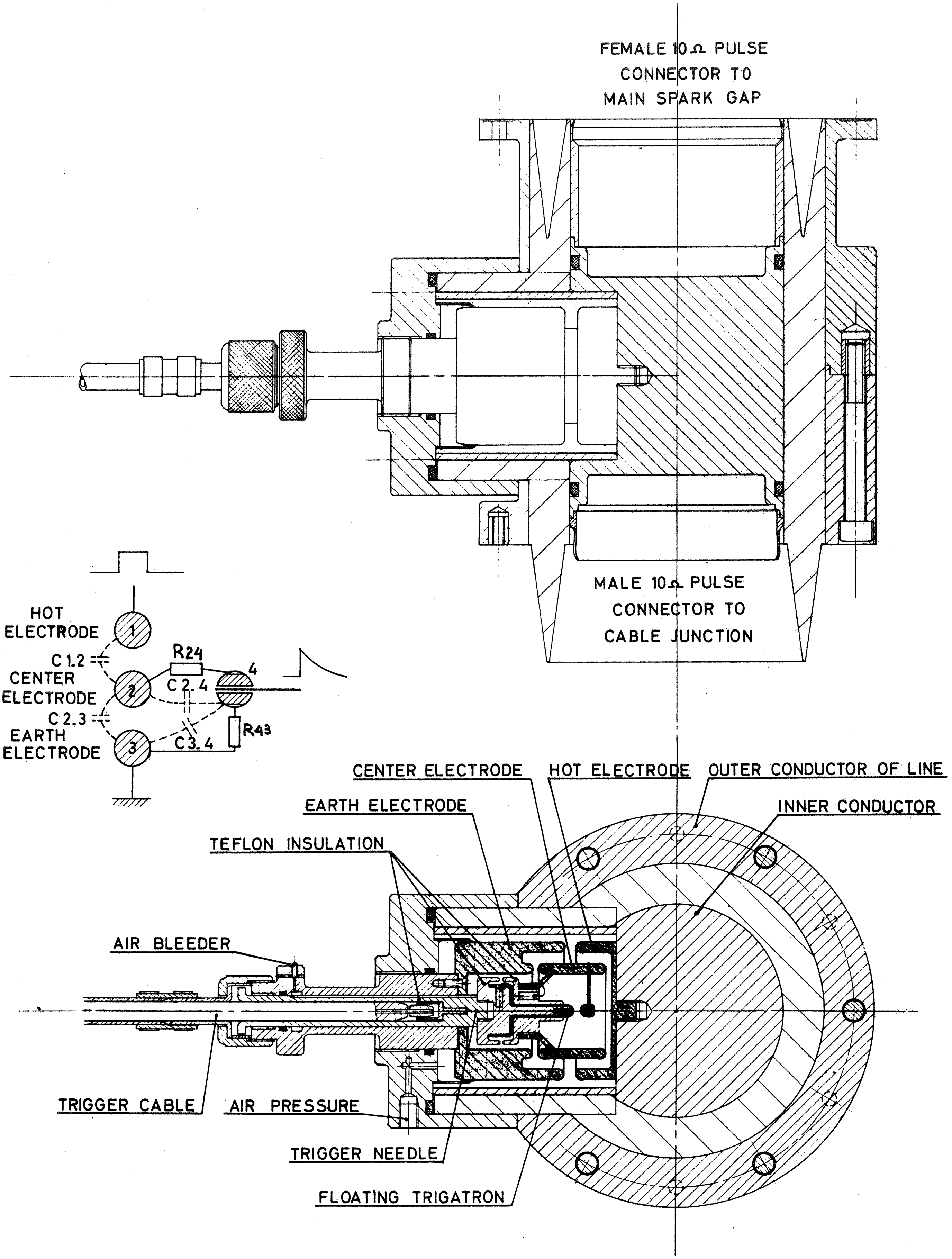
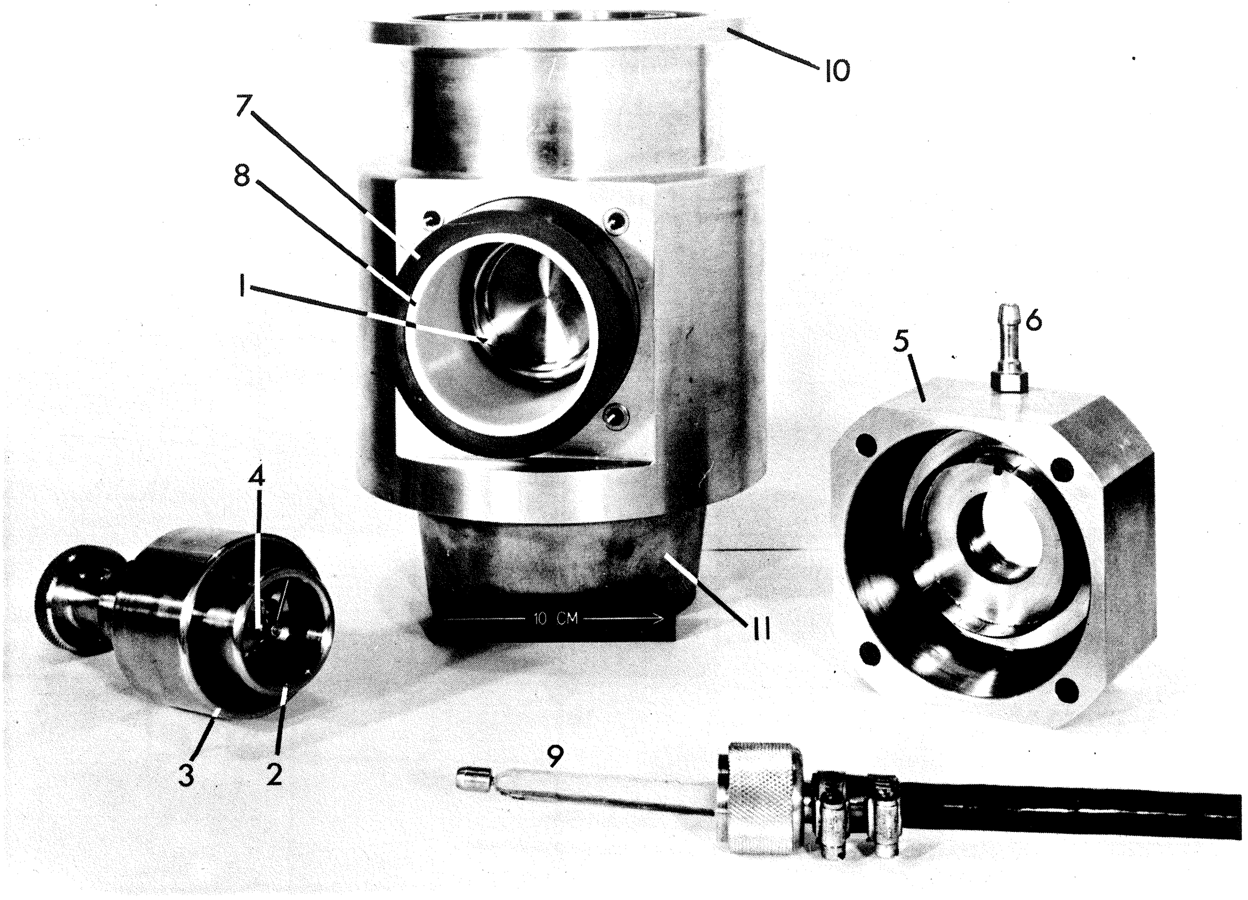
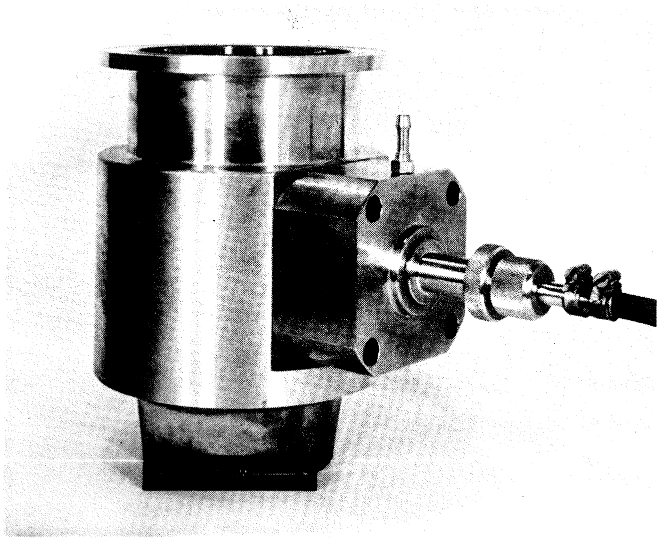


Fig. 7a Drawing of the 97-kicker 30 kV - tail clipper.



a) In components



b) Assembled

Legend:

1) Hot electrode
2) Center electrode
3) Ground electrode
4) Floating trigatron
5) Housing
6) Compressed gas inlet
7) Loaded epoxy resin
8) Teflon insert
9) Connector on trigger cable
10) Female 10 Ohm pulse connector
11) Male 10 Ohm pulse connector

Fig. 7b Tail clipper elements.

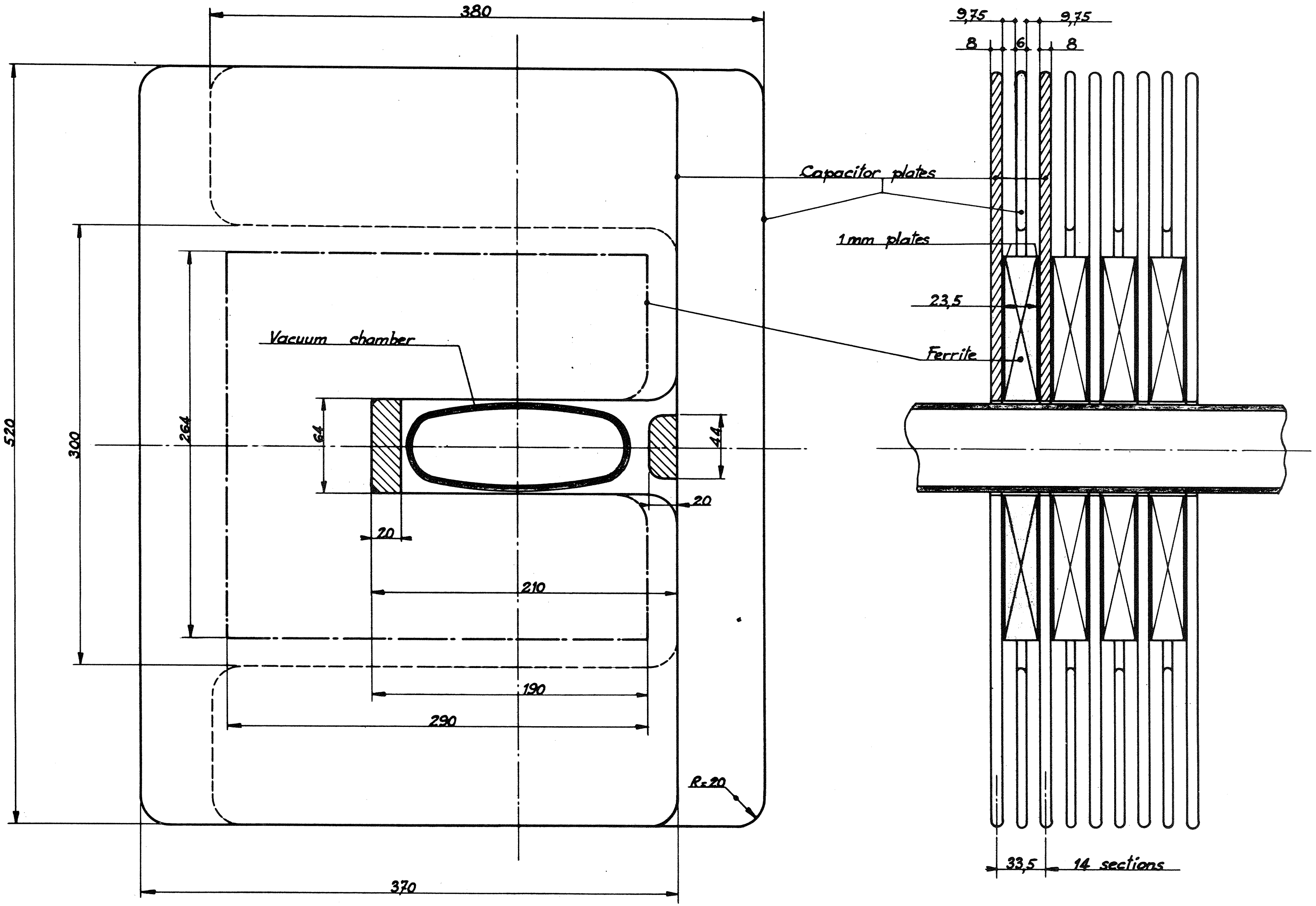

380
520
300
264
64
44
20
20
210
190
290
370
R=20
Vacuum chamber
9,75
9,75
8
6
8
Capacitor plates
1mm plates
23,5
Ferrite
33,5
14 sections

Fig. 9

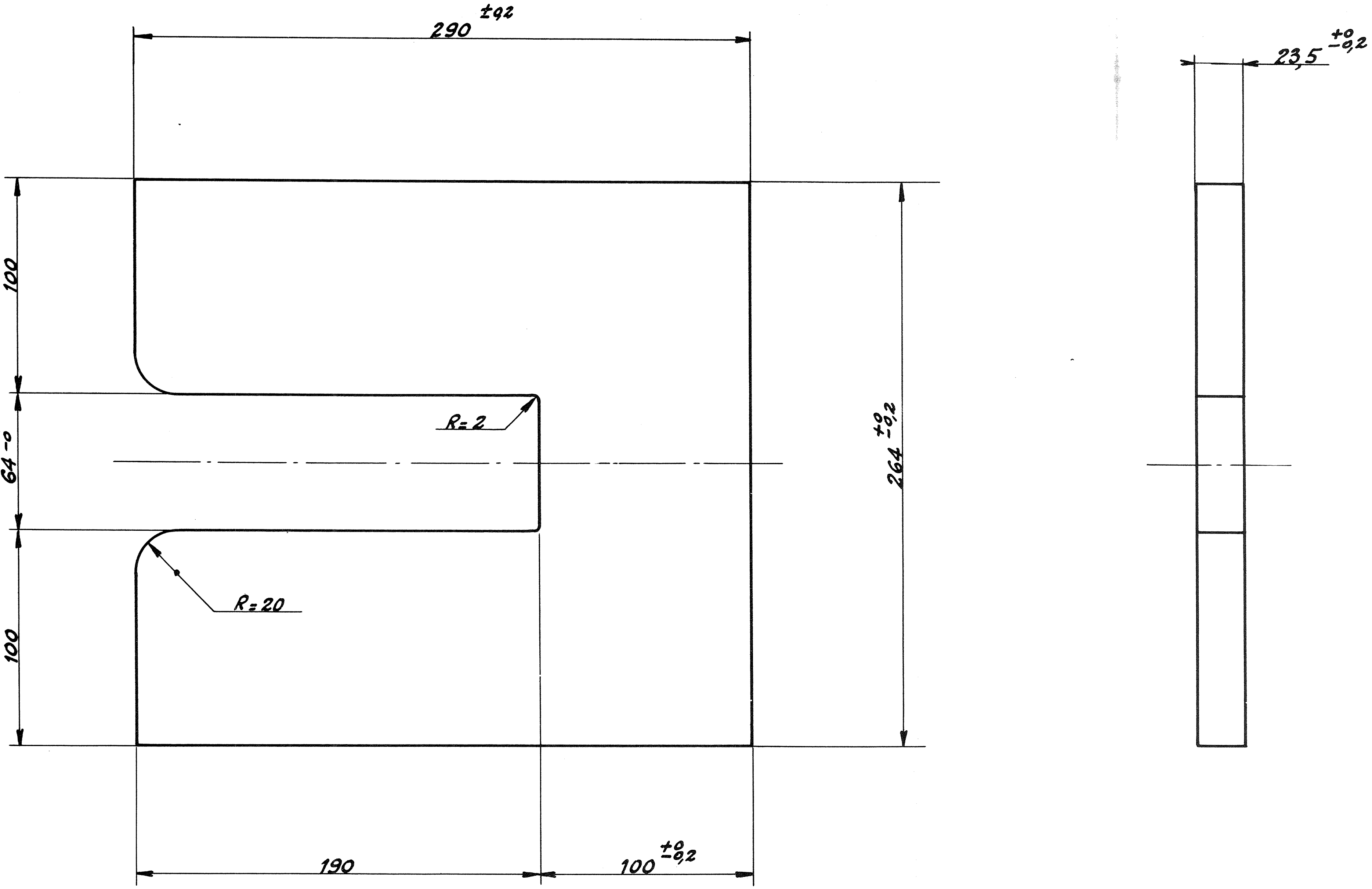
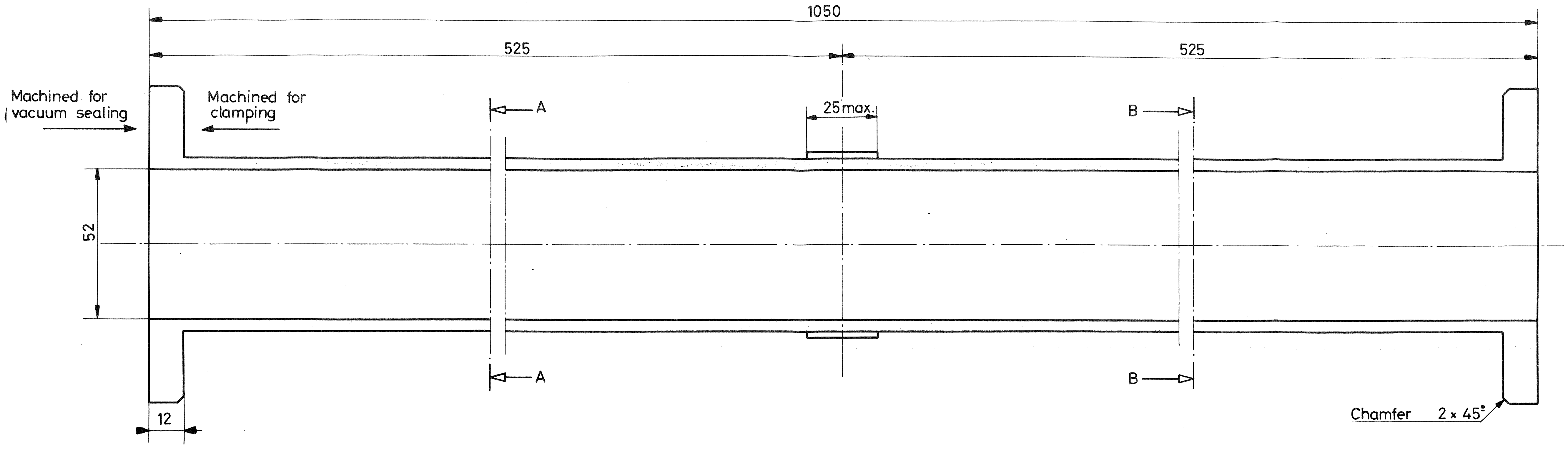
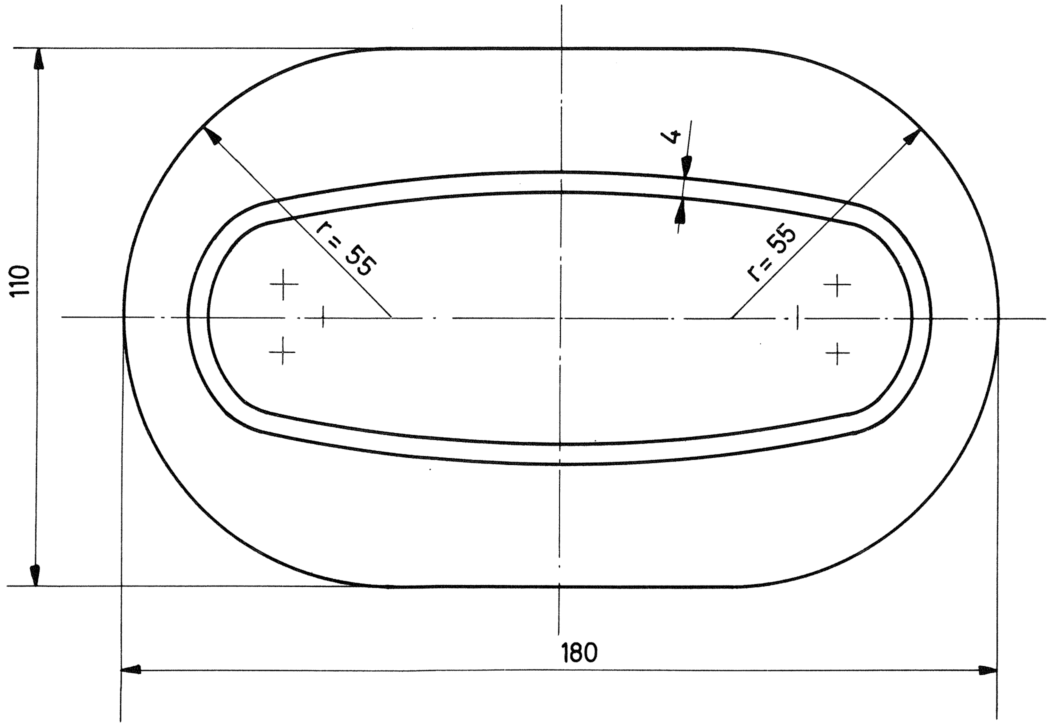


Fig. 10 FERRITE CORE.

13-6-1968





View AA and BB

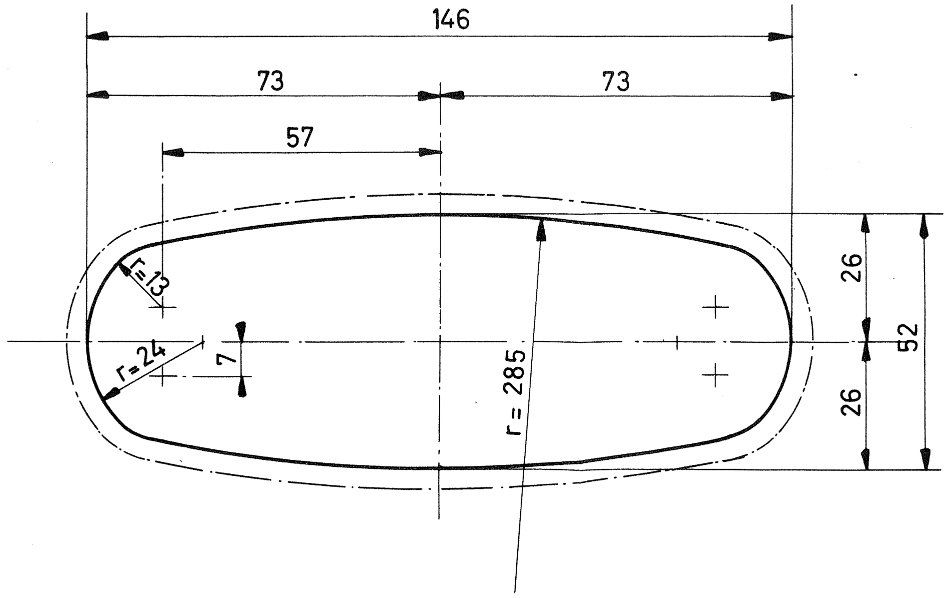
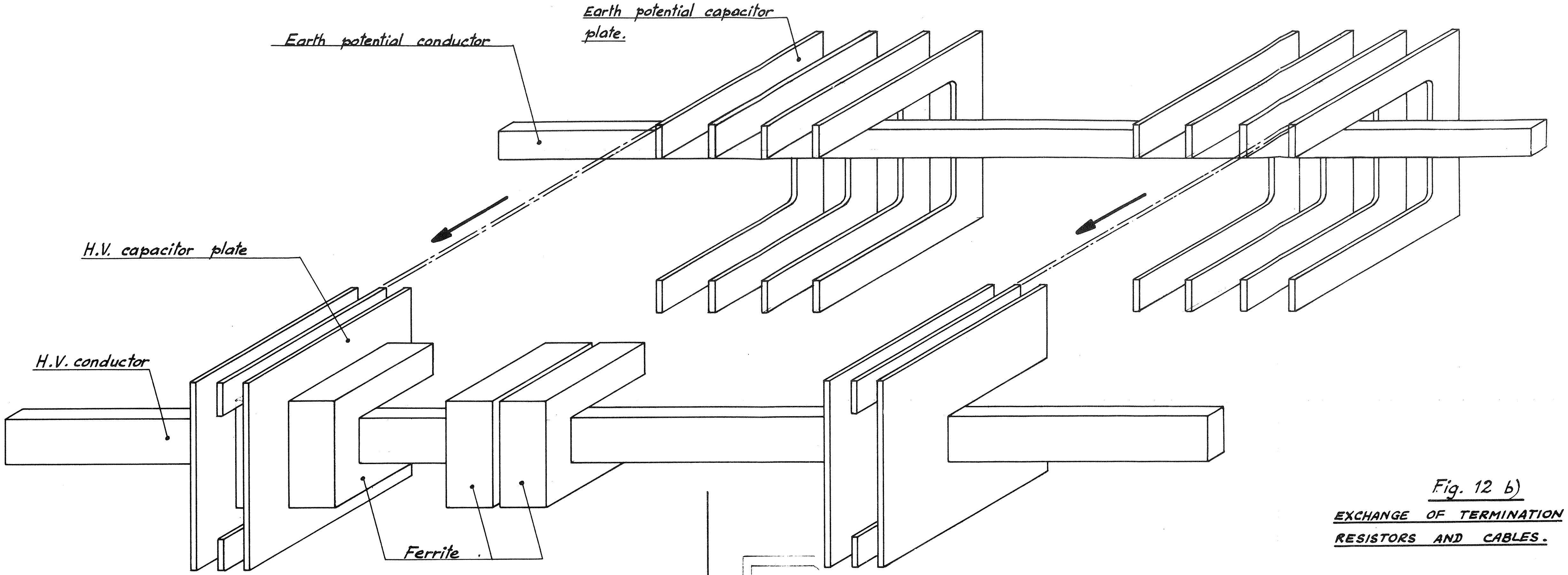


Fig. 11

NOMBRE DE PIÈCES	DÉSIGNATION	POS.	MATIÈRE	OBSERVATIONS
	CERAMIC VACUUM CHAMBER	ECHELLE 1/1		DESSINÉ CONTROLÉ VU REMPLACE REMPLACÉ PAR RÉDUCTION
CERN	ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE - GENÈVE	M.P.S.		



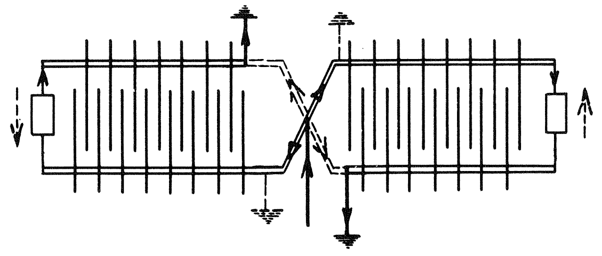


Fig. 12 a)

TERMINATION RESISTOR POSITION FIXED.

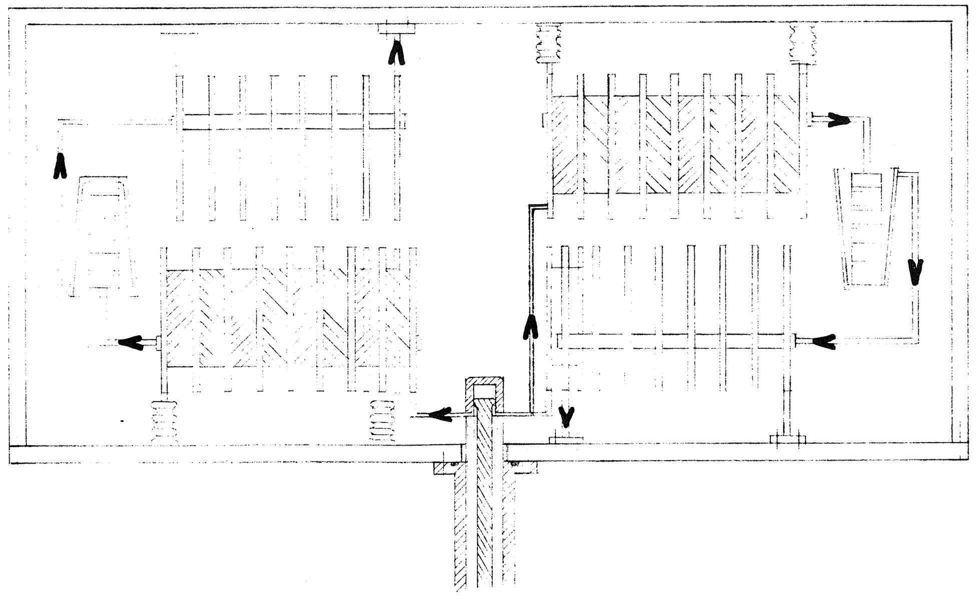
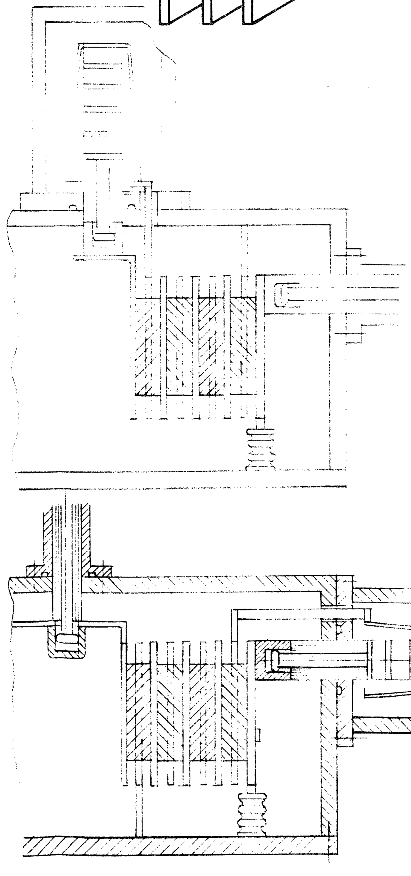
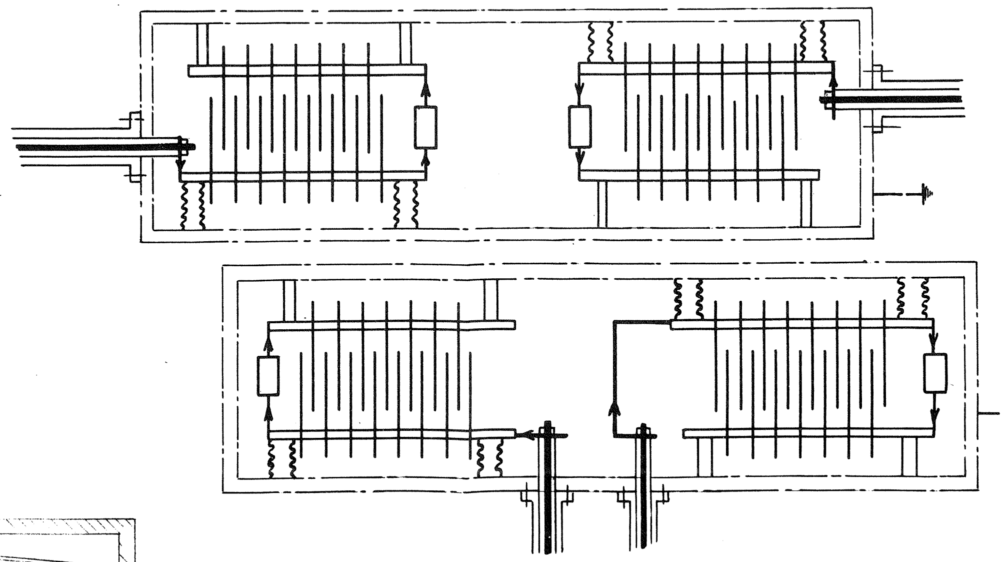


Fig. 12 b)

EXCHANGE OF TERMINATION RESISTORS AND CABLES.





NOMBRE DE PIÈCES

DÉSIGNATION | POS. | MATIÈRE | OBSERVATIONS

POLARITY CHANGE OVER SCHEMES FOR 2 KICKER MODULES.

ECHELLE
DESSINÉ
CONTROLÉ
VU 8-8-68
REMPLACE
REMPLACÉ PAR
RÉDUCTION

CERN ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE - GENÈVE

M.P.S.

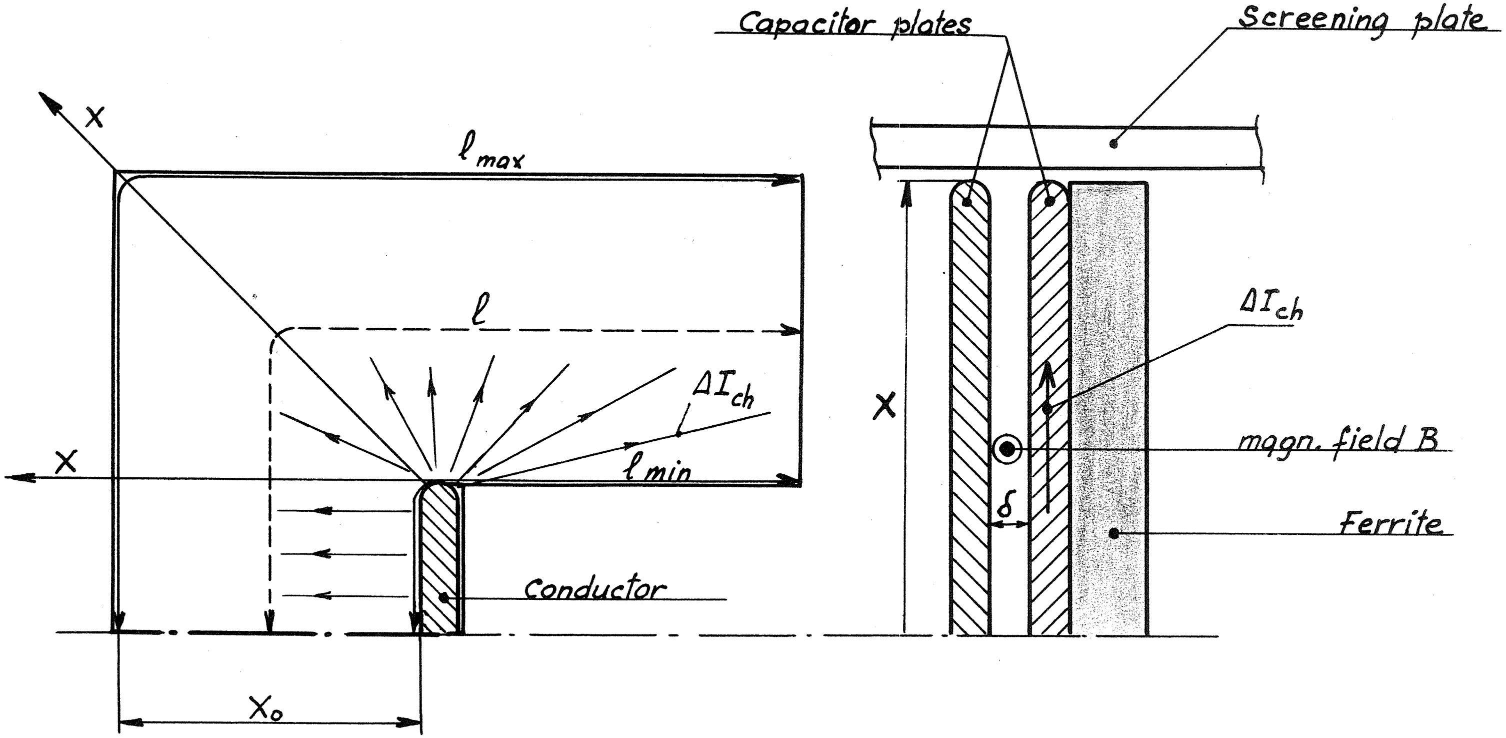

Capacitor plates
Screening plate
X
l_{max}
l
ΔI_{ch}
X
l_{min}
conductor
X_o
X
ΔI_{ch}
magn. field B
δ
Ferrite

Fig. 13

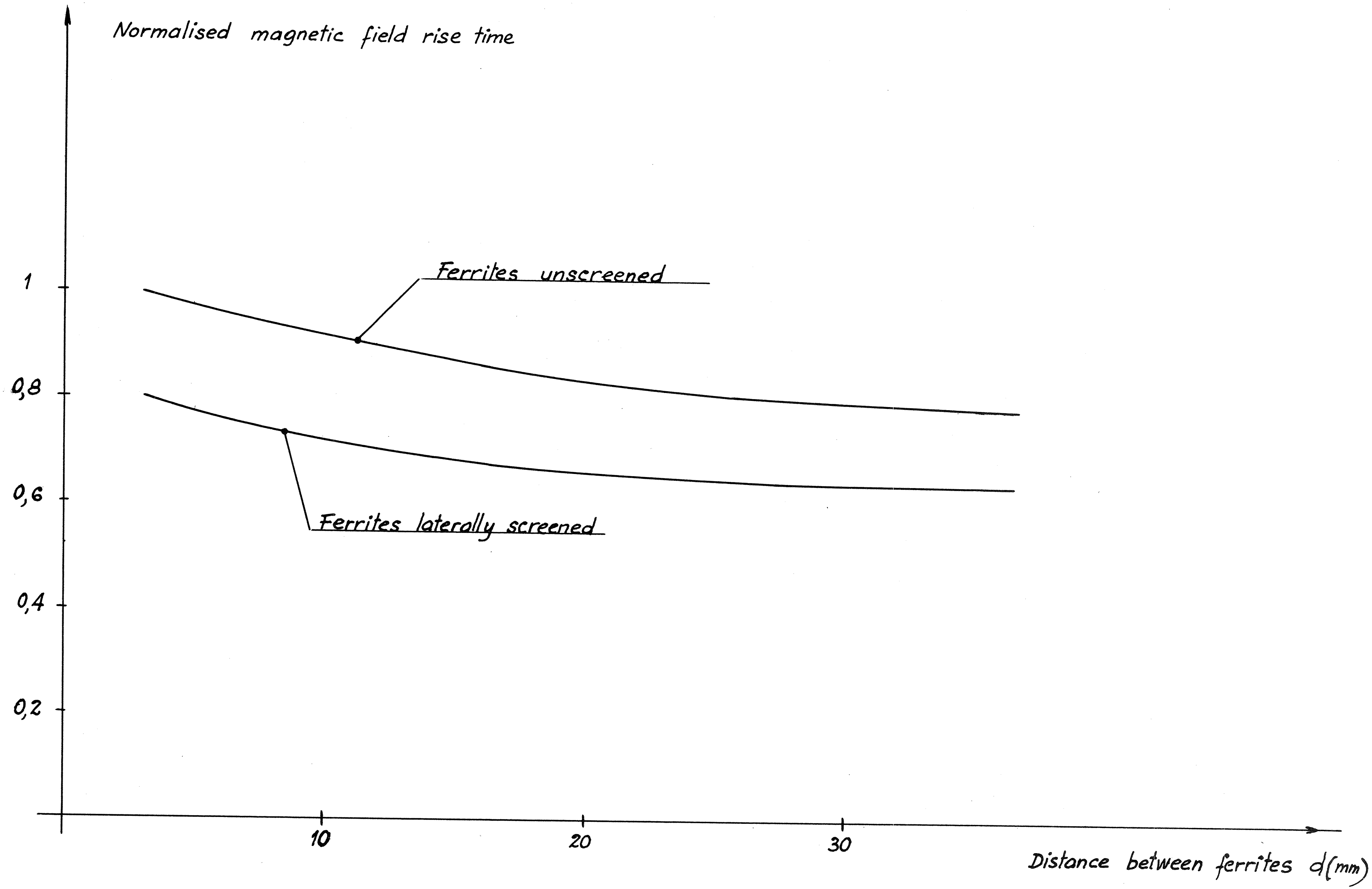
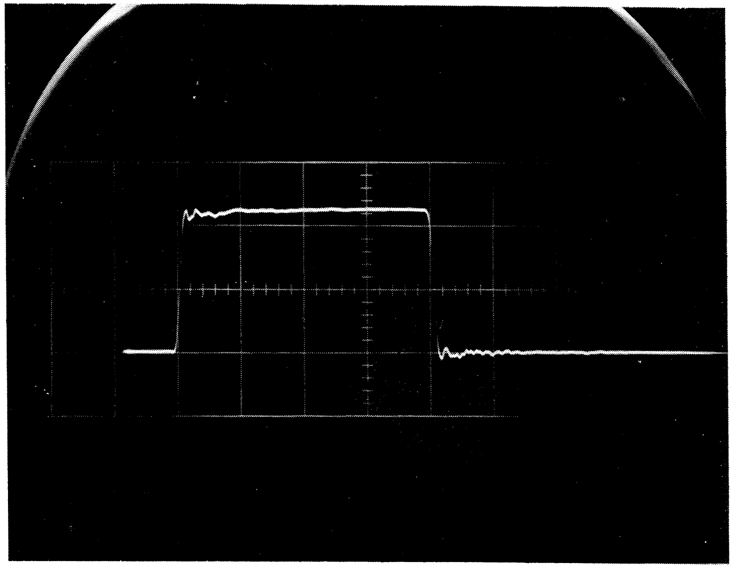

Normalised magnetic field rise time
1
0,8
0,6
0,4
0,2
Ferrites unscreened
Ferrites laterally screened
10
20
30
Distance between ferrites d(mm)

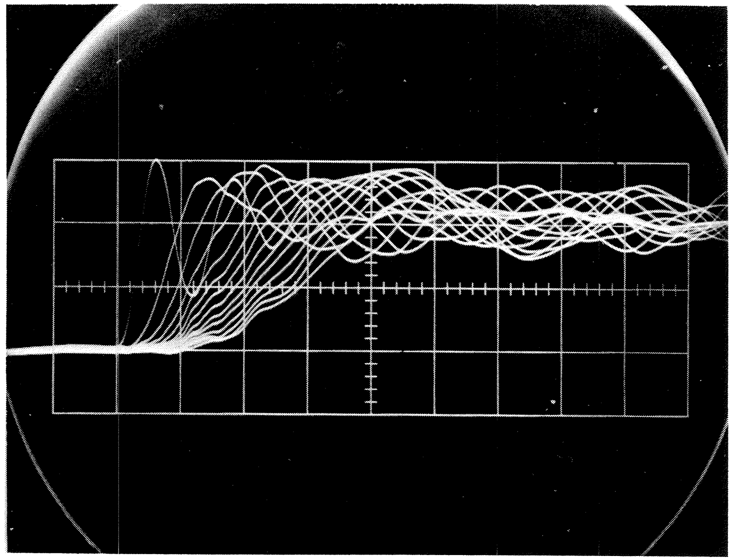
Fig. 15



T= 100 ns/cm

Incident 12....13 ns-rise time pulse, measured on terminating resistor.

Fig. 14

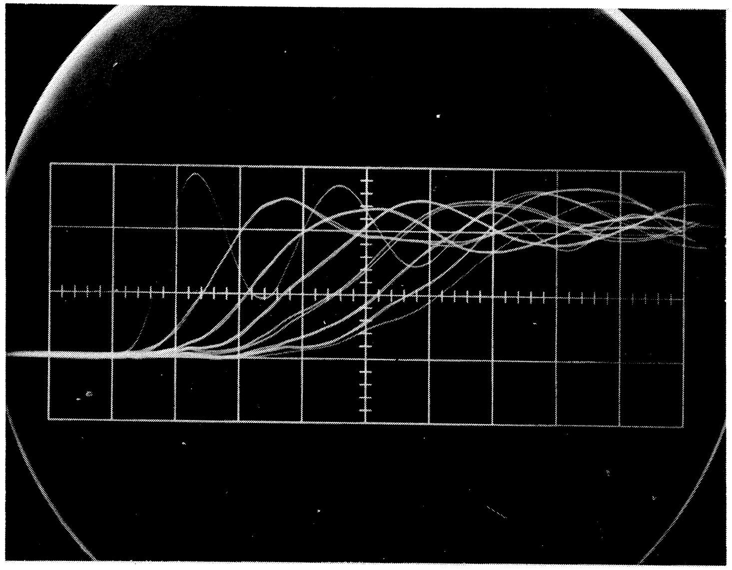


T= 40 ns/cm

First model: Voltage pulses along the magnet after a ferrite core.

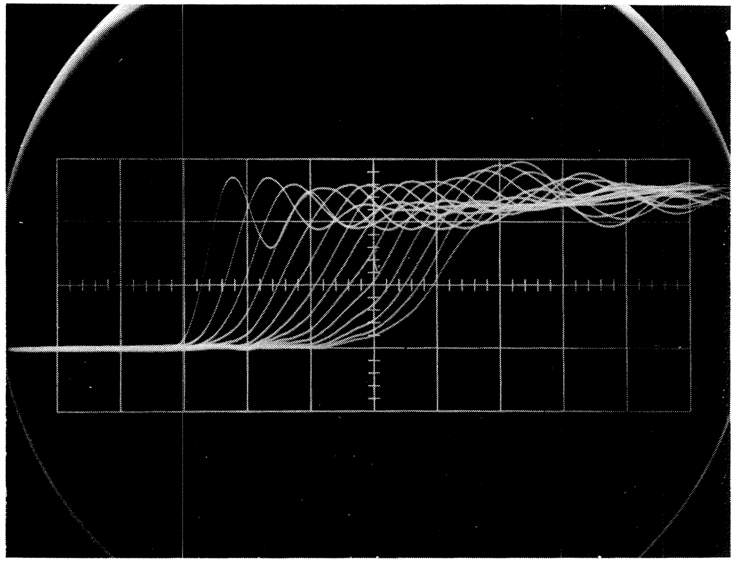
Incident pulse rise time 12....13 ns.

Fig. 16



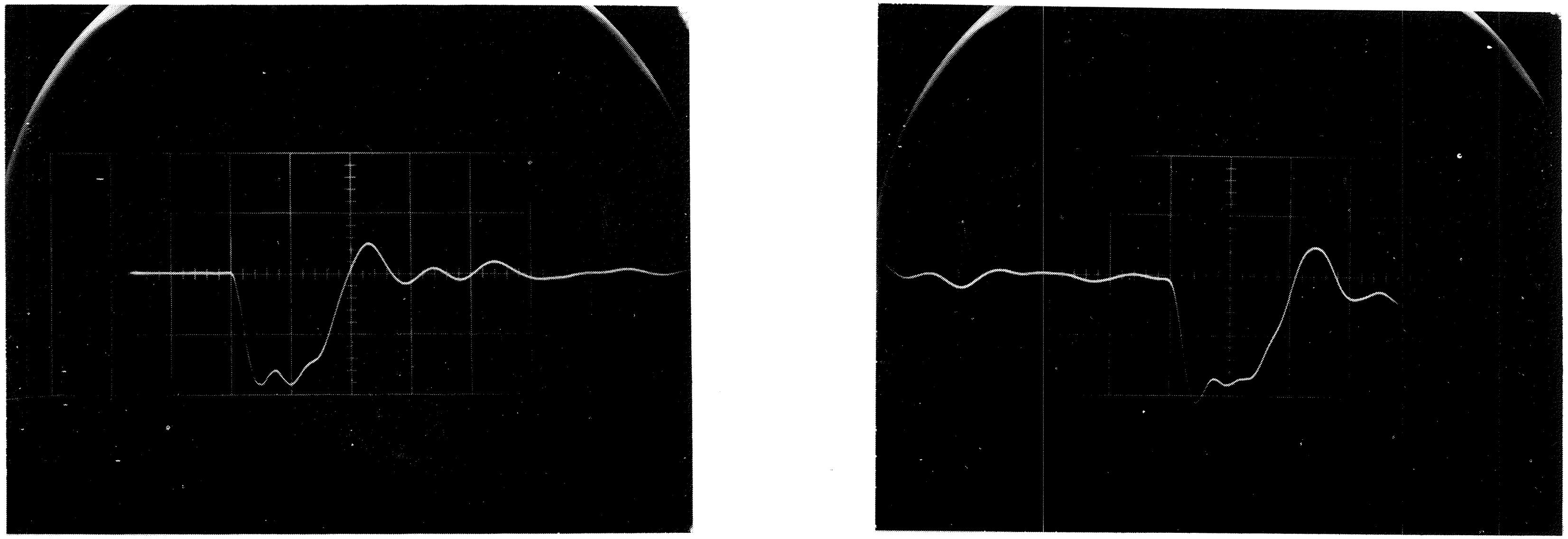
T=20 ns/cm ; First model : Every second ferrite core removed - Voltages across same sections as in fig 16 - Incident pulse rise time 12.... 13 ns.

Fig. 17



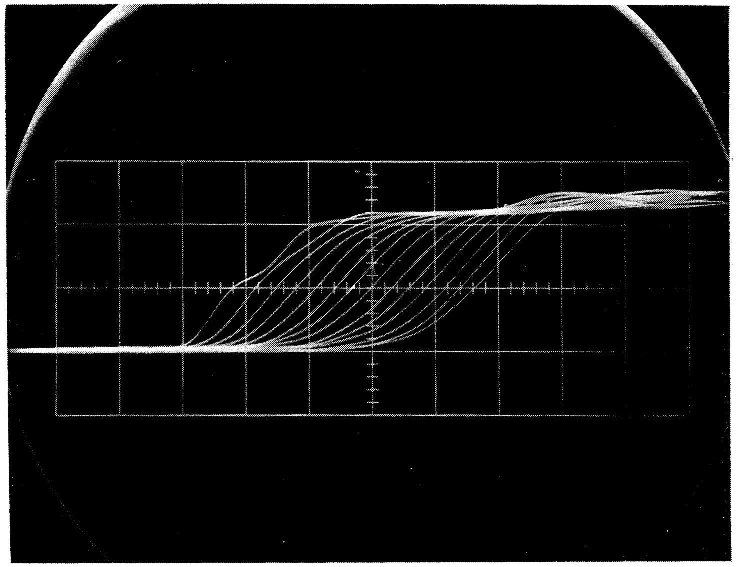
T=20 ns/cm ; second model with all 13 ferrite cores in place - Voltages after individual ferrite cores for incident pulse with a 12.... 13 ns rise time -

Fig. 18



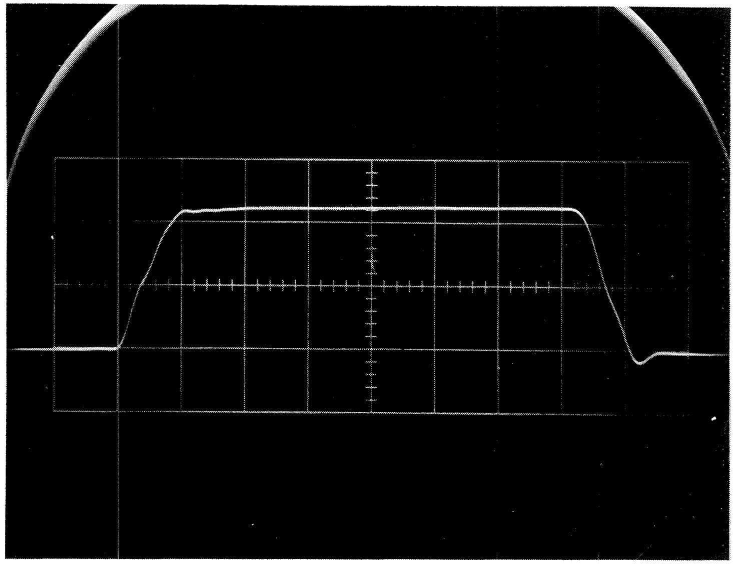
T= 50ns/cm ; Magnetic field $\frac{d\phi}{dt}$ at rise (left) and fall (right) measured on the second model for an incident 12.... 13 ns-rise time voltage pulse.

Fig. 19



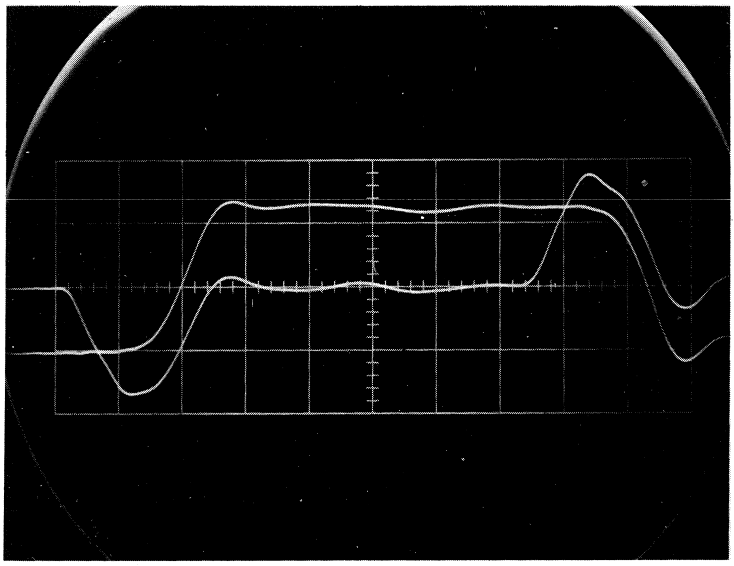
T = 20 ns/cm ; second model : Incident pulse rise time slowed down to 50 ns; voltages after individual ferrite cores.

Fig. 20



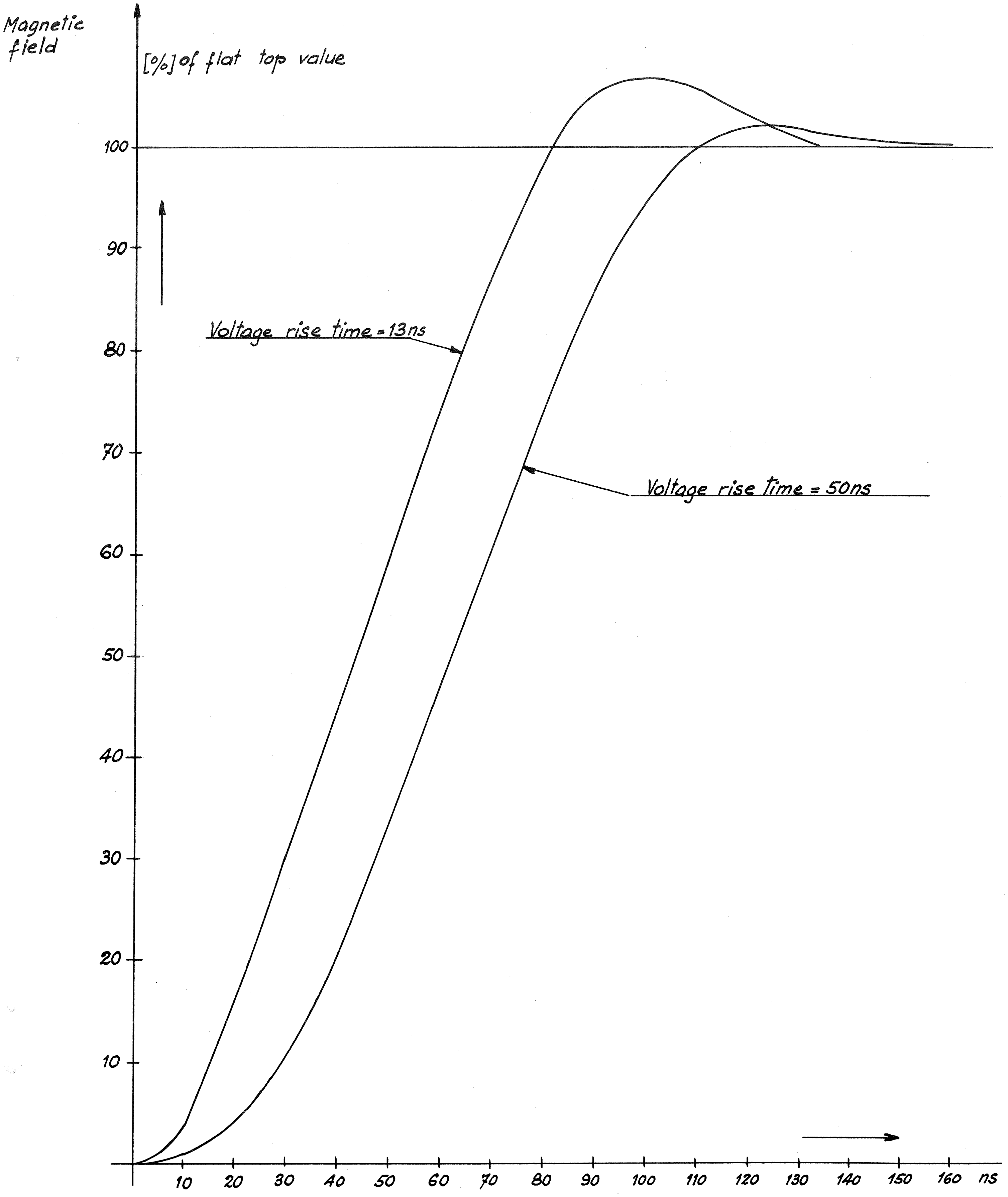
T = 50 ns/cm ; second model : Incident 50 ns-rise time pulse measured on a 14.2 Ω-terminating resistor.

Fig. 21



T = 50 ns/cm ; second model : voltage pulse (above) . and magnet $\frac{d\Phi}{dt}$ at rise and fall (below) for incident voltage pulse with 50 ns - rise time.

Fig. 22



Second model : Field rise for 12....13 ns- and 50ns- rise time incident voltage pulses.

Fig. 23