EUROPEAN ORGANIZATION FOR NUCLEAU RESEARCH

CERN/MPS/SR 72-2
3.7.1972

DF/iw

THE FAST BUMPER MAGNETS AND ASSOCIATED PULSE GENERATORS FOR 11 TURN EXTRACTION OF THE PS BEAM

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1. Introduction

Implicit in the choice of the CPS as the SPS injector was the necessity to investigate new ejection techniques for the CPS. Two schemes of CPS-SPS transfer were favoured(1), namely, rapid bunch by bunch fast extraction and multi-turn shaving. Both involved additional hardware for the CPS but the shaving technique was new and, at the time of its proposal, untried. Therefore a decision was taken in mid-1971 to concentrate the available effort on hardware construction for a full scale trial of eleven turn shaving ejection from the CPS. A provisional time scale of 8 months was fixed for building the hardware, leaving about 8 months for trials before having to pronounce, in December 1972, on the suitability of multi-turn shaving for the CPS-SPS transfer.

The principle of multi-turn shaving is fully described by C. Bovet in his report (2). This shows the hardware necessary for CPS trials to be :

a) the electromagnetic septum magnet in straight section 16,

b) the electrostatic septum in 83,

c) quadrupoles in 73 and 89,

d) slow bumps at 16 and 83 and

e) two programmable fast bumpers in 71 and 95, excited by a staircase eleven step pulse.

With the exception of the fast bumpers all other items were already installed or available in the PS. This report describes these new fast bumpers and their associated pulse generators.

2. Specification for fast bump

It is often impossible to lay down a rigid specification for hardware being developed for new ejection processes. The fast bumpers for the multi-turn shaving were no exception to this situation.

Certain points, however, were firmly specified, as summarized below :

Ejection energy	- 10 GeV/c
Maximum required kick	- 0,5 m.rad.
Shaving duration	- 11 PS turns
Number of individually adjustable steps	- 11
Step length	- 1 PS turn variable by ± 50 nsecs.
Bumper location	- Straight section 71 and 95
Equality of kick	- Better than 2%
Aperture	- Full (147 x 53 mm).

In the all important aspect of field rise time for the bumpers no firm specification was given. It was left to the hardware designers to obtain the fastest possible rise time consistent with reasonable cost and getting the job done on time. Preference was to be given to a design which would ensure at least a fast rise time for the first step as this would largely determine how much of the beam would stay behind in the machine after the eleventh step.

The individual step heights were unspecified. As general guidance it was to be assumed that the first step height would be approximately one half that of the eleventh and that all steps would be positive. The eleventh step could be expected to be the largest, being up to 25% higher than the tenth. The actual "staircase" pulse required for constant ejected beam current during eleven turns would depend upon the operating conditions within the PS ring, e.g. slow bump amplitude, beam radial position, beam size. Flexibility in the pulse generator control was therefore to be given priority.

The absence of a rigidly imposed rise time specification permitted the bumper and pulse-generator design to be based more on engineering and commercial considerations than might otherwise have been the case e.g. on the availability of standard high voltage coaxial cable and low cost thyratrons.

3. Choice of hardware

3.1 Magnets

In all applications involving fast pulse magnets there are generally three basic designs from which to choose, namely, the lumped inductance, multi-cell delay line and hybrid (Serpukhov) types. In the event that rise time is of major importance, as in most fast ejection schemes, one is generally obliged to take the delay line or hybrid magnet, even though this choice considerably increases the magnet and vacuum tank costs. However, wherever rise time and reflexion considerations permit it is always advantageous to take the simple lumped inductance magnet. Rough calculations showed that for the fast bumpers the choice of a lumped instead of a delay line magnet increased the first step 5/95% field rise time by only 25% yet permitted the use of a vacuum tank at least three times smaller, with consequent savings in cost and manufacturing time. The lumped inductance design was therefore chosen for the project.

There remains the further choice of magnet form between the window frame and c-core construction. In terms of field uniformity and remanent field the window frame is always to be preferred. It is frequently not used for delay line magnets because it has the disadvantage that the ferrite generally is subjected to high electric stress. However, this disadvantage need not apply if the magnet is of the lumped inductance type, because it may then equally well be located after the termination resistor and thus be subject to pulse voltage only during flux change. The stress conditions obtaining during the pulse flat top in delay line magnets are thus avoided and the window frame construction may be chosen with less risk.

3.2 Pulse Generators

There are numerous possibilities, more or less complicated, for the production of a fixed time, variable amplitude eleven step pulse. Certain of these possibilities have to be discarded when it is realized that the required pulse current is close to 1000 ampères and that control flexibility and step rise time are important.

In the early design stage two solutions were retained. The first was to build the "staircase" out of a series of individual pulses of decreasing length, stacked on top of one another. This solution is possible using eleven separate pulse forming networks (P.F.N's), the longest corresponding to eleven turns, the shortest to one turn and charging to the necessary differential voltages. The PFN's are connected in parallel and triggered in sequence into a single transmission line leading to the magnet. In order that this arrangement may work, each PFN must be decoupled from all others by substantial impedance which leads to the inclusion of a non-negligible resistor in series with each PFN. In the final analysis this solution has but one advantage, namely reasonably equal rise time for each step, and numerous disadvantages. The first and not least, is that flexibility of control is impaired by the form in which the staircase is built up. Any change required in the first step height implies a change in the PFN voltage supplying the 23 µsecs (11 turn) pulse and automatically all remaining ten steps increase. Thus to change the first step it would be necessary to raise one voltage and lower the remaining ten. The second important disadvantage is that the PFN decoupling resistors consume a large proportion of the pulse power and consequently much of the energy stored in the PFN's is wasted. This needlessly increases PFN and power supply costs.

The second solution was to construct the pulse from a series of individual 2,1 µsecs full amplitude pulses stacked time-wise behind one another(3). This solution is feasible if one uses a series arrangement of eleven PFN's with intervening switches. In order to be of practical use for excitation of the fast bumpers, this solution must have the following attributes. Firstly the series switches must be capable of holding off the maximum step voltage, but must conduct without excessive jitter for very low (say 1 kV) step voltage. Secondly, the PFN attenuation must be very low as access to the magnet for any given step is via all the preceeding PFN's. Thus whilst the rise time for the first step is that due to the magnet inductance and PFN + terminator impedance (and is thus at the choice of the designer) the rise time of the eleventh step is principally that due to the distortion of the eleventh pulse transversing ten series PFN's. Subject to suitable switches and PFN's being available this solution has decided technical advantages. Firstly control of each individual step is independent of all others and secondly there is no waste of stored energy in decoupling resistors.

It was decided that the advantages of this second solution were so great as to warrant its adoption for the project. Model work was immediately put in hand to find solutions to the switching and PFN attenuation problems, the results being reported in(3).

4. Hardware design

4.1 System impedance

The choice of system impedance is linked to the magnet design by rise time and kick strength considerations.

The magnet inductance is given by $L = \frac{NBw\ell}{I}$ where w and ℓ are the aperture width and magnet length respectively, N the number of magnet turns. The kick strength of the magnet is $B\ell$. The magnet current for a correctly terminated system is $\frac{V\text{charge}}{2Z_o}$, Z_o being the chosen system impedance. Thus the time constant of the magnetic field which is $\frac{L}{2Z_o}$, may be expressed as $\frac{Nw \cdot \text{Kick Strength}}{V\ \text{charge}}$. Therefore, for any given aperture width, kick strength and imposed limit on operating voltage the minimum time constant is obtained for a single turn magnet.

For any given magnet aperture the kick strength of the magnet is proportional to its length, the number of turns and the line charging voltage and inversely proportional to the system impedance. Since for rise time considerations a single turn design should be chosen and there is an upper practical limit to usable line voltages, there remain only two parameters which may be varied to achieve the desired kick strength. These are the magnet length and system impedance. Both are expensive commodities in their own way - length because all PS straight section length is at a premium and impedance because the lower this is chosen, the greater is the system stored energy and the higher the cost of the pulse generator (not to mention technical difficulties for fast switching).

The choice of the series PFN solution for the pulse generator also has indirect implications in the choice of system impedance. The series PFN arrangement can only work if low attenuation coaxial cable PFN's are used. With an overall time scale of eight months it was essential to choose from the range of standard low attenuation RF cable. This is marketed in impedance values of 50 and 75 ohms but for the best high voltage withstand 50 ohms cable should be used. The choice of system impedance was therefore restricted to 50, 25 and 16 2/3 ohms ohms, in ascending cost order. Taking a limit of 50 kV for the cable charging voltage and using the full PS short straight section length for a bumper magnet, the impedance level was fixed at 25 ohms.

4.2 Magnet

The essential magnet parameters are given in Table 1.

TABLE 1

Aperture (width x height)		148 x 53,5 mm	
Active length		850,5 mm	
Vacuum tank overall length, including bellows		1272 mm	
Vacuum pumps (Vac ion)		2 x 400 litre/sec.	
No. of turns		1	
Inductance	calculated (without strays)	3,00 µH	
	measured (with strays)	3,20 µH	
Current for 0,5 mrad deflecting power at 10 GeV/c		835 A	
Air gap flux density		190 gauss	at 835 A excitation
Ferrite back leg average flux density		800 gauss	
Peak ferrite flux density		1200 gauss	
Uniform field region $\pm\,\overset{0}{0{,}5}$ %		86 mm	symmetrically disposed about geometric centre line
Uniform field region $\pm\,\overset{0}{1}$ %		98 mm	
Remanent flux density (835 A excitation)		0,8 gauss	
Ferrite type		Philips 4 A 4 Indiana H2	

Fig. 1A is a photograph of the magnet with the semi-circular vacuum tank cover removed and prior to mounting the vacuum pumps. The final installation in the PS is shown in Fig. 1B. Stainless steel was used for the tank and base plate. Magnet construction materials, in addition to ferrite, were aluminium or anticorodal alloy and ceramic for high voltage insulation. No organic materials were used in vacuum.

The terminating resistor was of the forced oil cooled carbon mass type, mounted in a coaxial housing which was attached to the flange of the base plate (Fig. 1B). Incorporated around the conductor between resistor and magnet was a fast response current transformer (Pearson type 110, rise time 20 nsecs) for observation of the magnet current. The pulse was fed to the resistor from the remotely located pulse generator via 2 RG220/U cables with LEMO high voltage connectors.

4.3 Pulse Generator

The pulse generator comprises four major parts, namely, the PFN cables, the high voltage switches, the recharging power supplies and the control system. The overall pulse generator schematic is shown in Fig. 2. Fig. 3 is a general view of the pulse generator, in which only part of the PFN cable is shown.

4.3.1 PFN Cables

The cable chosen was RG220/U. Two cables were paralleled for each PFN to give the desired 25 ohms impedance. Thus a total length of 10 km was required to form the eleven steps for the two bumpers. The nominal maximum charging voltage for the design magnet current of 835 ampères would have been 42 kV in an attenuation free system. However, the transmission losses of the initial 10 steps (Fig. 4) required that the eleventh step voltage be raised by about 17% in order to achieve the design magnet current. The pulse generator thus had to be engineered for a working voltage of 50 kV.

The current rise in the magnet was also slowed down by the attenuation of the RG 220/U. Fig. 5 shows the normalized rise current in the magnet for the eleven steps, the first step having a 10/90% rise time of 176 nsecs compared to 805 nsecs for the eleventh step.

RG 220/U was selected because it was the lowest attenuation polythene cable readily available. Its RMS voltage rating of 14 kV was somewhat meagre in relation to the desired 50 kV charging voltage. However, this was considered a justifiable risk in view of the experimental nature of the project and the absolute necessity to construct quickly. Furthermore it was known that similar cable was in use at NAL on PFN duty at 70-80 kV with varying degree of success according to the source of supply. In addition the precaution was taken to test short lengths of cable to destruction at the manufacturers; the results indicated that the 50 kV lifetime would exceed that required for completion of the trials programme. Nevertheless for any final CPS-SPS transfer equipment the RG 220/U should be replaced by more expensive lower attenuation gas impregnated cable of superior high voltage withstand.

4.3.2 High voltage switches

Hydrogen thyratrons were selected for switching. This decision was taken because of the need to switch with low jitter over a very wide voltage range due to the different step height requirements. Thyratrons offer the further known advantages of very low spontaneous breakdown rate and long trouble-free operating life when employed in well designed circuits. Further they have the ability to withstand a reasonable reverse voltage, a feature which is necessary if negative steps in the staircase are to be contemplated.

Eleven thyratrons were employed per pulse generator. The first (type CX 1159) separating PFN 1 from the magnet, was of higher voltage rating (33 kV) than the others (type CX 1191) on account of the anticipated 20 - 25 kV amplitude of the first step. The CX 1191 tube rating of 16 kV was considered adequate for the anticipated maximum of 12 kV for any of the remaining step heights. All thyratrons were required to operate with floating cathodes, leading to the necessity of fully isolated heater and grid supplies.

Two possibilities were considered for the triggering of the CX 1191 tubes. These were self triggering from the grid/cathode capacitance on the fall of anode voltage as the preceeding PFN emptied and pre triggering by an external trigger pulse via fully insulated trigger transformer. In terms of hardware economies the first solution was the more attractive, but resulted in the waveform of Fig. 6. This exhibits significant holes at the end of each step due to the finite anode delay time of the thyratron. This switching defect was overcome by the adoption of the second solution resulting in the much improved staircase waveform of Fig. 7. The use of an external trigger pulse further permitted fine adjustment of each step length, particularly as the PFN cable length employed for each step deliberately exceeded the PS rotation time by about 100 nsecs.

4.3.3 Recharging power supplies

In order that a series PFN arrangement with comparatively low voltage intermediate switches may function it is essential that the PFN's be simultaneously recharged and that the charging time be sensibly independent of the voltage level to be reached. The differential voltages appearing across the switches are thus held to a minimum. The ideal power supply for this system is the pulsed resonant power supply.

A variety of circuit designs for pulsed resonant power supplies exists. The type chosen for this application was identical to that which had been life tested for the F.A.K. project(4) and which has proven reliability and stability. The step-up transformer was chosen to give a recharge time of about 2,5 milliseconds and maximum output voltage of 50 kV. Eleven identical power supplies were used, each being required to charge the PFN cables of a given step but for both bumpers. This arrangement ensured that identical voltages would be applied to the two PFN's, reduced the cost and simplified the controls.

One of the attributes of pulsed resonant power supplies is their ability to pulse at short intervals. This system is no exception and it would be possible to produce "staircase" pulses at 14 millisecond intervals should this ever be necessary. At present the power supply primary capacitor bank system is restricted to single pulse operation at one second intervals.

4.3.4 Controls

In view of the purpose for which this equipment has been constructed the controls have been kept to a bare minimum consistent with the ability to operate and carry out certain adjustments with reasonable efficiency.

Step length and timing adjustments are possible but only locally at the pulse generator. Step amplitude adjustment is possible, either locally or from the MCR. PFN voltage digital display and magnet current waveforms are available both locally and in the MCR. A reasonably comprehensive fault display is available locally.

Considerable effort was put into the protective systems of the pulse generator on account of certain risks which are inherent in such a design. The use of low voltage thyratrons and series PFN's is potentially hazardous to the equipment if for some reason one power supply fails to operate. This would result in a serious forward overvoltage for one thyratron and , worse still, a serious reverse overvoltage for a second thyratron. Clearly it cannot be known in advance if all eleven pulsed resonant power supplies will function correctly but at least reverse voltage protection can be provided across each thyratron so as to detect excessive reverse voltage and limit the fault condition to a single shot.

Further difficulties can also be experienced in the event of thyratron spontaneous breakdown. The breakdown of any single tube in the series chain of eleven inevitably triggers off the remaining ten, thus pulsing one of the magnets, the waveform depending much on the location in the chain of the faulty tube. Spontaneous breakdown detectors can be incorporated so as to limit the number of such breakdowns before shutting down the system.

Both the above protective devices have been incorporated in the generators, and are further supplemented by conventional overvoltage protection for each PFN. In addition there are the usual oil coolant and vacuum protection systems.

5. Operating experience

The hardware was constructed within the budget and time scales laid down and has since been successfully commissioned. Considering the complexity of the system, commissioning difficulties were remarkably few. In the all important aspect of magnet performance the design specification was fully satisfied; measured step rise times were in good agreement with the predicted values (Table 2) and the design kick strength of 0,5 mrad at 10 GeV/c for 835 A excitation was confirmed by observation of the kicked PS beam.

Ejection trials started in early May 1972 since when the bumper system has been pulsed about 10^5 times, generating a variety of waveforms including constant amplitude 11 turn pulses (Fig. 8), ascending staircases (Fig. 9) and ascending and decending staircases (Fig. 10). The latter form whilst not originally foreseen, was necessary for constant external beam current for eleven turn ejection during a recent trial (Figs. 11 and 12). Thus the versatility and ease of control have been proven, vindicating the choice of system for the generator.

The pulse waveform was in most respects satisfactory. Two reflexions, nevertheless, were observed on each step both due to inherent mismatches in the thyratron switches. The first reflexion arose because of the inability of the first thyratron to fully transmit the inevitable reflexions originating at the lumped inductance magnet. These reflexions were thus partially returned to the magnet and appeared as positive flat top imperfections after twice the transmission line transit time. The second reflexion was due to the inability of the series thyratrons to fully transmit the backward wave propagation in the PFN's. This manifested itself as a negative magnet flat top imperfection occuring after twice the step PFN transit time. The harmful effects of these reflexions were nearly completely cancelled out by making the wave propagation time of the transmission system identical to that of a step PFN.

TABLE 2

	Step rise times 10/90% (ns)	
Step	Predicted from circuit time constant and cable attenuation	Measured
1	176	170
2	215	200
3	265	250
4	322	280
5	392	310
6	467	380
7	535	480
8	615	560
9	683	580
10	742	620
11	805	660

6. Acknowledgements

This work has been carried out as part of the cooperative agreement between Labs I and II. The degree of progress indicates that this cooperation has worked smoothly.

The realisation of the hardware was in the hands of many MPS staff, too numerous to mention by name, who by their hard work ensured the success of the project. However, special mention must be made of the contribution of D. Grier who proposed the series PFN system and engineered the most delicate part, the thyratron switching.

It goes without saying that C. Bovet, the proposer of multiturn shaving, offered much helpful advice.

References

1. A design of the European 300 GeV Research Facilities. Chapter 3.

2. Continuous transfer from CPS to 300 GeV - A numerical analysis of Fast-Shaving Ejection. C. Bovet 300-DI-PA/INS 2.

3. Proposal for a "Staircase" Pulse Generator for continuous transfer from CPS to SPS. D. Grier MPS/SR/Note 71-36.

4. A resonant charging pulsed power supply for kicker magnet pulse forming networks. D. Fiander, P. Pearce CERN/MPS/SR 69-11.

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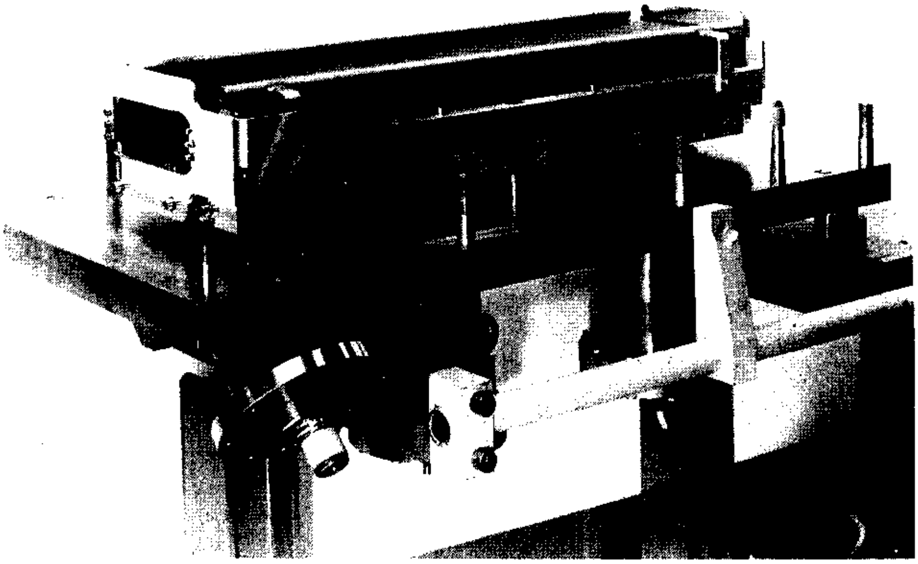


Fig. 1 a) Magnet with vacuum tank cover removed

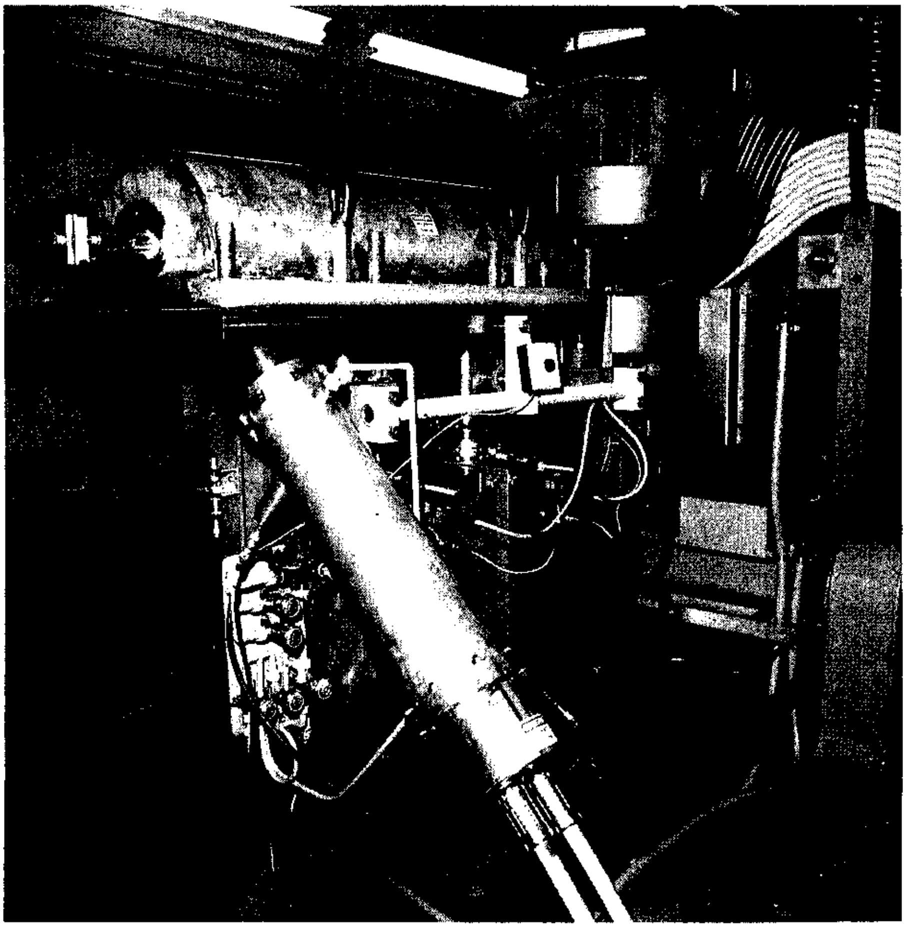


Fig. 1 b) Magnet installed in Straight Section 71

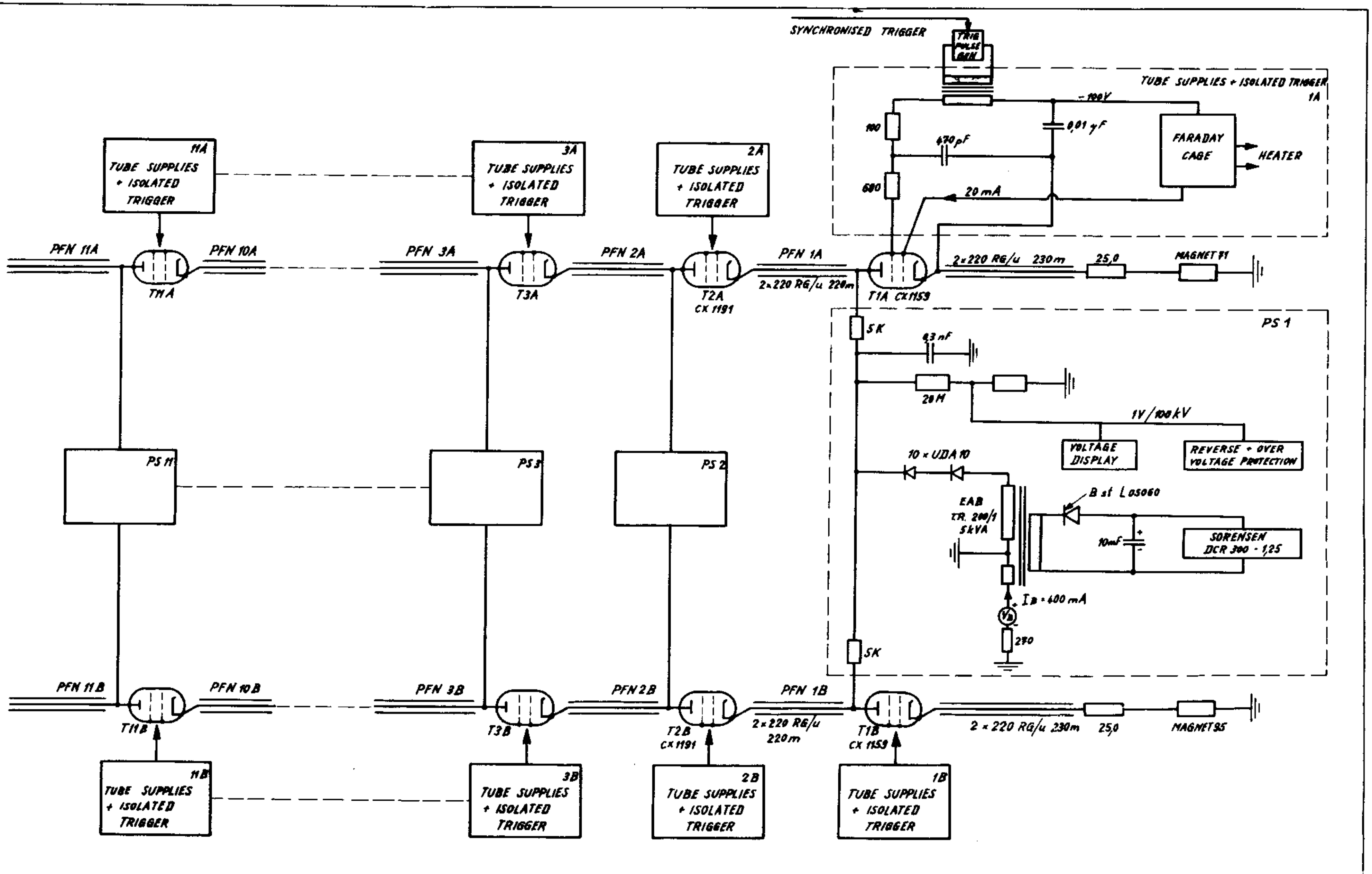


FIG. 2 OVERALL SCHEMATIC DIAGRAM
11 TURN SHAVING.

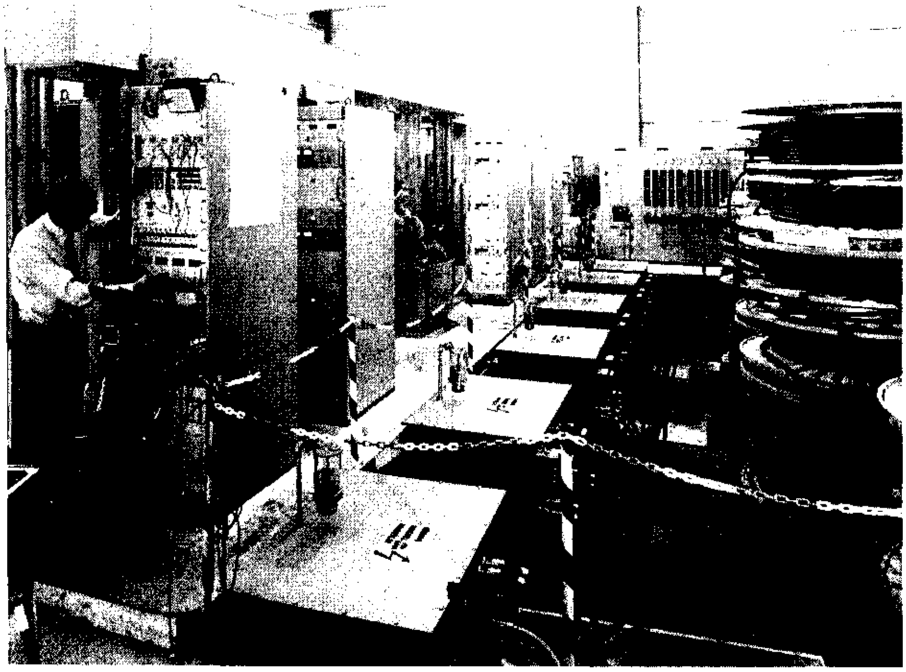


Fig. 3 View of pulse generator

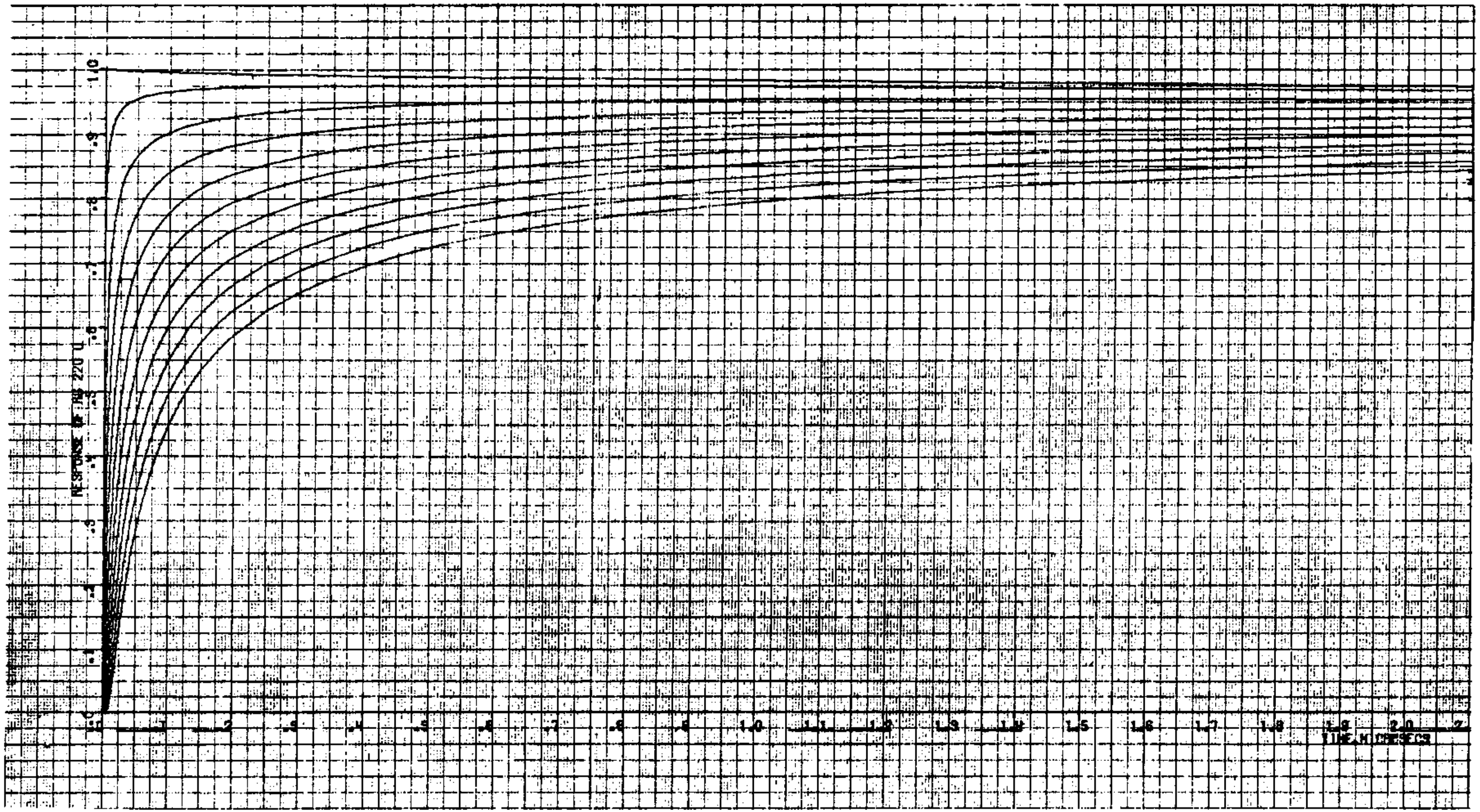
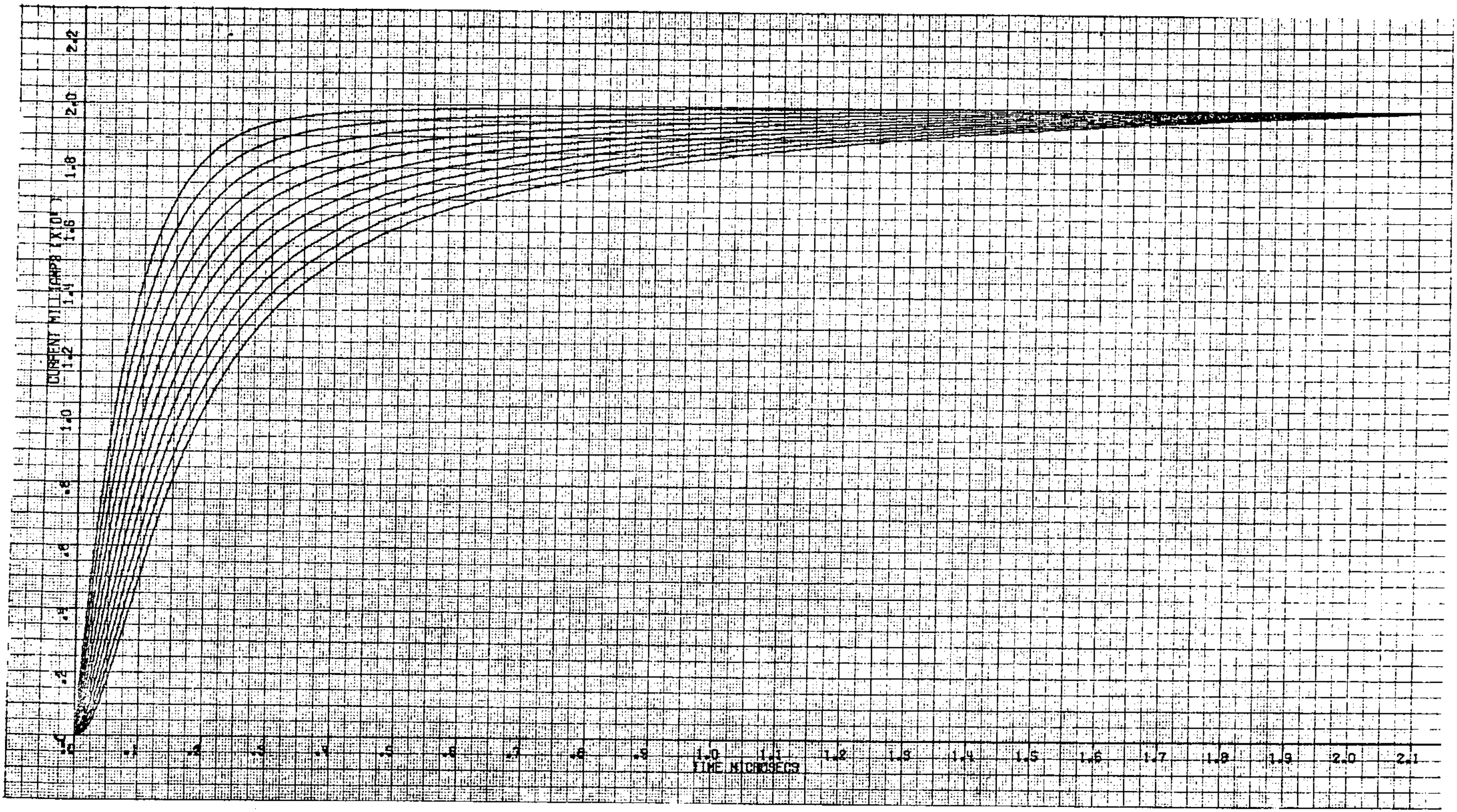
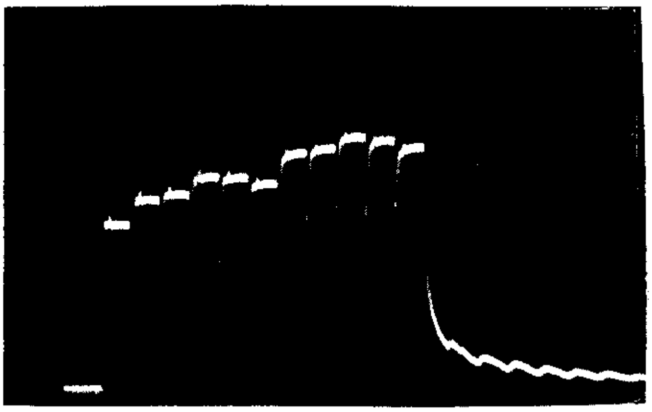


Fig. 4 P.U. output pulse of PFN's 1-11 into matched load

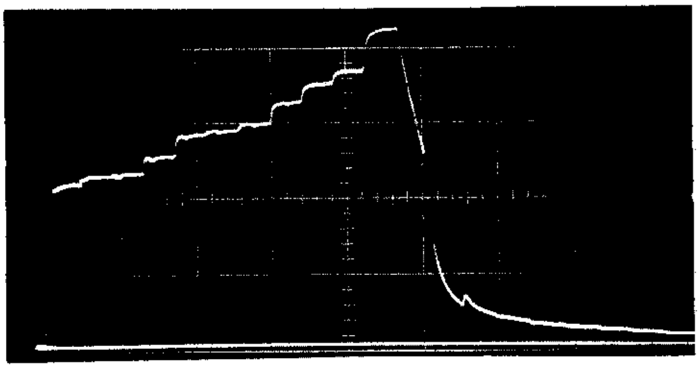


<u>Fig. 5</u> Normalized magnet current for steps 1-11 (assumed $L_M = 3{,}6\mu H$)



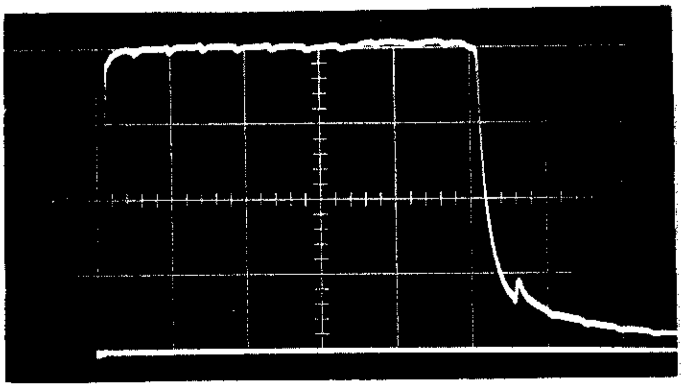
5 µsec/cm

Fig. 6 Typical magnet current with thyratron in self triggering mode



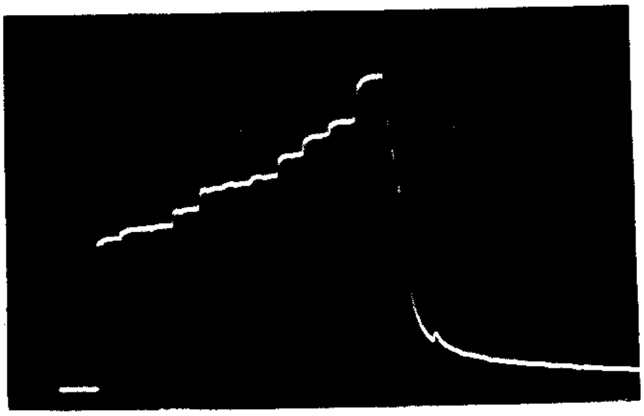
5 µsec/cm

Fig. 7 Typical magnet current with external triggering of thyratrons



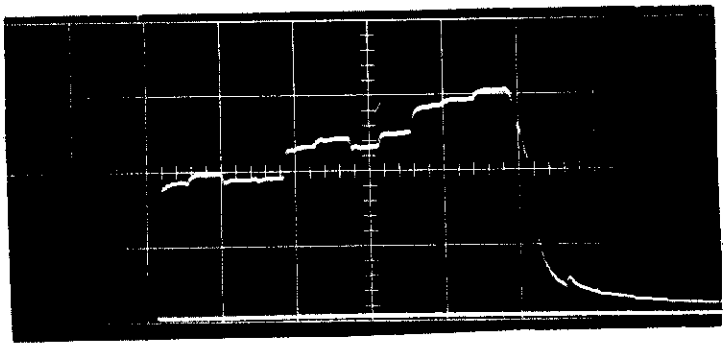
5 µsec/cm
120 A/cm

Fig. 8 11 turn flat top current pulse



5 µsec/cm
120 A/cm

Fig. 9 11 step ascending staircase current pulse



5 µsec/cm
240 A/cm

Fig. 10 Ascending and descending staircase pulse used in PS trials

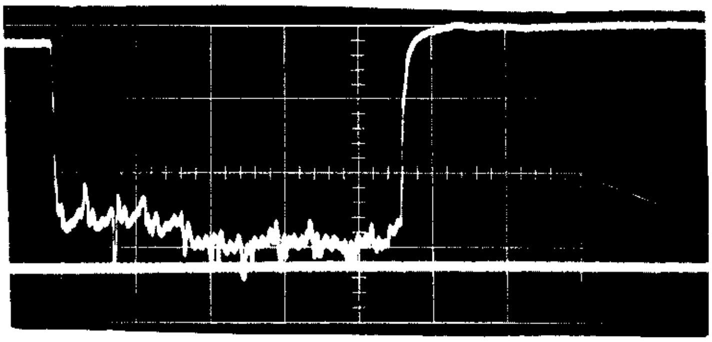


Fig. 11 External beam current with bumpers excited with waveform of Fig. 10

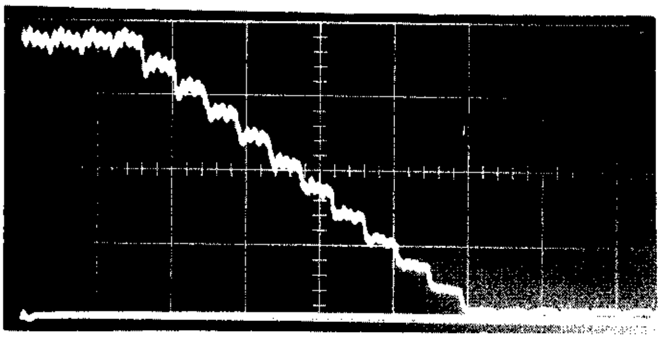


Fig. 12 Falling intensity of PS circulating beam over 11 turns corresponding to ejected beam intensity of Fig. 11