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FAST PULSED MAGNET SYSTEMS FOR PROTON AND ANTIPROTON INJECTION INTO THE CERN 400 GeV PROTON SYNCHROTRON

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SUMMARY

After transformation for its part-time use as a $p\bar{p}$ collider, the CERN 400 GeV accelerator (SPS) is equipped with two new fast inflectors for protons and antiprotons.

The new proton inflector has been designed for injection energies up to 26 GeV and can fill the SPS with up to 5 proton batches for fixed target operation and with short proton bunches during collider operation. It consists of 12 delay line type kicker magnets of 0.7 m length each with parallel plate matching capacitors under vacuum. The magnets are powered in parallel pairs by pulses with a kick rise time of 145 ns, a duration of up to 12 μs and a current amplitude of 2.4 kA. The pulses are generated in pulse forming networks charged to a voltage of 60 kV and discharged by double cathode thyratrons.

The antiproton inflector comprises 3 independent kicker systems which create a fast compensated bump for multiturn injection. The magnet modules are of the same design as the modules of the proton inflector. The generators consist of cable pulse forming networks of 400 ns electrical length and 2.4 kA current amplitude, each discharged by its own thyratron. The jitter of the timing is less than 5 ns over several weeks.

The design and the performances of both inflectors as well as the operational experience will be presented and discussed.

1. INTRODUCTION

The CERN 400 GeV proton synchrotron (SPS) has been transformed during a long shutdown in 1980/1981 for its part-time use as a proton-antiproton ($p\bar{p}$) collider. Antiprotons at a momentum of 3.5 GeV/c are produced in a target by a high intensity proton beam which is extracted from a pre-accelerator (CPS) at a momentum of 26 GeV/c. The production efficiency is only about 10^{-6}. Therefore, more than 10^4 $\bar{p}$ pulses are accumulated in a small storage ring for about one day to achieve sufficient intensity. Antiprotons are then pre-accelerated to 26 GeV/c in the CPS and sent to the SPS in 3 short high intensity bunches, each of 5 ns duration, via a specially built transfer line. In the SPS, which has already been filled with 3 bunches of counter rotating protons, all 6 bunches are accelerated to 270 GeV/c, the maximum energy which the SPS can achieve in d.c. operation. The particles collide then with a centre-of-mass energy of 540 GeV at 6 interaction points of which 2 are equipped with sophisticated detectors for physics experiments1). The $p\bar{p}$ complex has been brought into operation in 1981 and its performance is now being actively developed. Experiments have been performed at a centre-of-mass energy of 540 GeV using 2 p bunches and 1 $\bar{p}$ bunch. Their respective intensities per bunch were $6 \cdot 10^{10}$ and $5 \cdot 10^9$ particles. The initial luminosity is about 10^{27} cm^{-2} s^{-1}.

In addition to the transformation of the SPS into a $p\bar{p}$ collider, an intensity improvement program is being executed with the aim of increasing the beam intensity for fixed target operation2). This program foresees to accelerate protons repeatedly in the CPS to 10 GeV/c and to place them successively around the circumference of the SPS, where they are circulating at injection momentum until the ring is filled and the acceleration to 400 GeV/c can start. This scheme has been described in a previous report3).

Apart from an antiproton inflector (MKA), these modifications and improvements of the SPS required also a new proton inflector (MKP) for two reasons:

- For $p\bar{p}$ operation, the injection momentum had to be raised from 10 GeV/c to 26 GeV/c, to avoid perturbing the short, high intensity proton bunches at transition.
- For the injection of up to 5 bunches for fixed target operation, a rise time of the magnetic field of less than 175 ns was required which is about 4 times shorter than that of the previous inflector.

This paper gives a general description of both inflector systems. Thereafter, the magnet modules and the pulse generators are discussed in more detail. Emphasis is put on the technical aspects, as the theoretical problems have been treated in a previous paper4). Finally, the performance and the operational experience will be discussed.

2. SYSTEM DESCRIPTION

2.1 The proton inflector

2.1.1 Performance requirements

The maximum required injection angle is about 5 mrad, corresponding to a kick strength of 0.43 Tm at maximum injection momentum (Table 1).

The pulse duration is determined by the different injection requirements: for fixed target operation, between 2 and 5 proton batches must be injected depending on the required intensity. Two batch injection requires a pulse duration of 11.5 μs which must be reduced to 4.2 μs for the injection of 5 batches. The latter option determines the required rise time of the magnetic field, integrated along the path of the protons, to about 175 ns. This latter parameter is called "kick rise time" in the following. For $p\bar{p}$ operation 3 bunches of 5 ns duration must be injected equidistantly around the SPS circumference at an energy of 26 GeV. This is done with pulses of about 1 μs duration.

2.1.2 Main parameters

In view of the performance requirements given above, the main parameters of the system are chosen in the following way:

As for all other fast pulsed magnet systems at the SPS, the maximum voltage of the generators is limited to 60 kV. This level guarantees reliable operation of the thyratron switches at pulse durations exceeding 10 μs. It allows furthermore the use of standard coaxial cables type RG 220/U, connected in parallel, as transmission line between the generators, located in an auxiliary building on the surface and the magnets, housed 60 m underground in the accelerator tunnel.

With aperture, voltage and strength of the magnetic field fixed, the system must be split into twelve independent magnet modules in order to achieve the required short kick rise time. Eight of the modules, with an aperture (vertical × horizontal) of 61 mm × 100 mm (type S), are used at the injection momenta of 10 GeV/c as well as 26 GeV/c. Their kick rise time is 145 ns. The remaining four modules which require for beam optical reasons an aperture of 54 mm × 140 mm (type L), are only required for injection at 26 GeV/c. For standardization reasons, all modules have the same magnetic length of 0.7 m. Because of the larger aperture ratio, the field rise time of the "L" modules is 220 ns.

The inductance of the magnet modules is matched to the characteristic impedance of the system by parallel plate capacitors inside the vacuum tank (delay line-type construction), in order to achieve a good pulse response with negligible reflections of the wave front. For similar reasons, a characteristic impedance of 12.5 Ω has been chosen for the magnet modules, the highest value which can be accomodated in the available space. The transmission lines are composed of 4 coaxial cables in parallel each with a characteristic impedance of 50 Ω.

The pulse generators are lumped element pulse forming networks, equipped with three switches, in order to produce pulses of adjustable duration and short fall time. For reasons of economy, two magnet modules are connected in parallel to one generator whose characteristic impedance is therefore 6.25 Ω. The parallel configuration is acceptable because the contribution of the generator to the kick rise time is small.

The electrical block diagram of one system is shown in Fig. 1. Table 2 summarizes the main parameters.

2.2 The antiproton inflector

2.2.1 *Injection principle*

The antiprotons are injected into the SPS through the channel which is normally used for the extraction of protons in opposite direction at an energy of 400 GeV. Before entering the first pair of kickers (MKA 1,2, Fig. 2a), the antiprotons pass an electrostatic septum (ES) which provides a region of strong electrostatic field to deflect the incoming particles, adjacent to a region of vanishing field where the particles circulate after injection. The electrostatic field is generated between an array of wires of 0.1 mm thickness (the septum itself) at earth potential and an h.t. electrode. For the injection of the first 3 $\bar{p}$ bunches which are equidistantly placed around the SPS circumference, only the first pair of kickers is excited.

To increase the particle intensity, it is foreseen to inject antiprotons up to 3 times into the same longitudinal SPS position (radial stacking). This is done in the following way: the second pair of kickers (MKA 3,4) deflects a circulating antiproton bunch and brings it in a coherent betatron oscillation near to the zero field side of the septum. The timing of the next injection is then arranged such, that at the same moment a new bunch arrives through the injection channel at the septum's high field side (Fig. 2b). Both bunches whose centres are roughly 1 bunch diameter plus the septum thickness apart, travel then to the first kicker pair, one betatron wavelength downstream from the second pair, where the oscillation is cancelled. A fifth kicker is necessary, when the wavelength of betatron oscillation is not equal to the distance between the two pairs of kickers.

2.2.2 *Main parameters*

The pulse duration of the $\bar{p}$-inflector can in principle be very short, as the antiproton bunch length is only 5 ns. Nevertheless, a kick flat top duration of about 200 ns has been chosen to avoid deflection errors due to jitter or drift of the anode delay time of the electronic switches. As protons are injected prior to antiprotons, the kick rise and fall times must be shorter than 600 ns to avoid deflecting the counter rotating protons. The injection angle is about 1 mrad corresponding to a kick strength of 0.086 m Tm at an energy of 26 GeV (Table 1).

For standardization reasons, the design of the magnet modules is the same as for the modules of the proton inflector. Each module has its own cable pulse forming network with a characteristic impedance of 12.5 Ω, charged to a maximum voltage of 60 kV and discharged by a ceramic thyratron. The main parameters are listed in Table 2.

3. THE MAGNET MODULES

3.1 Electrical circuit

The electrical circuit of the magnet has been designed by means of computer modeling in order to obtain an optimum pulse response. Only circuits in which the inductance of the one-turn conductor is subdivided into several sections which are connected to capacitors to form a matched LC ladder network, give an acceptable pulse response[4]. The adopted circuit is composed of 22 cells. This is a compromise between the requirements for pulse response and size of the capacitor plates.

3.2 Yoke configuration

For the yoke cross-section, a C-shape was chosen with shims at the edges of the pole profile near the open side of the gap, to improve the field quality in radial direction (Fig. 3). The return conductor is essentially inductance free and can be earthed at the magnets input and output. Compared to a window-frame magnet, the C-shaped cross-section allows therefore to use coaxial feedthroughs with earthed outer conductors. It avoids furthermore the risk of flash-over between the conductors along the ferrite surfaces.

3.3 Construction

The high rate of current rise calls for a high resistivity Ni-Zn ferrite as magnetic material. The Philips type 8C11 has been chosen because of its high saturation induction ($B > 0.3$ T at 10 Oe and 20 °C) and its low coercitive force ($H_c < 0.25$ Oe). This material has furthermore excellent vacuum properties due to its low porosity ($g > 5.1$ g/cm^3). It is manufactured in C-cores of overall dimensions 195 mm × 136 mm × 26 mm. Twenty-two of these bricks, interleaved with AlMg^3 plates of about 40 cm × 50 cm area, form the h.t. part of the magnet module, with a length of about 0.7 m. On each side of these capacitor plates, at a distance of about 4 mm, similar AlMg^3 plates are mounted as earth electrodes of the matching capacitors.

The characteristic impedance of the system is determined by adjusting individually the distance between the capacitor plates. A photograph of the magnet assembly is given in Fig. 4.

The magnet is excited by a one-turn high voltage conductor of 61 mm height and 5 mm width (type S), fixed tightly into the ferrite gap and providing the interconnections between the h.t. capacitor plates (Fig. 3). The earthed return conductor of 2.5 mm thickness is placed in front of the open side of the C cores at a distance of 6.5 mm from the ferrite. It is fixed to support-plates which form the base of the earth electrodes of the capacitors. In case of bad steering, the proton beam can hit the return conductor. To avoid damaging the magnet module, the return conductor is made of beryllium, into which, due to its low density, only a small amount of beam energy can be deposited.

3.4 The vacuum tank

All magnet modules are housed in vacuum tanks of omega cross-section. The 3 tanks of the proton inflector are each about 3.5 m long and contain 4 modules (Fig. 5), whereas 2 modules are housed in each of the 2 shorter tanks of the antiproton inflector. The modules are positioned and aligned in a common frame which poses at 3 points on the base plate of the tank. The omega shaped cover has the same diameter of 0.7 m for all tanks and is equipped with flanges for alignment-supports and connections to the adjacent vacuum chambers. An 8 m long aluminium gasket of diamond cross-section provides the vacuum tightness between base plate and cover.

The tanks are made of electro-slag-refined stainless steel, type 304L, and despite their size have been stress relieved at a temperature of 960 °C. The long tanks are equipped with 4 sputter ion pumps with a pumping speed of 360 ℓ/s each. In addition, 4 titanium sublimation pumps are used to shorten the pump down time. For the smaller tanks, half the number of pumps provide about the same specific pumping speed. To achieve the design pressure of $2 \cdot 10^{-9}$ Torr, all metallic surfaces (about 100 m^2 per large tank) undergo a thorough chemical cleaning procedure. The ferrite blocks are backed at 400 °C under vacuum prior to assembly. Figure 6 shows the positioning of the modules into the frame of a large tank.

3.5 Terminating resistor

The first and last capacitor plates of the magnet are connected via short matched striplines to coaxial feedthroughs in the base plate of the vacuum tank. On the input side, a silicone insulated connector box with 4 coaxial h.t. sockets receives the cable connectors of the transmission line from the pulse generator. On the output side, a coaxial matched resistor has a particularly low stray inductance and is designed to hold a voltage of 30 kV. It is built up of 10 Allen-Bradley ceramic resistor discs, each 1 inch thick with 3 inches outer diameter and a central hole of 1.25 inches, mounted in a coaxial housing and insulated and cooled with silicone fluid. The discs are interleaved with flat metallic spirals which provide a good electrical contact and permit an efficient flow of the cooling liquid. A resistor of similar design has been described previously[5)].

4. THE PULSE GENERATORS

4.1 The proton inflector

The requirements on the excitation pulse call for a lumped element pulse forming network (PFN) discharged by 3 switches: A "main" switch initiates the discharge, a "clipper" shortens the tail of the pulse and a "dump" switch discharges any residual energy of the pulse forming network. To achieve short rise and fall times, stray inductances between switch and pulse forming network must be minimized. Therefore, the switches are mounted directly on top of the PFN (Fig. 7). To avoid interference between them, all switches are housed in their own metallic tank (Fig. 8) and are branched through separate coaxial "plug-in" connections to the appropriate position of the PFN. This type of construction allows in addition a rapid exchange of switch tanks in case of thyratron faults.

The physical separation between the anodes of main and clipper switches introduces, however, an unwanted stray inductance which is suppressed by connecting both anodes via a matched stripline. The 36 cells of the PFN are arranged in 2½ rows. They are composed of capacitors of 30 nF and solenoids of 1.17 μH, giving a characteristic impedance of 6.25 Ω. The capacitors of cylindrical shape have an insulating outer case and are mounted over nine tenths of their length into metallic pots which are fixed vertically into the base plate of the PFN tank. Constructional details of the prototype generator have been reported previously$^{3)}$.

The switches are three-stage ceramic deuterium filled thyratrons with 2 cathode assemblies, type EEV CX1171B. Double ended thyratrons are required because of the large product of flat top current and pulse duration (4.8 kA × 12 μs) which cannot be handled by single ended tubes.

Two pulse generators are charged in parallel by one resonant charging power supply$^{5)}$. The resonant charging allows to operate the thyratrons at a higher gas pressure. This measure decreases their plasma formation time and hence the rise time of the current pulse. It reduces furthermore the risk of quenching and prolongs therefore the lifetime.

4.2 The antiproton inflector

The short excitation pulse is generated in a cable pulse forming network of 40 m length, composed of 4 coaxial cables in parallel, each with a characteristic impedance of 50 Ω. This PFN is discharged through a three stage ceramic thyratron, type EEV CX1171A. The cable, manufactured by Felten & Guilleaume, Cologne, has an outer diameter of 46 mm, an ionization inception voltage above 45 kV r.m.s. and an attenuation at 30 MHz of 1 dB/100 m. Its solid inner copper conductor is fitted with a semi-conducting layer, over which the low density polyethylene insulation is extruded in one passage. A thin layer of brushed graphite is applied to the outer polyethylene surface, to improve the voltage holding. Two aluminium foils, one mounted axially, the other wrapped tangentially, form together with a tinned copper braid the outer conductor. Due to its comparably high impedance and its braided outer conductor, the cable has a bending radius of only 0.7 m which facilitates handling and installation.

The coaxial cable connector, designed for a withstand voltage of 60 kV, is a constructional element of particular interest. The connector socket on the tank has an epoxy insulator with a conical aperture, into which the cable plug is fitted under high axial pressure. To avoid breakdown via air gaps along the mating surfaces between socket and cable plug, a soft polyurethane layer is moulded onto the conically machined polyethylene insulation of the cable (Fig. 9). The same design is used for the smaller RG 220/U connectors. More than 600 of these connectors are in use in the SPS and their operational reliability is excellent.

For reasons of short pulse rise time, also the antiproton inflector is equipped with resonant charging power supplies.

5. PERFORMANCE

5.1 Magnets

The kick of the magnetic field is measured at a voltage of 20 V by integrating the voltage difference between the first and last capacitor plate using a trapezoidal pulse with appropriate rise time. Complementary measurements are made with a matched stripline probe. The probe measurements are then repeated at high voltage. Figure 10 shows the kick rise time of a proton inflector module (type S) at a generator voltage of 60 kV; Fig. 11 gives the kick signal of the $\bar{p}$ inflector derived from low voltage measurements.

The non-uniformity of the magnetic field across the horizontal plane is determined in computer simulations and checked with a.c. probe measurements. Apart from a small region near the return conductor which cannot be occupied by the beam, the non-uniformity is negligibly small.

The electrodes of the h.t. capacitors with a total area of 15 m^2 per module under an electrical stress of up to 75 kV/cm, are conditioned with d.c. rather than pulsed voltage. Because of the large electrode area and the correspondingly large predischarge current at high voltages, the current is programmed to raise linearly, until a spark occurs or a present voltage of 35 kV, corresponding to a stress of 85 kV/cm, is reached. After each conditioning spark the current amplitude restarts at zero. Compared to a constant conditioning current, a raising current results in a more regular increase in voltage holding. This conditioning method has been found much faster and more efficient than the usually applied conditioning with a pulsed voltage.

Although tests on a full scale prototype module had shown excellent voltage holding at stresses up to 120 kV/cm, the withstand voltage of the final modules was initially insufficient due to magnesium oxide particles which stuck loosely to the $AlMg_3$ electrode surface and were not removable with chemical cleaning methods. On the prototype plates which came from a different delivery batch, these particles had not been found. Etching away a layer of 20 µm thickness from the electrode surface in an aqueous solution of caustic soda cured this problem. Though the etching increased the surface roughness, all modules could be reliably conditioned at voltages exceeding 35 kV.

5.2 Pulse generators

The flat top ripple of the long pulse of the proton inflector is minimized to less than ±1% by adjusting at low voltage the inductances of the solenoids while the pulse forming network is discharged with a mercury wetted relay. Prior to installation each pulse generator is tested at design voltage with 10^5 pulses. A typical oscillogram of the current in the termination resistor is shown in Fig. 12. Because of the large product of current amplitude and pulse duration, it is important that the main thyratron operates at a high reservoir voltage to avoid short current interruptions in the pulse flat top (quenching).

Figure 13 shows the 6 pulse generators of the proton inflector installed in their auxiliary building.

6. OPERATIONAL EXPERIENCE

Both injection systems are in operation since June 1981 and work as anticipated. Thanks to the thorough life testing of all components prior to installation, the operational reliability of the complex systems, containing 23 ceramic thyratrons, 250 m^2 of h.t. electrodes and 26 racks of electronics, is excellent.

The inflectors are remotely controlled from the SPS control room via several sets of computer programs, written in the interactive language NODAL. One group of progams sets directly parameters of the inflectors, e.g. it turns on the mains, sets the charging voltage or the trigger instant and surveys the status of more than 50 interlocks. It gives alarms in case of faults. Other programs are written for a higher operation level, e.g. the operator chooses the type of injection required and the computer selects then the settings of the inflector system.

The oscillograms of the kicker signals can be displayed via BIOMATION transient recorders on the TV screens of the control room, together with signals of the beam current. This information is very useful for the detection of injection timing errors. A remotely controlled signal switching matrix connected to every transient recorder, allows to select 2 out of 16 signals for simultaneous display. The optimum BIOMATION display settings of each signal are stored in the computer together with the name of the signal and loaded into the transient recorder, when a specific signal is selected. This procedure ensures always a correct display of signals with different amplitudes, durations and trigger instants and facilitates substantially the operation of transient recorders. Figure 14 shows a TV display of the standard two-batch injection scheme.

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Table 1

Performance requirements of inflectors

	Inflector	
	Proton	Antiproton
Maximum injection momentum (GeV/c)	26	26
Deflection angle (mrad)	5	1
Kick strength (Tm)	0.43	0.087
Kick flat top duration (μs)	1-12 adjustable	0.2 fix
Kick rise time (ns)	175	600
Kick fall time (ns)	1300	600
Aperture (width × height, mm)		
type S	100 × 61	-
type L	140 × 54	140 × 54
Repetition rate	5 pulses, 0.65 s apart, within 12 s	2.4 s
Gas pressure in vacuum tank (Torr)	$2 \cdot 10^{-9}$	$2 \cdot 10^{-9}$

Table 2

Main inflector parameters

	Inflector	
	Proton	Antiproton
Maximum generator voltage (kV)	60	60
Characteristic impedance (Ω)		
generator	6.25	12.5
magnet	12.5	12.5
Current amplitude in generator (kA)	4.8	2.4
Number of magnet modules	12	5
Number of vacuum tanks	3	3
Magnetic length of module (m)	0.7	0.7
Kick rise time (2% - 98%) (ns)		
type S	145	-
type L	220	220
Kick fall time (98% - 2%) (ns)	690	220
System time jitter (ns)	< 5	< 5
Thyratron type (EEV)	CX1171B	CX1171A

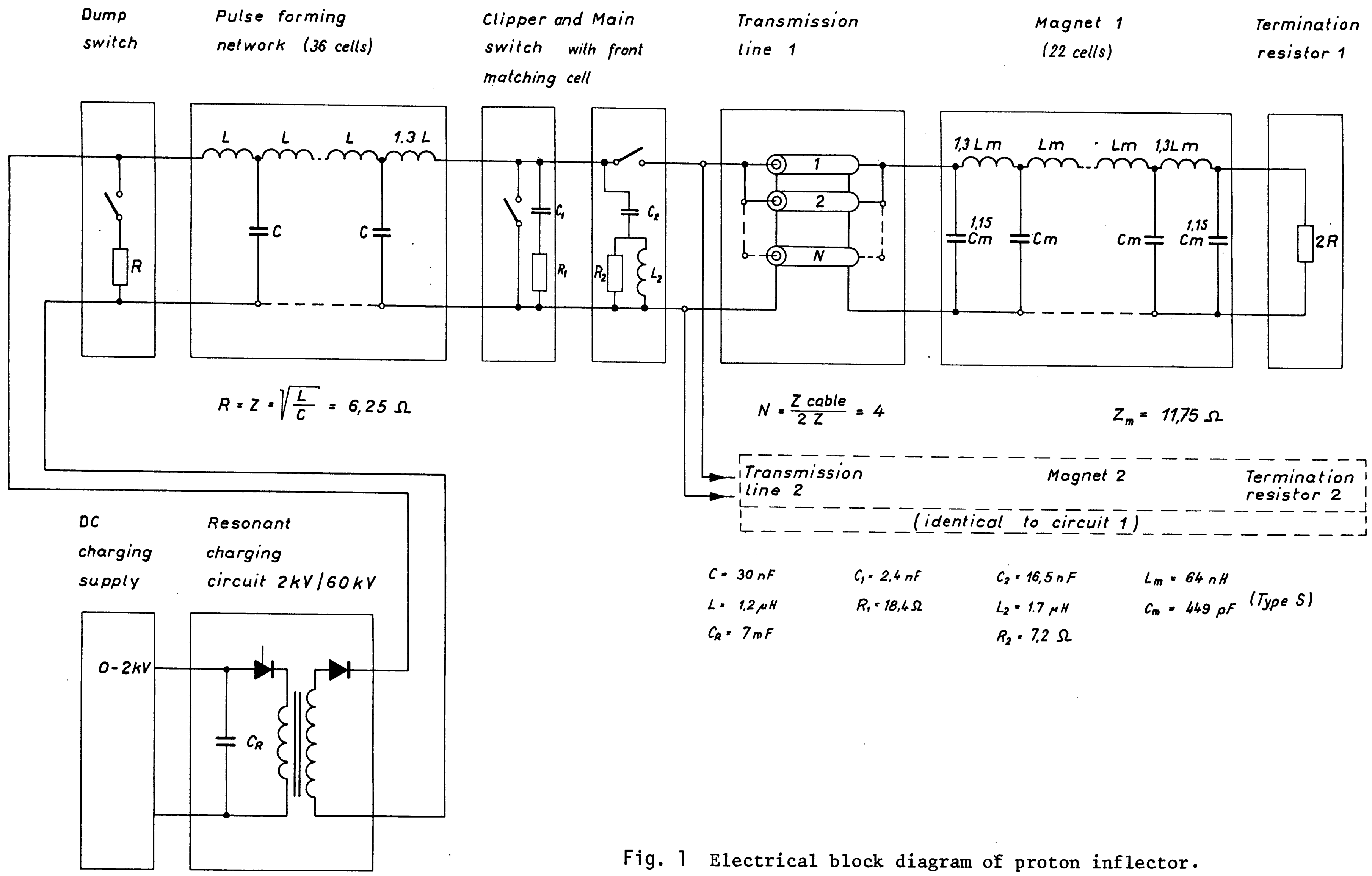

Fig. 1 Electrical block diagram of proton inflector.

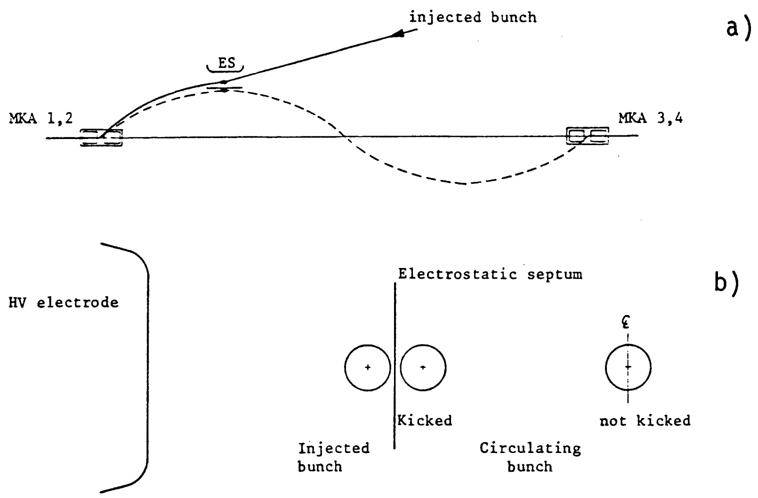

Fig. 2 Injection of antiprotons (schematic).
(a) Layout. (b) Radial position of bunches in the electrostatic septum.

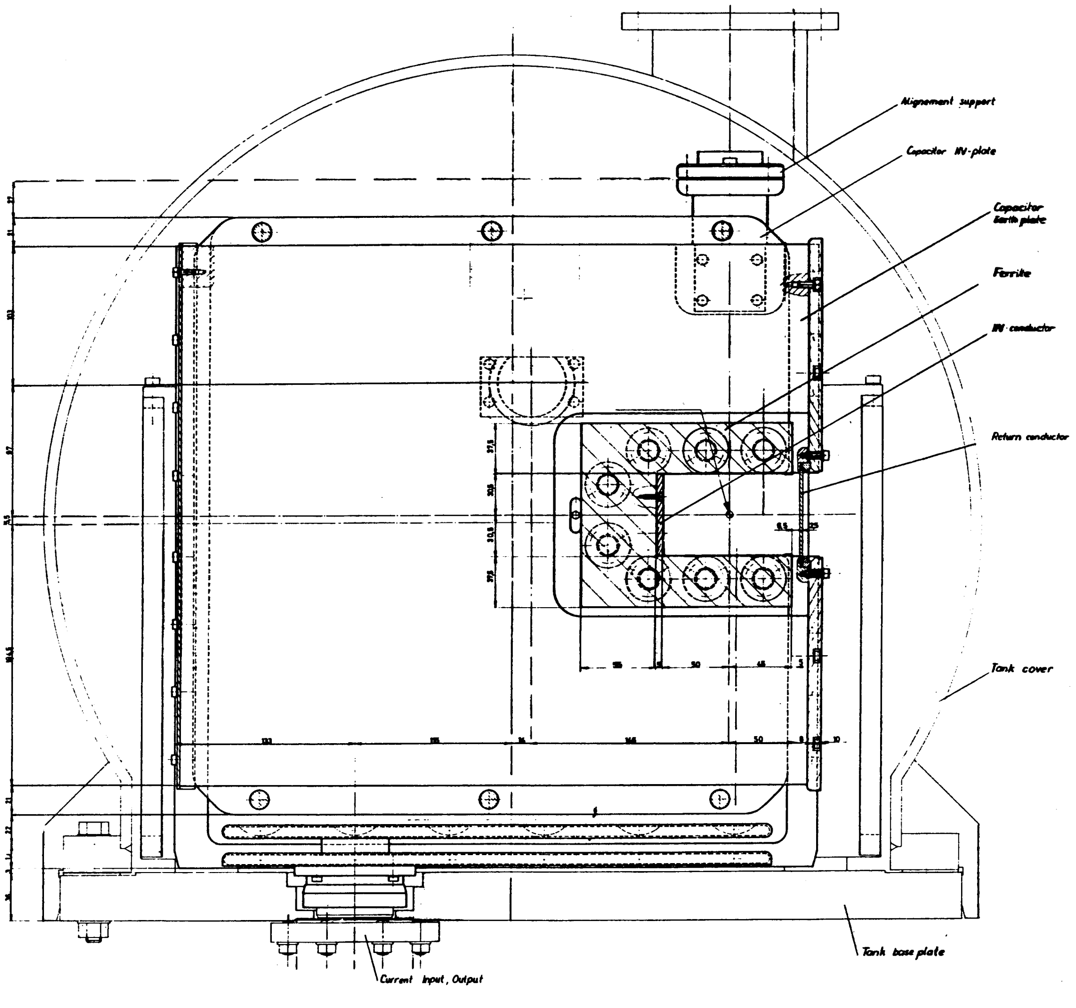

Fig. 3 Cross-section of the magnet module type S in its vacuum tank.

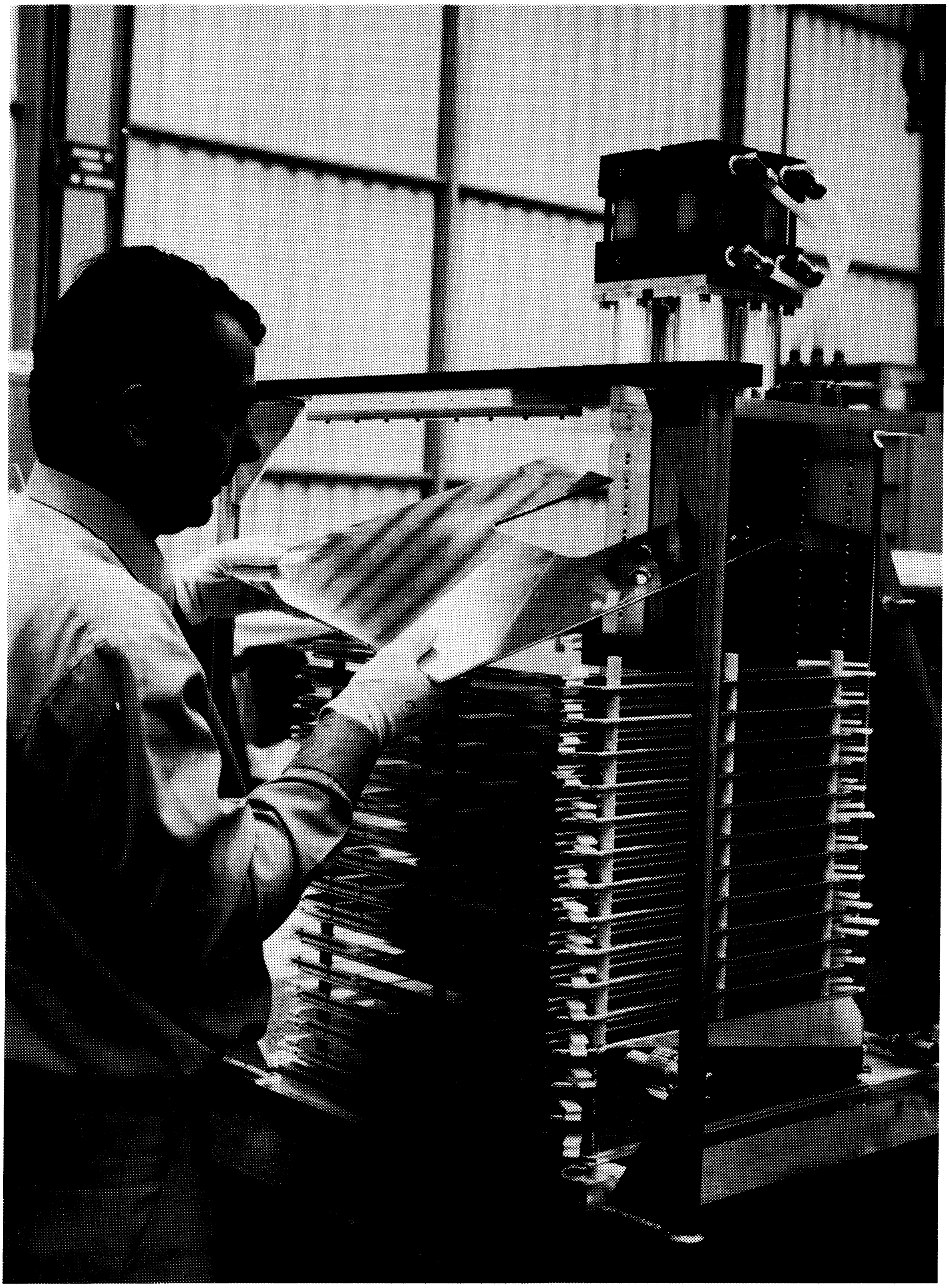

Fig. 4 Assembly of a magnet module.

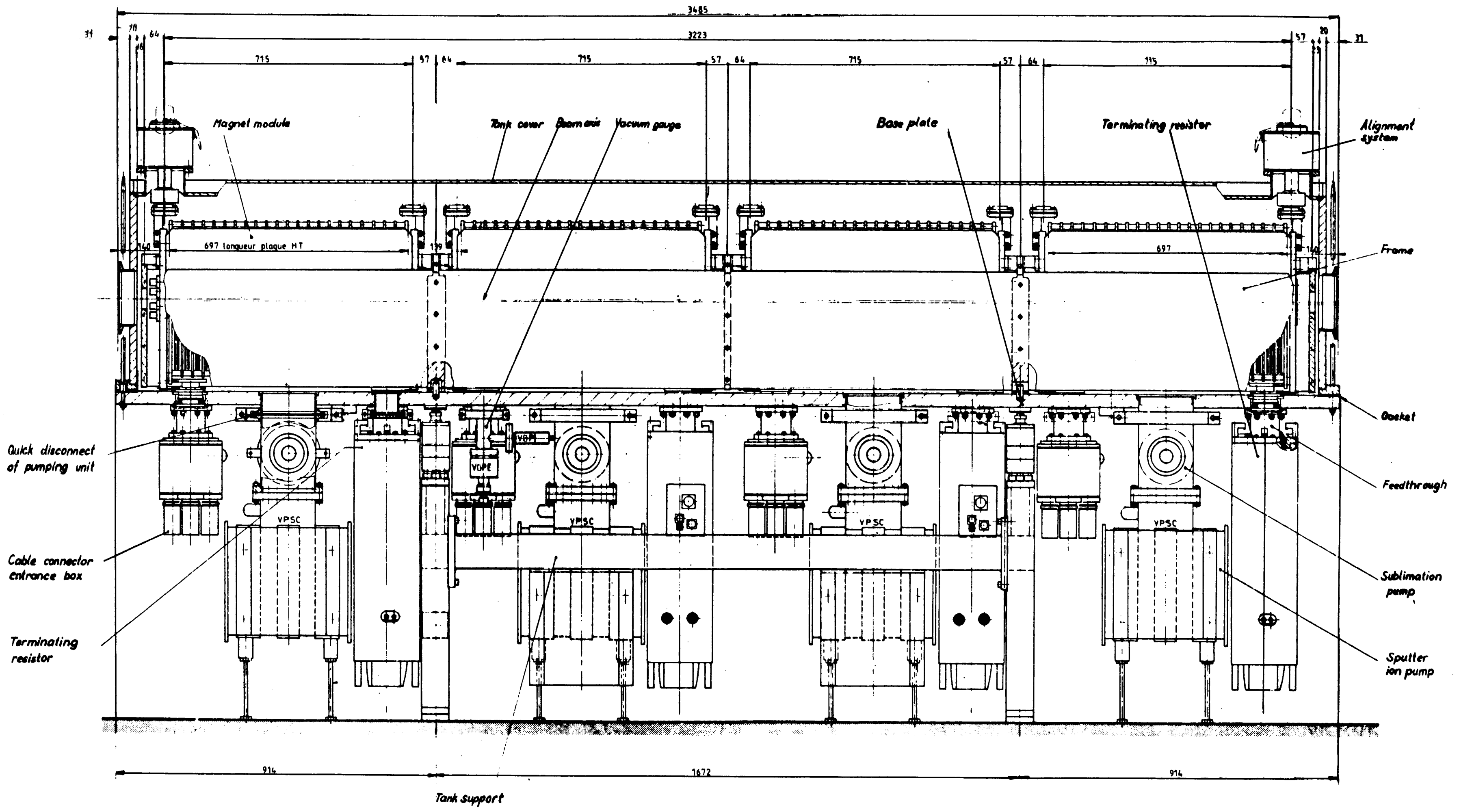

Fig. 5 Longitudinal section through the vacuum tank of the proton inflector, showing 4 modules in their frame, terminating resistors and vacuum pumps.

Fig. 6 The 4 modules of the proton inflector on the base plate of the vacuum tank.

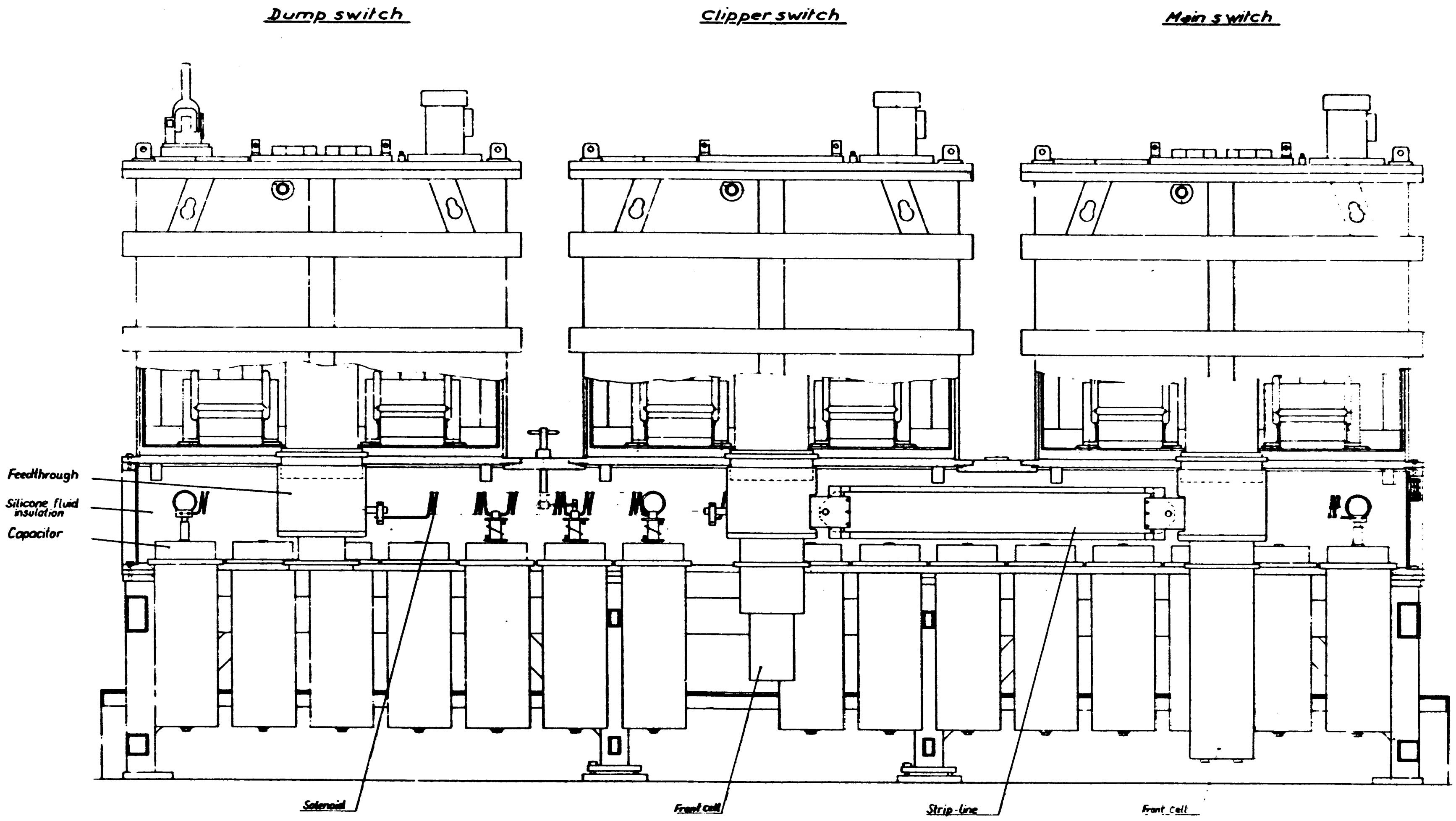

Fig. 7 Mechanical assembly of the pulse generator of the proton inflector.

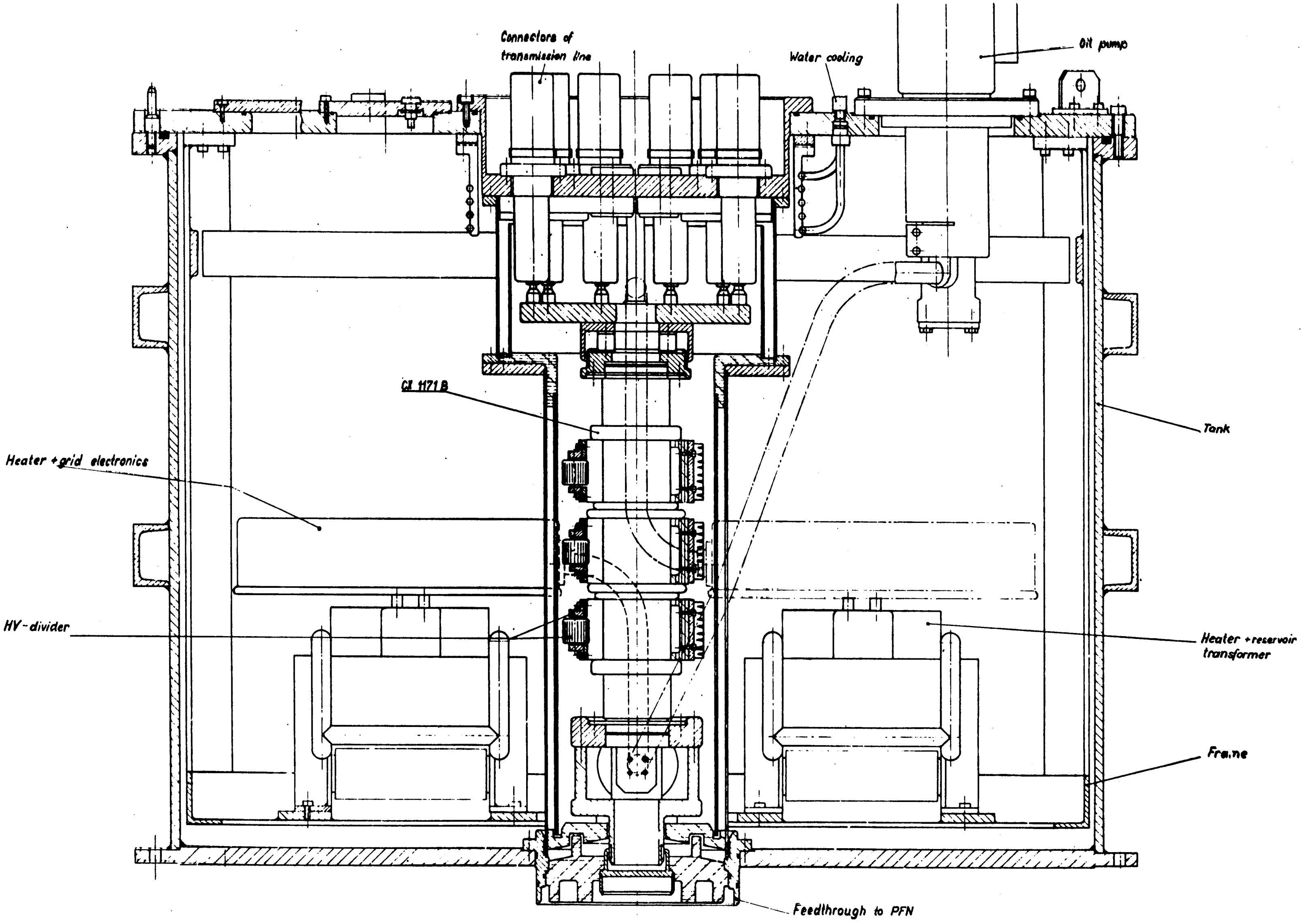

Fig. 8 Assembly of a thyratron tank.

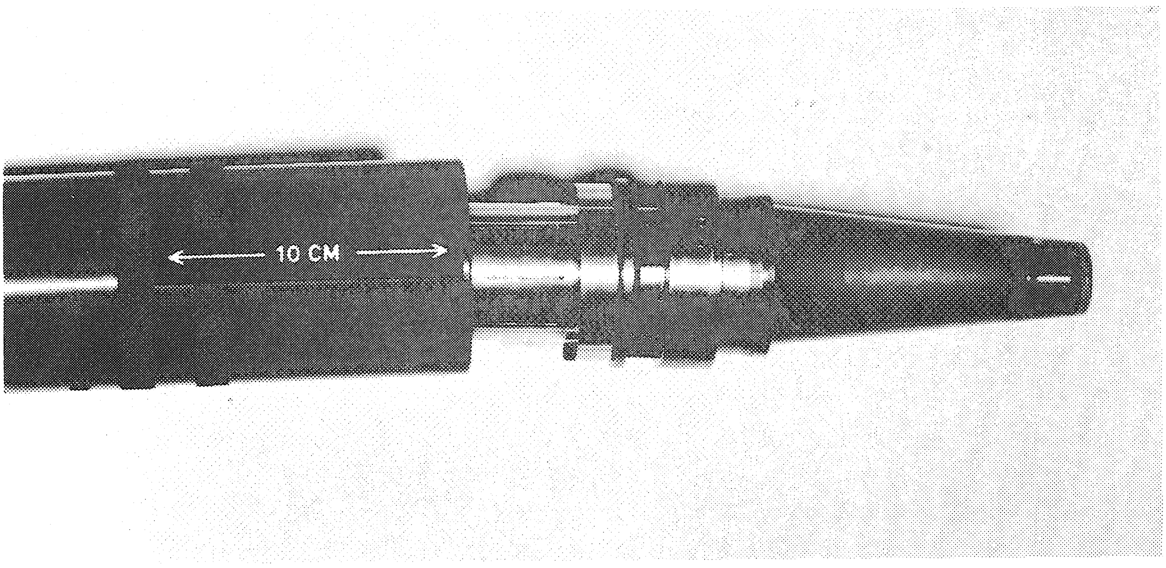

Fig. 9 Cable plug with polyurethane layer.

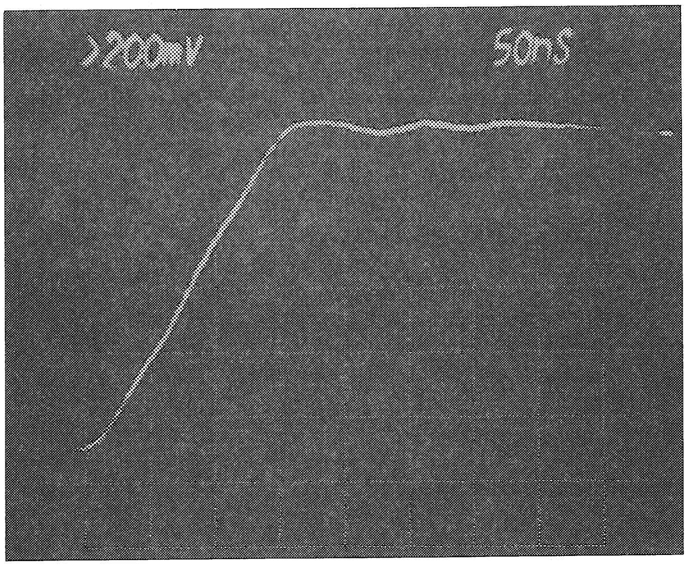

Fig. 10 Kick rise time of the proton inflector (module S) measured at a generator voltage of 60 kV.

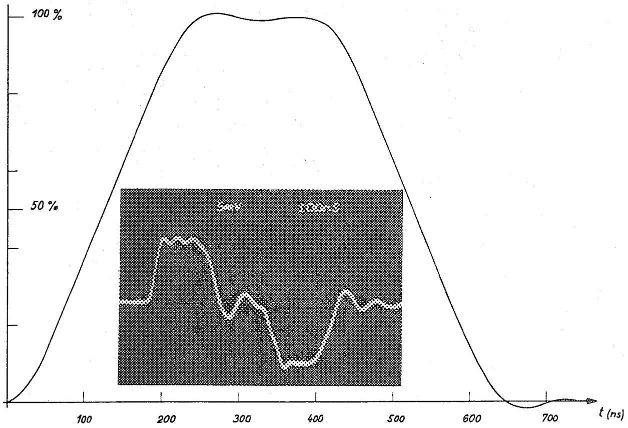

Fig. 11 Kick signal of antiproton inflector, derived from low voltage probe measurements.

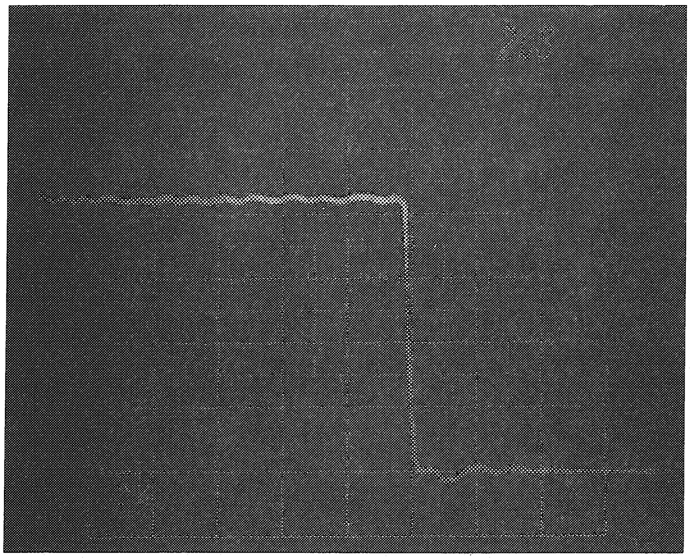

Fig. 12 Current pulse of the proton inflector measured on the termination resistor.

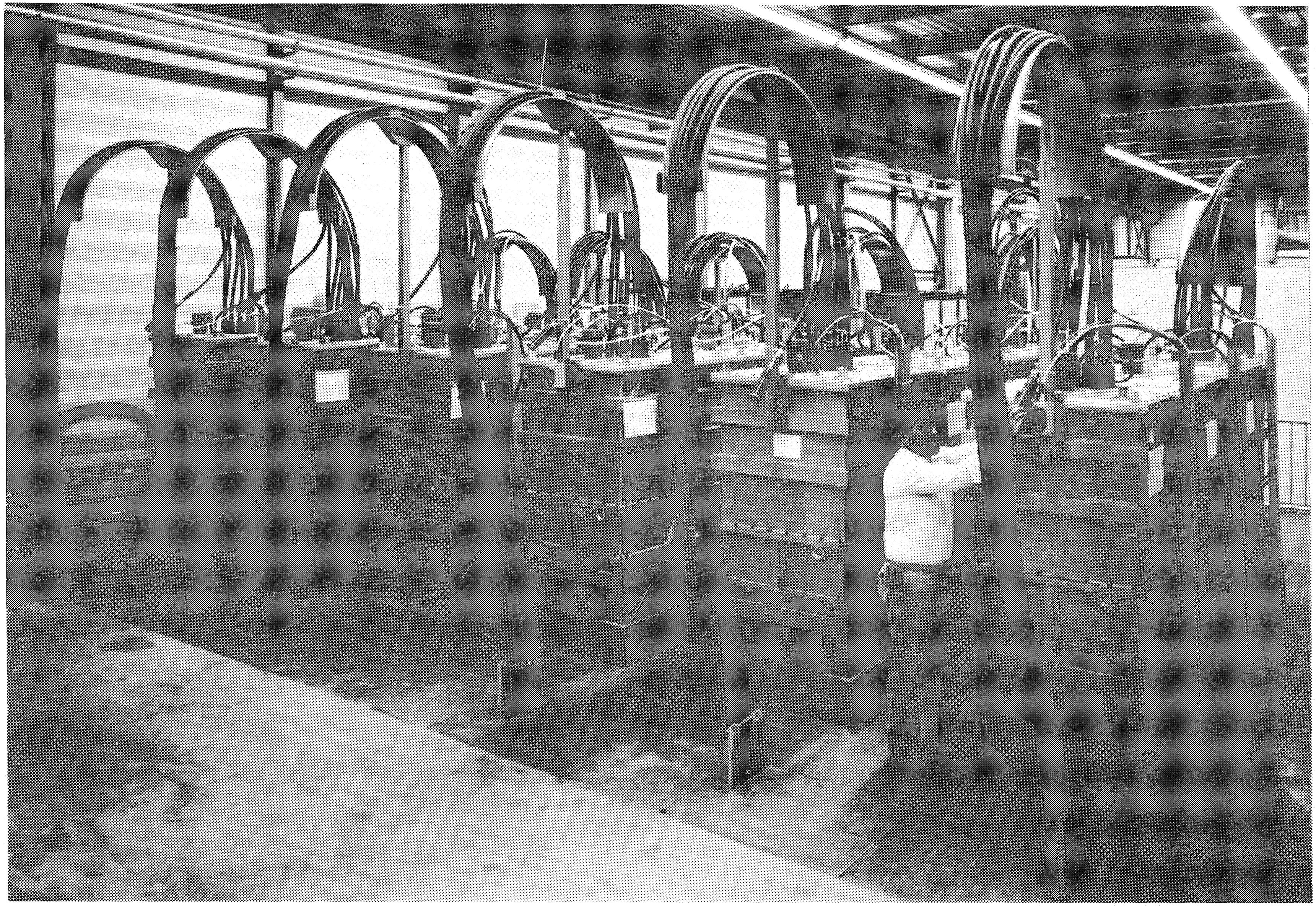

Fig. 13 The 6 pulse generators of the proton inflector system installed in the auxiliary building.

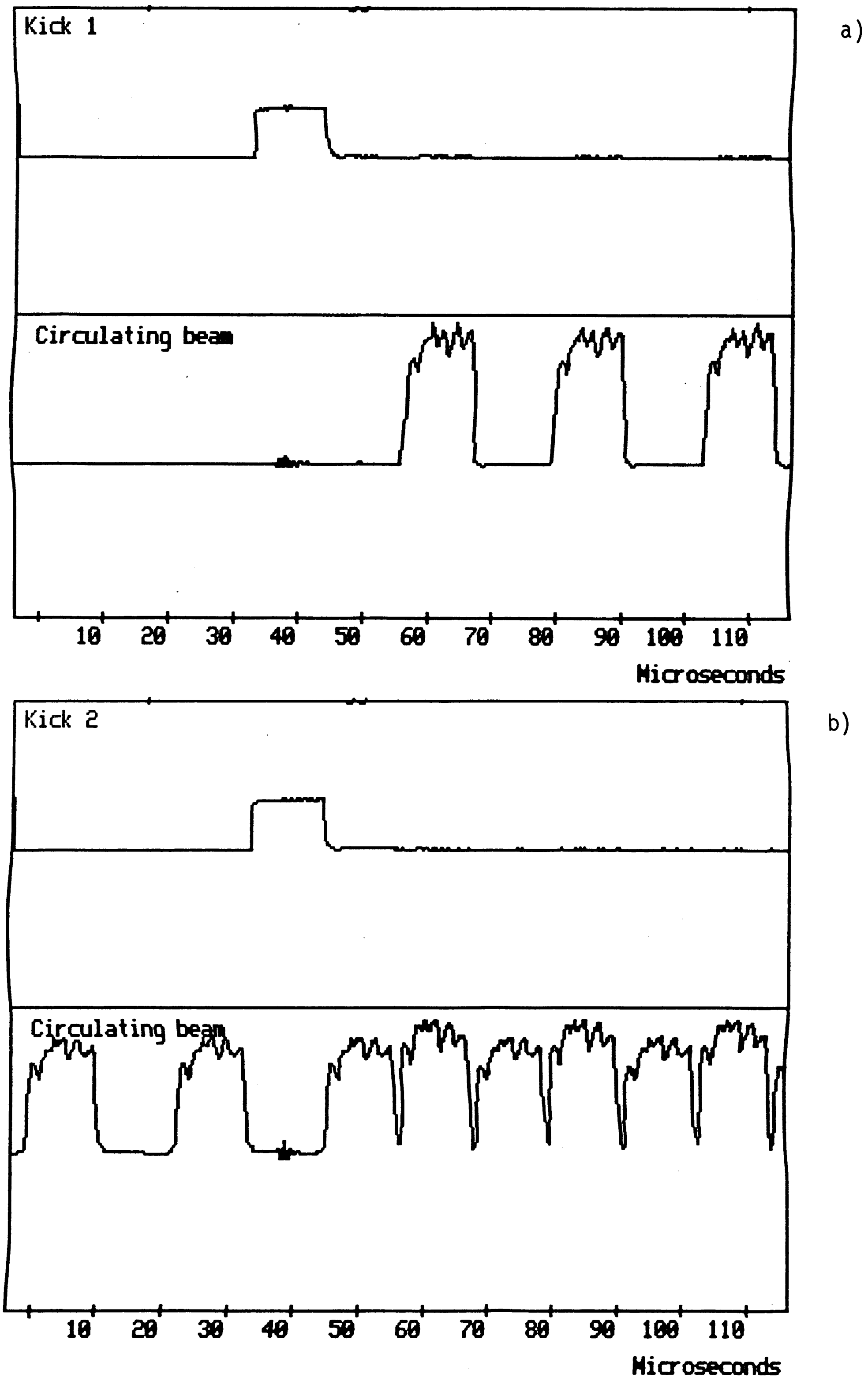

Fig. 14 Two batch injection into the SPS. Upper trace: magnetic field pulse of inflector; lower trace: proton beam intensity. (a) Injection of the 1st batch; half of the circumference is filled; 3 turns are displayed; (the delay of about 23 μs between the signals of inflector and beam current meter is due to the time-of-flight between both elements). (b) Injection of the 2nd batch 1.2 s later.