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FUTURE PHOTOMULTIPLIER ASSEMBLIES AND ASSOCIATED ELECTRONICS IN LARGE EXPERIMENTS

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G E N E V A

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ABSTRACT

The results are presented of a working group study on reducing costs of proposed counter experiments in high-energy physics where several thousand photomultipliers are involved. Photomultiplier design is briefly discussed and new designs are presented for tube housings and high-voltage supplies. An outline presentation is given of a simplified electronics system, based on the Eurocard, for fast logic, data handling, and associated power supplies, suitable for photomultipliers or wire counters. Substantial savings in cost are shown to be possible without affecting performance but with some loss in convenience.

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CONTENTS

1. INTRODUCTION

This report is an account of the activity of a working group on electronics for future counter experiments.

The aim, as proposed to the group by E. Picasso, was to consider new, economical, solutions for photomultiplier (PM) bases and high-voltage (HV) power supplies. The reason for this is given by the increasing use of large-scale PM arrays in high-energy physics experiments, for example in counter hodoscopes and total absorption calorimeters with a large number of elements.

The results of this part of the study are presented in Sections 2 and 3. It is important to note that the practical solutions indicated there are ready to be implemented now or in the near future.

In addition to the proposed aim, the group has spent some time discussing, in general terms, the question of fast logics and data acquisition electronics associated with the PM (see Section 4). The group has felt that it will become increasingly difficult for practical and financial reasons to keep the present NIM-CAMAC electronics system for detectors with at least an order of magnitude more PMs than in the past. The situation clearly calls for some re-designing of the electronics associated with PMs. Some requirements to bear in mind are:

- simplest possible design; only essential features and components should be included in order not to pay for rarely used facilities;
- fast data-handling rate; needed because of the size of the system.

Various ways could be envisaged to design such a system:

i) Improved (upgraded or, perhaps, downgraded) CAMAC (or NIM) system.

ii) The complete integration of the associated electronics (i.e. discriminators, delays, ADC, TDC, etc.) inside or immediately adjacent to the PM housing.

iii) Housing all the electronics concerned with the PMs in a system specially designed for simplicity. All the electronics, i.e. fast decision logic, signal digitizing, data handling, and HV supplies, could be included.

We have investigated the third possibility in some detail.

Although the opportunity to consider a new electronics system appears to us well justified, the conclusion reached is necessarily incomplete and preliminary. We feel, however, that it is interesting to present it as a contribution to possible future work in this direction.

2. PHOTOMULTIPLIER TUBES AND HOUSINGS

2.1 General

Owing to the evolution of the experimental arrangements at the big accelerators, and particularly at the SPS, the detectors make use of an ever increasing number of PMs. Certain recently planned experiments include 3000 to 5000 PMs, numbers that are an order of magnitude bigger than what we have been used to in the past. This situation makes it interesting to reconsider the criteria for selecting PMs and their associated electronics. In fact, the present study shows that considerable cost savings are possible without losing essential performance.

It is not, however, sufficient to replace the PM by a cheaper one, but the whole chain, including the PM, its housing, the HV supply and the associated electronics, must be taken into account if a really worth-while economy is to be achieved. Now the electronics and, to a lesser degree, the HV supplies have for a long time benefited from the continuous price-reducing influence of industrial competition, making the expected gain less spectacular than where the PMs and their housings are concerned. Even so, since the systems are very large, it is advantageous to provide for even limited reductions in cost.

Clearly the majority of the mechanical and electrical components that make up the system we describe here will have to be chosen from what is commercially available; it would not be realistic to base a system on components that will hopefully appear in the future or on special developments and techniques. The one exception to this is represented by the PMs, where CERN is a sufficiently big user to be able to discuss successfully with the manufacturers about developments and adaptations according to our particular needs. Such discussions with the two European manufacturers, Philips (RTC) and EMI, have been carried on by various groups at CERN. It would seem likely, however, that the best results would be reached by coordinating the requirements of the different users at CERN (and elsewhere!). In this connection it should be mentioned that since manufacturers of PMs are rare indeed, one should not carry the price competition between them so far as to risk losing the advantages of alternative sources.

Table 1 gives the principal characteristics of some PMs recently developed according to CERN suggestions. Prices for large quantities, say a few thousand, would be in the neighbourhood of SF 200.-. The performances of these tubes are sufficiently good to permit their use in many places where earlier much more expensive tubes were required.

Table 1

Principal characteristics of some low-cost photomultipliers

a) Diameter 2 in.					
Manufacturer	Type	Photocathode	Number of stages	Rise-time (nsec)	Gain
Philips	XP2232pp	Bialkaline	12	4	10^7
Philips	XP2232pc	Bialkaline	12	2.8	10^7
EMI	D 306B	Bialkaline	12	3.5	10^7
b) Diameter $1\frac{1}{2}$ in.					
Philips	XP2008	Super A	10	3.5	10^6
Philips	XP2010	Super A	10	3.5	10^6

2.2 Photomultiplier housing

Photomultiplier housings have, until now, almost exclusively been made of metal, employing rather artisanal methods. Metal is, of course, the ideal material, providing the necessary strength as well as the screening, but the price, even for a fairly simple housing, tends to be rather high. One should, therefore, look for other production methods. The very large number of housings that will be required makes it practical and economical to make them of injection-moulded plastic. Some preliminary studies of such housings can be seen in Figs. 1 and 2. It must be pointed out that these designs are in no way final. In fact, the design preparation of the moulds must be very careful, since their initial cost is very high and mistakes are impossible to correct afterwards. On the other hand, a complicated shape is not necessarily more expensive, so it should be possible to make a housing that is well adapted to the needs.

Preliminary estimates, including the cost of the three moulds, indicate a price of about SF 15.- if a series of 1000 is ordered, dropping to less than half for 5000 and more.

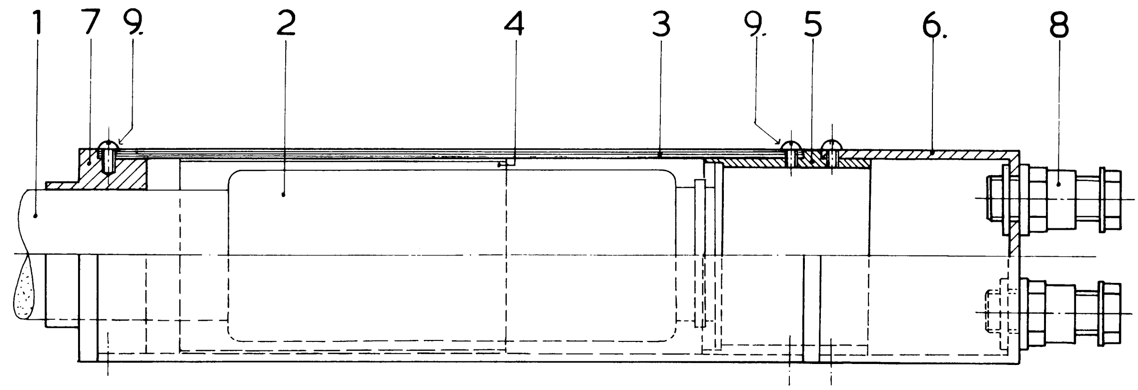

Fig. 1 Example of plastic housing for 2 in. photomultiplier tube, glued to the light guide. 1. Light guide; 2. Photomultiplier; 3. Outer cylinder; 4. Mu-metal screen; 5. Moulded electrical assembly; 6. Back cover; 7. Front-end piece; 8. Cable clamps; 9. Securing screws.

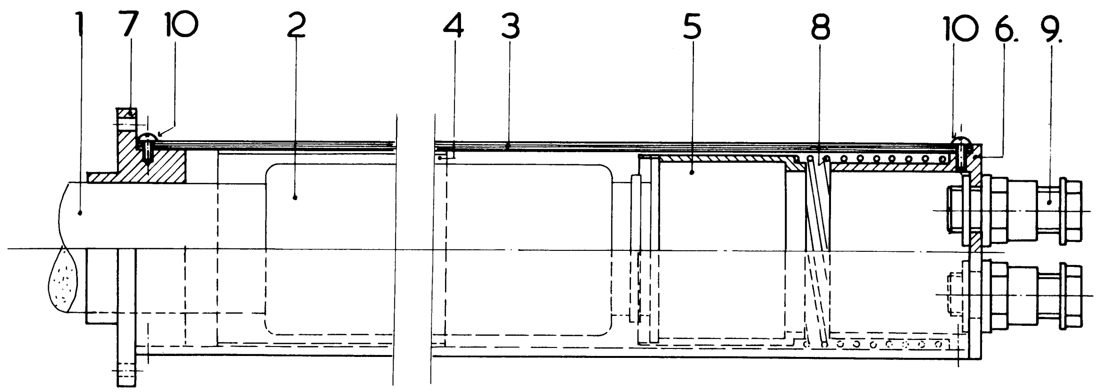

Fig. 2 Example of plastic housing for 2 in. photomultiplier tube, spring-loaded onto the light guide. 1. Light guide; 2. Photomultiplier; 3. Outer cylinder; 4. Mu-metal screen; 5. Moulded electrical assembly; 6. Back cover; 7. Front-end clamp; 8. Spring; 9. Cable clamps; 10. Securing screws.

2.3 Signal and power connections

It is obviously necessary to have some kind of electrical connection at the PM housing for the signal and power cables, although it would be attractive to be able to replace the BNC and SHV connectors by something less costly. Soldering the cables directly to the housing is, of course, a very cheap solution, but it is not really a practical one, since each housing would have to be used with a predetermined length of cable.

We propose, as a compromise, the use of "Fast-on" or similar clip-type connectors (see Fig. 29 in Section 4), which are quite robust and give good electrical contact. The connection can be made relatively easily and without tools, but the connector provides absolutely no isolation or protection against accidental contact. Therefore the connectors are mounted inside the plastic end-cover plate and the cables (multiwire for power and coaxial or twisted-pair for signal) enter the housing via plastic cable feed-throughs, which also lock the cables mechanically. To warn against the possible dangers of the HV, the housing and the end-cover plate are decorated with the appropriate warning labels.

2.4 Voltage divider chain

Various ways exist for supplying the necessary voltages to the PM electrodes. Of these, a d.c.-d.c. converter, producing the different high voltages by a high-frequency oscillator and rectifier from a distributed low voltage, has not been considered suitable for the PM housings studied here. The principle certainly has many advantages, but the over-all system price will not be as low as by using a resistive voltage divider, possibly with the addition of some kind of booster supplies for the last few dynodes. The choice between individual d.c.-d.c. converters and resistive dividers supplied from a central source does not involve a limitation on the performance of the PM itself; either principle can permit an optimum use of the tube.

A purely resistive voltage divider will not give a very satisfactory performance, even if driven with a fairly high current. The voltage sag at the later stages will introduce severe rate limitation. The way to improve the capability of handling high rates is to help the later stages with one or several booster supplies. It can be done in two ways, either to stabilize the last three dynodes*) by Zener diodes and add a booster current of some 3-5 mA through them, or to apply voltage-stabilized supplies of low internal resistance to the last dynodes. Both versions can, where rate requirements permit, also be run without the booster supplies.

The influence of the current, in the earlier parts of the divider chain, on the rate capability has been investigated. It was found that lowering this current from 2 mA to 0.2 mA (while keeping the booster supplies constant) would only decrease the maximum counting rate by a relatively small amount. The lowering of the divider chain current does not in itself give any significant cost advantage as far as the PM housing is concerned (there is the slight advantage of less heat to dissipate), but it will ease the requirements on the HV supplies considerably, and thereby reduce their cost.

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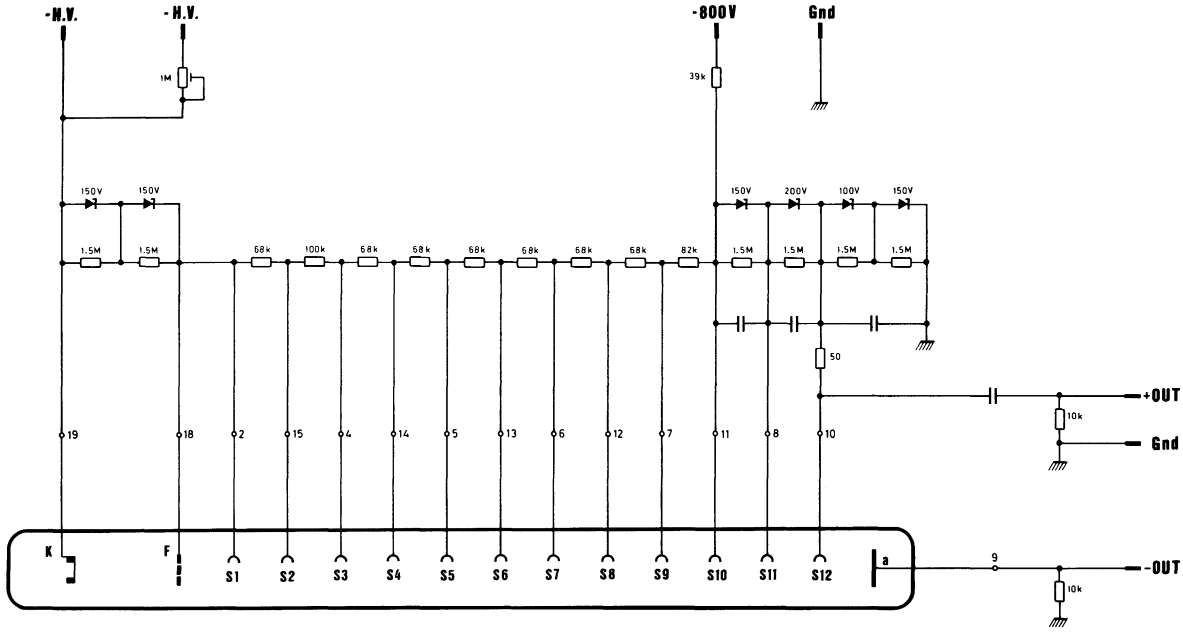
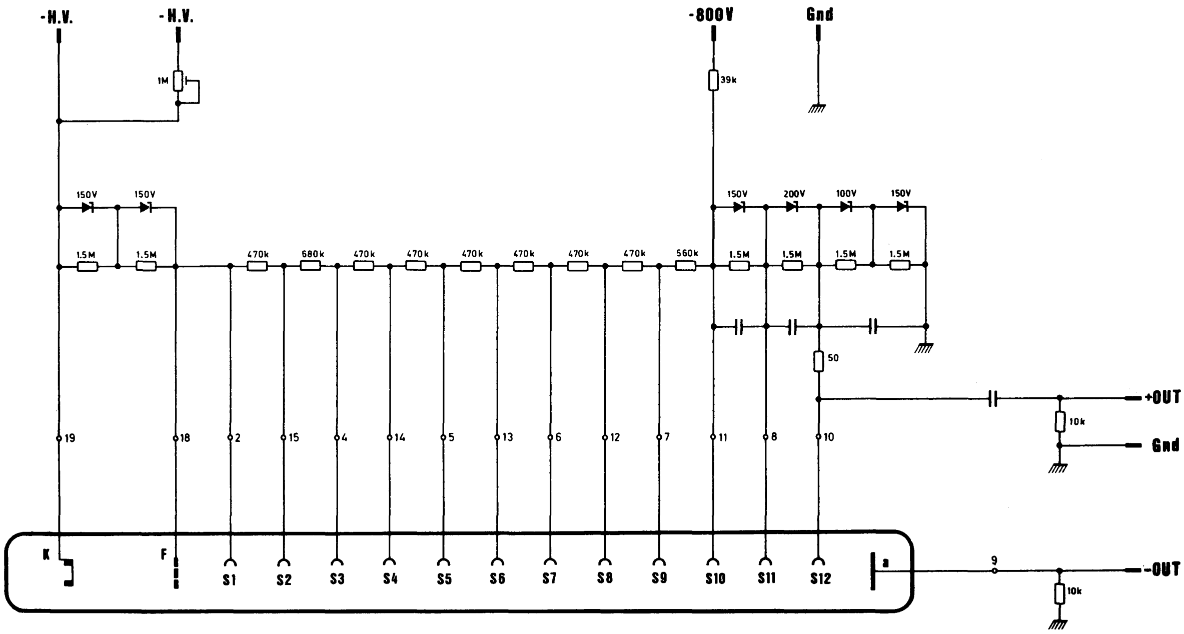
*) It seems probable that the last five dynodes will have to be stabilized in order to obtain the best rate independence. Measurements to confirm this are being carried out by one of us (P.D.).

The maximum counting rates for the different versions mentioned (see Figs. 3 to 5) are summarized in Table 2 and Fig. 6. The rates given are those where there is a ±10% change of amplitude (compared with the low-rate value) of a continuous train of pulses of an amplitude that has been arbitrarily set at 125 pC. It is worth remembering at this point that



PHILIPS : XP2232PP, XP2232PC
EMI : D306B

Fig. 3 High-current chain with booster current



PHILIPS : XP2232PP, XP2232PC
EMI : D306B

Fig. 4 Low-current chain with booster current

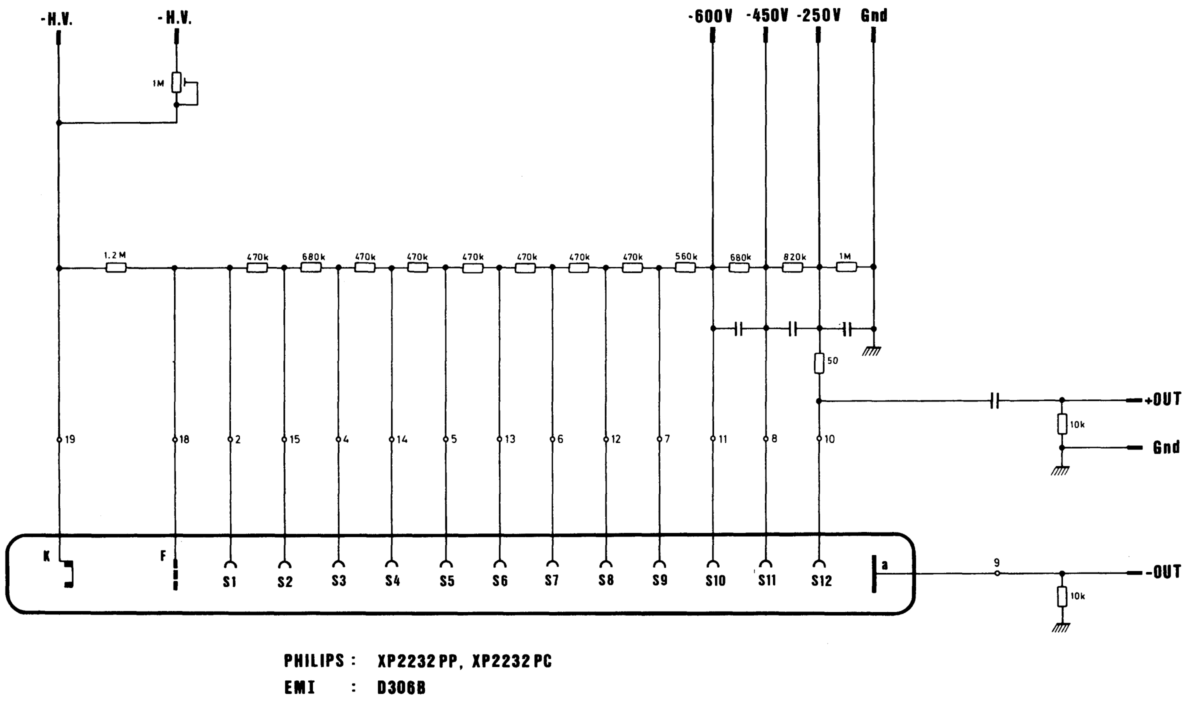


Fig. 5 Low-current chain with booster voltage

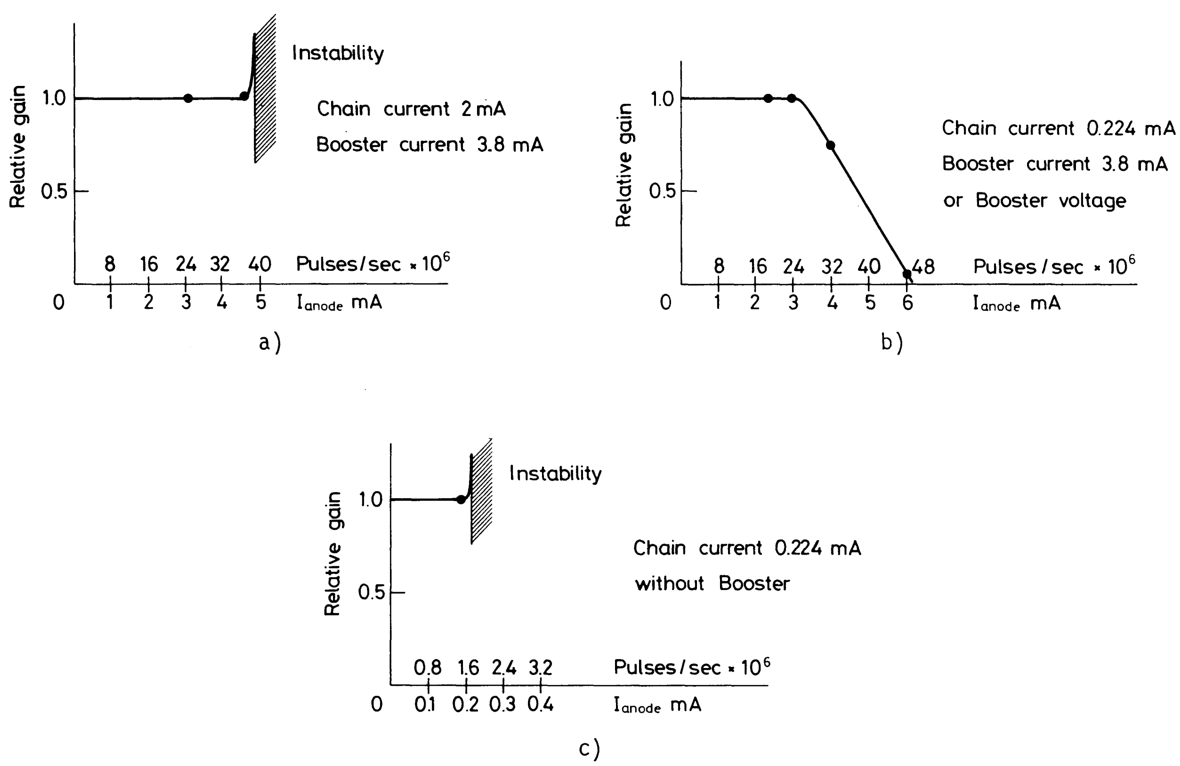


Fig. 6 Counting rate capability of a 12-stage PM tube as a function of the current in the voltage divider chain and of use of booster supplies. Pulse charge of 125 pC corresponds to average anode current values shown in abscissae.

Table 2

Comparison of the rate capabilities of three different voltage dividers

Chain type			Rate limitation	
Current (mA)	Booster	Fig. No.	Without booster (pulses/sec)	With booster (pulses/sec)
2	Current	3	8×10^6	36×10^6
0.2	Current	4	1.6×10^6	24×10^6
0.2	Voltage	5	2×10^5	24×10^6

the tube manufacturers recommend a maximum mean anode current of 2×10^{-4} A, which, under the above conditions, corresponds to a counting rate of 8×10^6 pulses/sec.

In addition to the rate limitation due to the high resistance of the divider chain, other factors contribute to gain instabilities. We list a few:

- Differential drift with temperature of the electrode voltage distribution. This factor can be diminished by the use of high stability resistors in the divider; it is also helpful to keep the current low. The use of Zener diodes should be considered with care, where high precision of amplitude is required, because of the temperature dependence they introduce.
- Recent, not yet published, measurements by one of us (P.D.) indicate that there are rate-dependent gain variations generated internally in the PM, even when electrode voltages are held ideally constant. Such variations can, under certain circumstances, amount to many per cent and can be remedied only by the manufacturer of PM tubes.
- The influence of the HV stability (and ripple) on the gain has been measured for a particular tube and divider chain combination considered in this report. The tube was an EMI type D 306B with a resistive divider at 2000 V and 0.2 mA. Booster voltages of 250 V, 200 V, and 150 V were applied to the last three stages. Under those conditions a variation of 0.1% (i.e. 2 V) of the HV changed the gain by 1%.

  The same variation, 2 V, of the sum of the booster voltages (at constant HV) also resulted in a gain change of 1%. Furthermore, if the last three stages had been stabilized by Zener diodes, a temperature change of 3°C would result in about the same gain variation. These figures may help in estimating the stability of the HV supplies needed for different types of work (logics, amplitude analogue, time-of-flight).

2.5 Practical examples

To test the realizability of the preceding design considerations, two prototypes of PM housings have been built and tested, representing two different ways of attaching the PM to the scintillator on the light guide. One is for use where the PM is glued onto the light guide (Figs. 7 and 8); the other is for use with detachable optical coupling and pressure spring (see Figs. 9, 10, and 11). The prototypes have been made from machined, not moulded, black plastic material and contain no magnetic shielding other than that needed against the

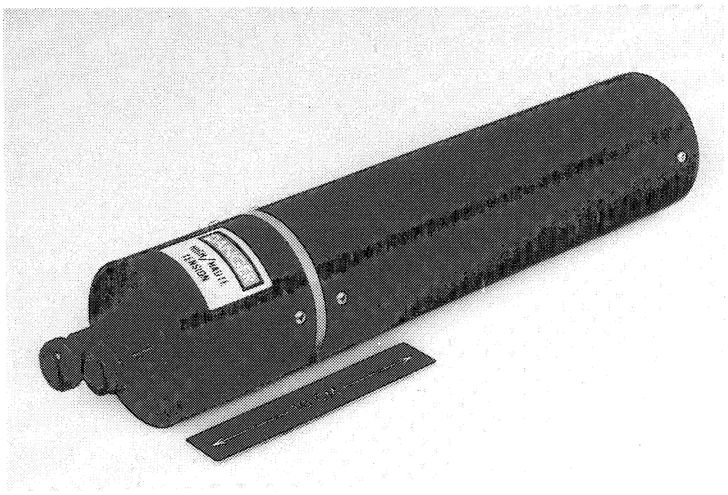


Fig. 7 PM housing corresponding to drawing in Fig. 1

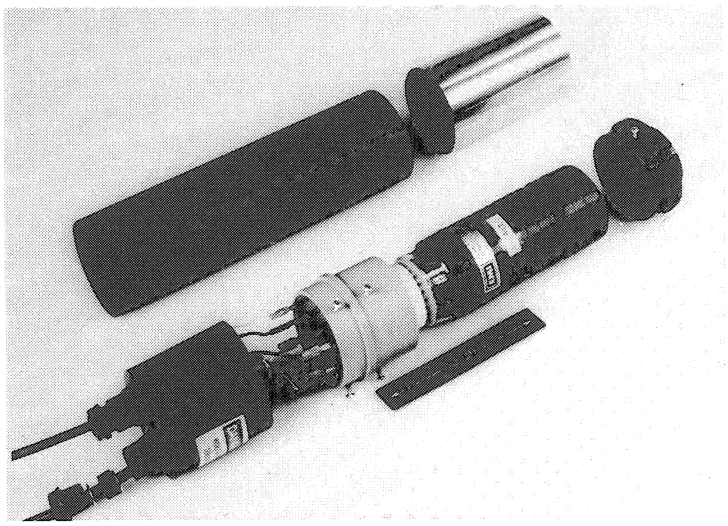


Fig. 8 Exploded view of the PM housing of Fig. 7

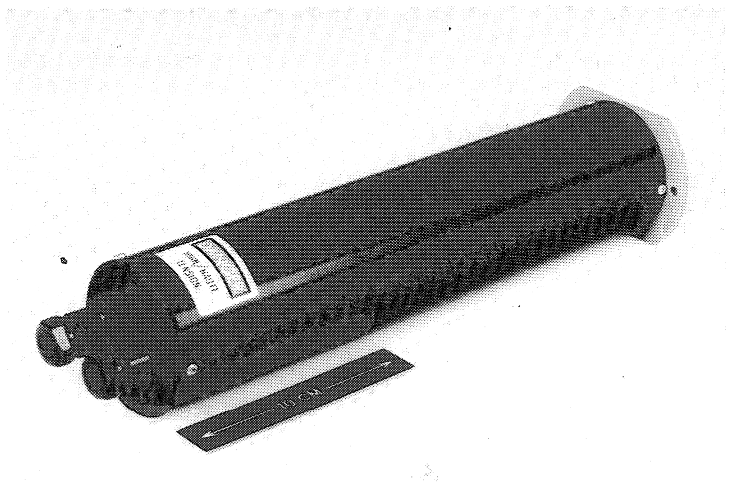


Fig. 9 PM housing corresponding to drawing in Fig. 2

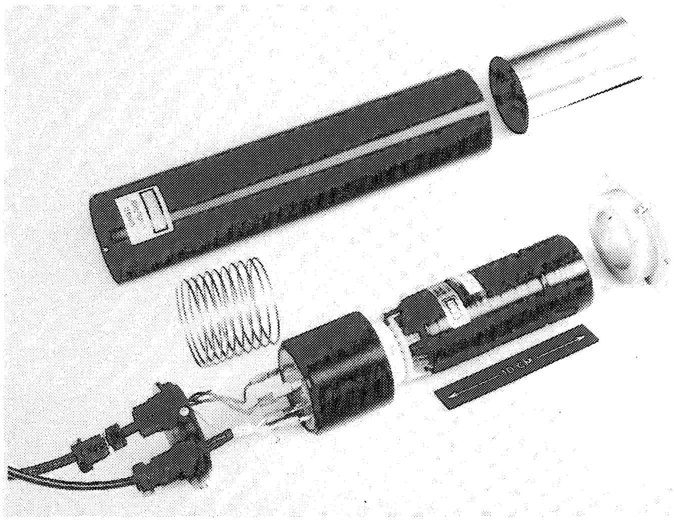


Fig. 10 Exploded view of the PM housing of Fig. 9

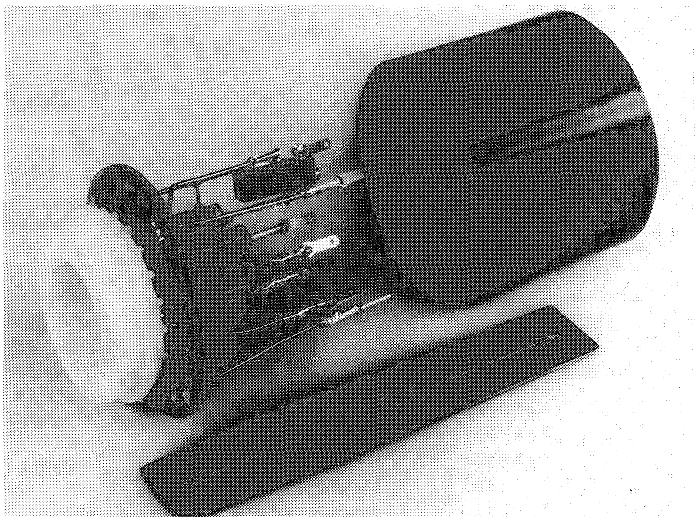


Fig. 11 PM socket and voltage divider

earth's magnetic field. All the 2 in. tubes mentioned in Table 1 can be accommodated, since they use the same socket and have the same pin layout. The voltage divider chains are imbedded in plastic and carry a current of 2 mA or 0.2 mA with the possibility of adding voltage booster supplies for the last three stages.

The price of a PM housing, complete with tube but without cables, could be estimated as follows, assuming that the quantity ordered is large enough to permit the minimum price to be attained:

PM tube	SF 200.-
Housing	SF 40.-
μ metal shield	SF 5.-
Total	SF 245.-

This price is about a third of the price of a housing + tube of traditional design and of only slightly higher performance.

2.6 Power requirements of a large system

The power requirements of the PMs are considered for a group of 1000 units.

2.6.1 HV supply

If it is assumed that the divider chain is designed to take 0.2 mA, one can use either one single supply delivering 200 mA at 2.5 kV (Fig. 12) or 63 supplies, each giving 3.2 mA at 2.5 kV (Fig. 13). This requires two commercially available multichannel HV units as described in the next section (each unit containing 32 individual supplies).

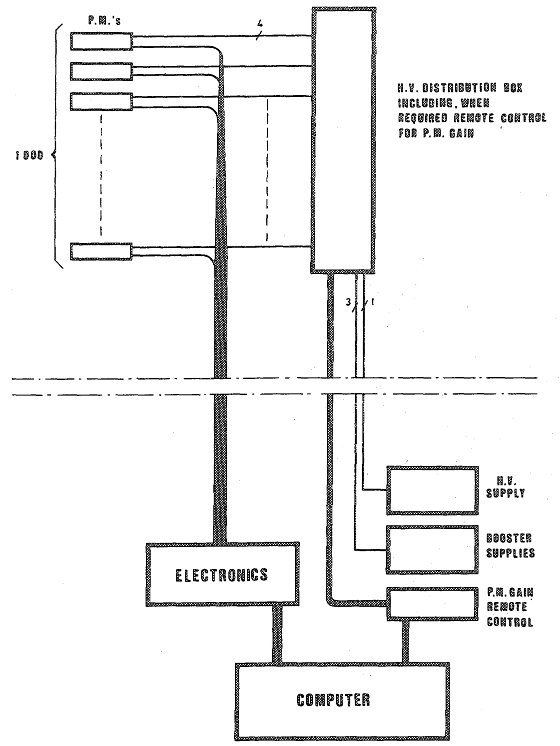


Fig. 12 High-voltage distribution scheme for a system of ∿ 10^3 PMs, when using a single HV, high-power supply

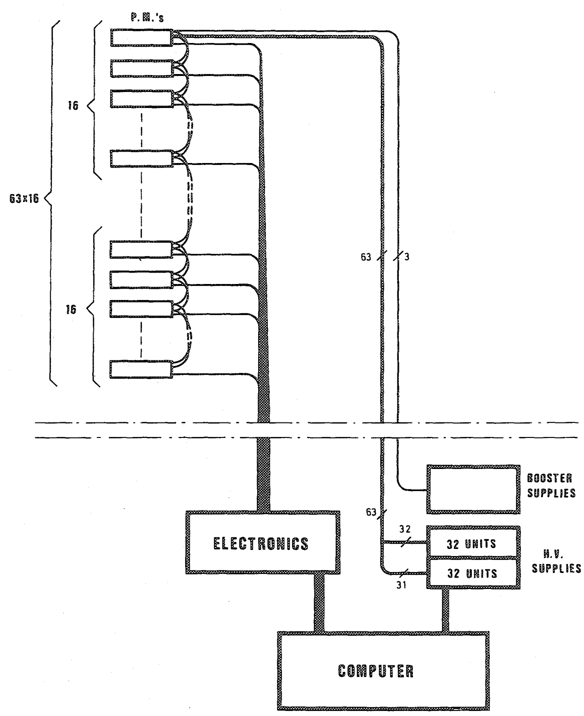


Fig. 13 High-voltage distribution scheme for a system of ∿ 10^3 PMs, when using 32-channel HV programmable supplies and PM grouping (e.g. 16 PMs per output)

2.6.2 Booster supplies

In calculating the power requirements for the voltage booster supplies, it is necessary to make an estimate of the counting rates and signal amplitudes likely to be encountered. We assume here a counting rate of 10^7 pulses/sec of an amplitude of 125 pC, corresponding to an average current between the last dynode and the anode of 1.25 mA. If we further assume that only 200 PMs in the group of 1000 carry a signal simultaneously, we arrive at a consumption of 250 mA. Since the gain per stage is about three, it follows that the two preceding stages require 85 mA and 30 mA, respectively. As can be seen, even quite modest power supplies are adequate for a large number of PM housings.

2.7 PM gain control

In most cases it is desirable to adjust the HV and, consequently, the gain of the individual PM. This can be done in different ways, according to the need for control and the type of HV supply and distribution used. Some possible schemes are mentioned below:

- A fixed resistor, selected to give the correct gain, in series with the HV supply to each PM, and either soldered into the circuit or placed in a holder, will provide a very low-cost control of the gain where neither high precision nor frequent readjustment is asked for.
- A more precise and convenient control is given by a variable resistor (potentiometer) in series with the HV. Apart from the obvious use of a screwdriver for adjusting, one could envisage the use of small d.c. motors (toy motors), temporarily attached to the potentiometer shafts for remote control of a group of PMs. Once the adjustment is finished, the motors could be removed and used elsewhere.
- The fixed or variable resistors of the two suggestions above could be mounted either in the PM housing or at a HV distribution panel. The latter choice is probably the better, where the PMs are mounted in more or less inaccessible positions.
- A much more sophisticated control could be exercised by a device consisting of a series of resistors, say eight, in binary progression and a short-circuiting transistor across each resistor. Remote control, either manual or by computer, is then easily applied (see Section 3.4).

3. HIGH-VOLTAGE SUPPLY SYSTEMS FOR PHOTOMULTIPLIERS

3.1 General

As pointed out in the previous section, the number and size of detectors in high-energy physics experiments is increasing along with the energy of the new accelerators and the complexity of events to be identified. This is putting tough requirements on the electronic equipment, which has to offer the best reliability and performance at a cost per channel that, for budget reasons, has to decrease inversely to the number of channels.

How to meet these requirements where the PM tubes and their housing are concerned has been discussed in the previous section. Here the problem of supplying, setting, and monitoring the high voltages required for efficient PM operation is considered. Some features not essential in smaller experiments, such as computer control, optimized layout and, obviously, low cost per channel, should also be taken into account. The matter is discussed in three steps:

i) Conventional systems

Some solutions adopted in past and present small- and medium-scale experiments are briefly reviewed to give the reader a familiar comparison term for cost and flexibility.

ii) Computer-controlled high-voltage supplies

Computer-controlled systems which are in the advanced development stage are described. They are shown to offer a good and reasonably priced solution in medium-scale experiments.

iii) Low-cost high-voltage systems

Solutions suitable for large-scale experiments are discussed, including new, not yet developed systems that could offer some of the computer-controlled features with substantial cost savings.

3.2 Conventional high-voltage systems

Of the large variety of devices used in practice, two basic configurations may be recognized, depending on whether high voltages or low voltages are distributed to the PM tubes.

3.2.1 Distributed high voltage

Several PMs (between ten and a few hundred) are powered by a single HV supply (or stack of such supplies). The adjustment of individual PM voltages is made by variable resistors in series to each PM, or by matrix selection of step voltages. A resistive voltage divider chain, often including some Zener diodes, is mounted in the PM housing to obtain the required dynode voltages. The whole PM voltage setting can be recorded via standard multiplexers and voltmeters, as shown schematically in Fig. 14.

This powering scheme offers good reliability and long-term stability of PM voltages. Manual adjustment and voltage read-out are possible at the expense of HV cable layout over large areas or distances.

The cost per channel varies according to the combination of instruments adopted. In the example of Fig. 14 one arrives, for instance, at the costs shown in Table 3.

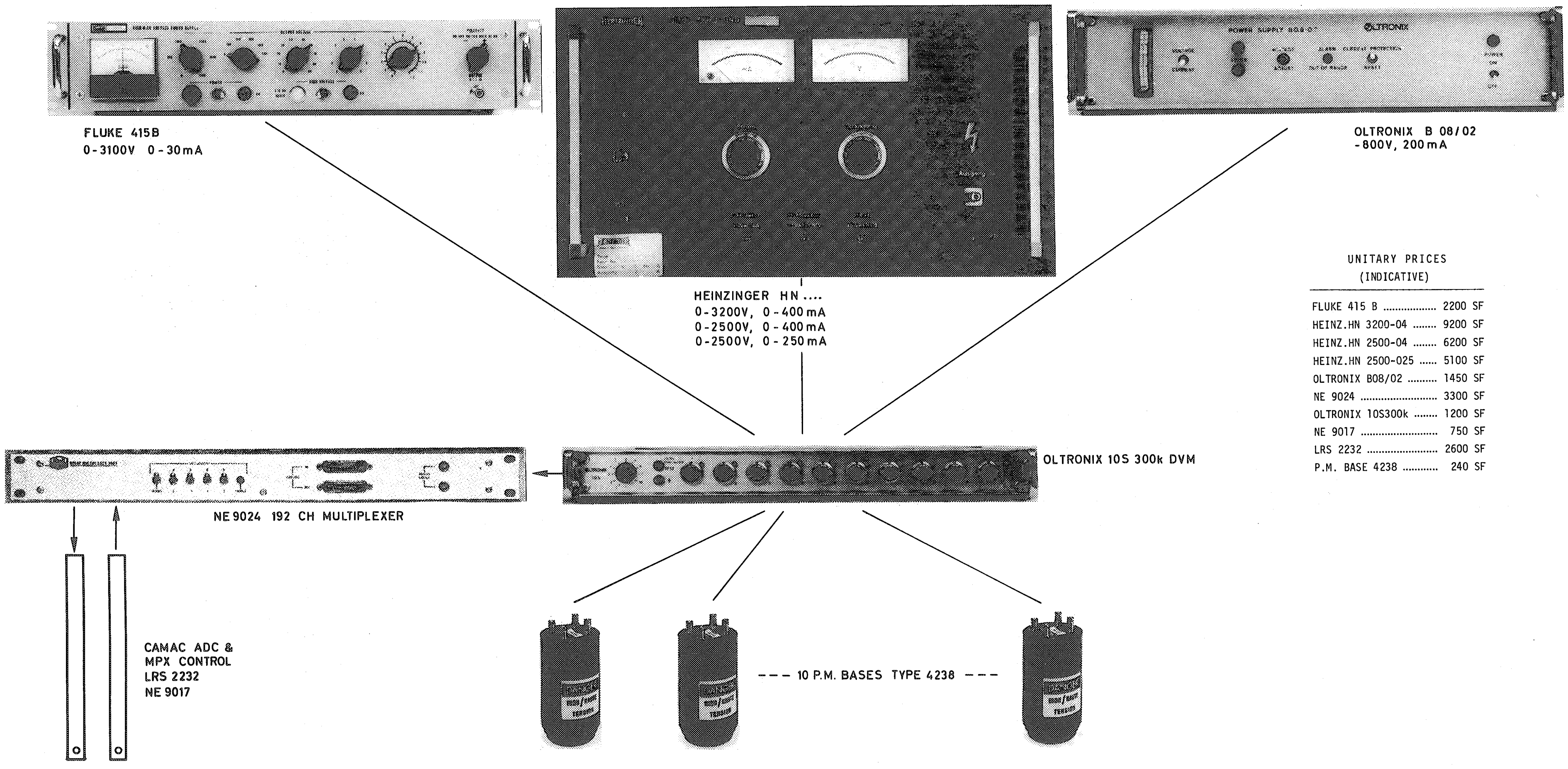
Table 3

Cost per channel of a distributed HV system

	SF
HV power supply (larger size → lower cost)	50-220
Dynode booster medium voltage supply	30
Series resistor unit (or equivalent)	100-150
Voltage-monitoring system	27
HV cable (80 m)	55
HV cable (dynode booster)	30
Total power supply cost per channel	292-512
PM base with voltage divider chain	240

3.2.2 Distributed low voltage

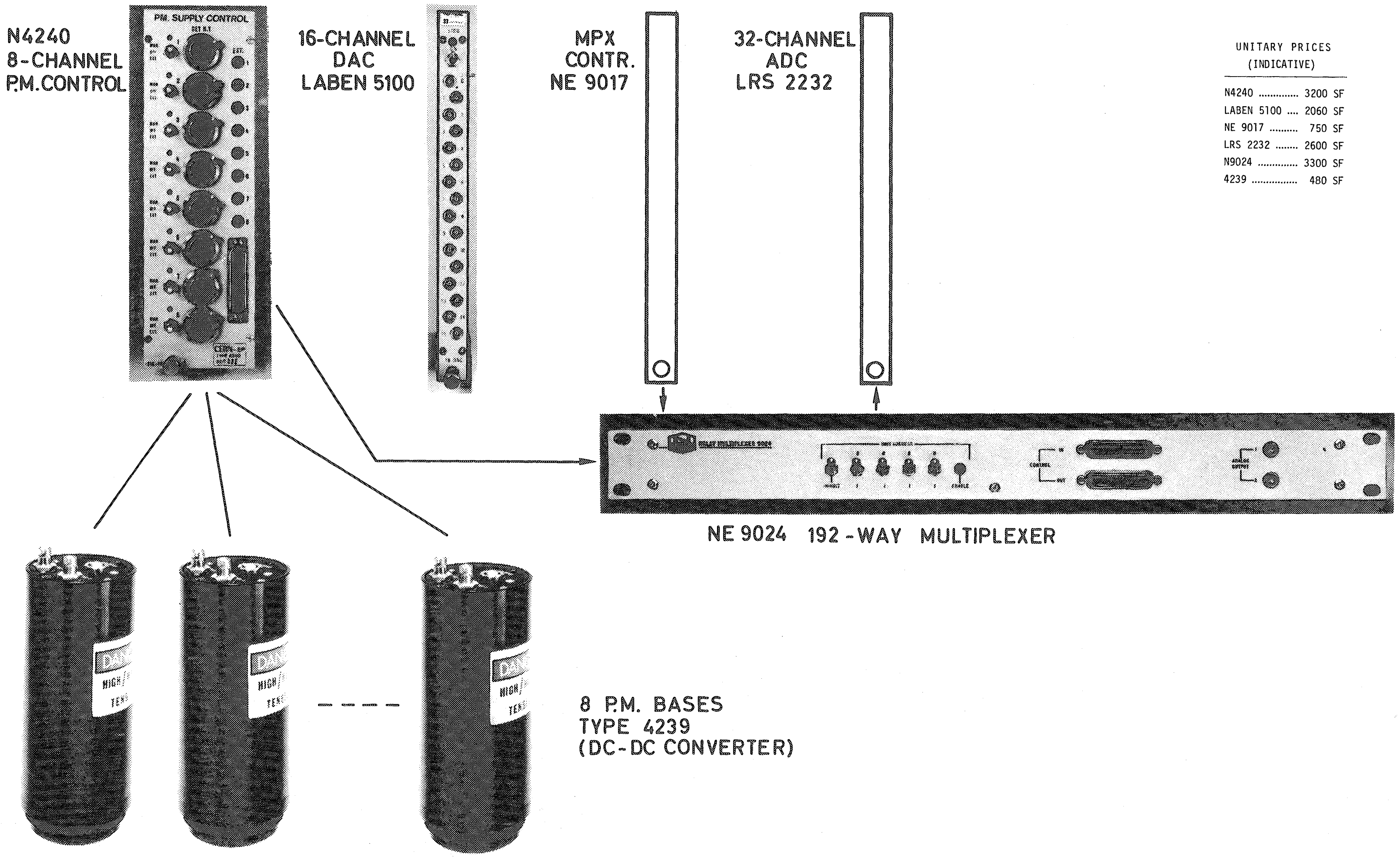
This powering scheme (Fig. 15) is based on the distribution of low-voltage power and control lines. A voltage-multiplying d.c.-d.c. converter is housed in each PM base to provide stabilized dynode voltages. In addition to read-out facility, this scheme allows for



UNITARY PRICES
(INDICATIVE)

FLUKE 415 B	2200 SF
HEINZ.HN 3200-04	9200 SF
HEINZ.HN 2500-04	6200 SF
HEINZ.HN 2500-025	5100 SF
OLTRONIX B08/02	1450 SF
NE 9024	3300 SF
OLTRONIX 10S300k	1200 SF
NE 9017	750 SF
LRS 2232	2600 SF
P.M. BASE 4238	240 SF

Fig. 14 Distributed HV system. Several PM bases are powered by each HV supply. The PM working voltages are adjusted by variable series resistors or matrix selection of step voltages (not shown). The counting rate capability provided by the resistor voltage divider chain can be improved by "booster" power supplies for the last few dynodes. The over-all voltage setting can be monitored by standard multiplexers and voltmeters.



UNITARY PRICES
(INDICATIVE)

N4240	3200 SF
LABEN 5100	2060 SF
NE 9017	750 SF
LRS 2232	2600 SF
N9024	3300 SF
4239	480 SF

Fig. 15 Distributed low-voltage system. A d.c.-d.c. converter housed in each PM base supplies all the necessary dynode voltages. Low-voltage power and control signals are distributed by multichannel control units. Computer control can be extended to HV setting by standard DACs.

computer setting of PM voltages by means of standard multichannel digital-to-analogue converters (DACs).

The cost per channel of the system in Fig. 15 is given in Table 4. Another control facility will be mentioned in Section 3.3.

Table 4

Cost per channel of a distributed low-voltage system

	SF
NIM control unit (including crate)	230
Voltage monitoring system	27
Computer setting via CAMAC multi-DAC	27
PM base with d.c.-d.c. converter	480
Total cost per channel	764

3.3 Computer-controlled high-voltage systems

3.3.1 *Philosophy*

The expanding use of large sets of PMs has favoured the development of new multichannel HV supplies by two major manufacturers.

The basic idea, and improvement, is to concentrate in a single instrument all the devices normally required for PM operation and mentioned in Section 3.2. This frees the user from the tedious task of selecting and putting into operation several non-homogeneous instruments, and offers better compactness and reliability at no price increase. Intelligent built-in control and some other features make the new units equally easy in operation in either local-manual, remote-manual, or computer-controlled mode.

The final advantage of these units is to rationalize the layout of HV connections, for instance by installing the HV supplies near the detectors rather than near the operator.

3.3.2 *Description of the system*

Since the systems announced hitherto are very similar in conception, they can be described as if they were the same system.

The main unit is a 19 in. rack-mounted instrument (Figs. 16 and 17) housing 16 dual HV cards, control circuitry and a low-voltage power supply. Each HV card provides two d.c.-d.c. converter blocks, giving a total of 32 independent, regulated HV outputs. Each output can supply up to 3.0 kV, 2.0 mA, and is short-circuit proof. The voltage setting of each channel is entered and stored in digital form; then, in a continuous internal cycle, digital data are taken out of the memory, converted into analogue voltages, and sent to the converter cards, where they are stored in analogue form during the cycle time.

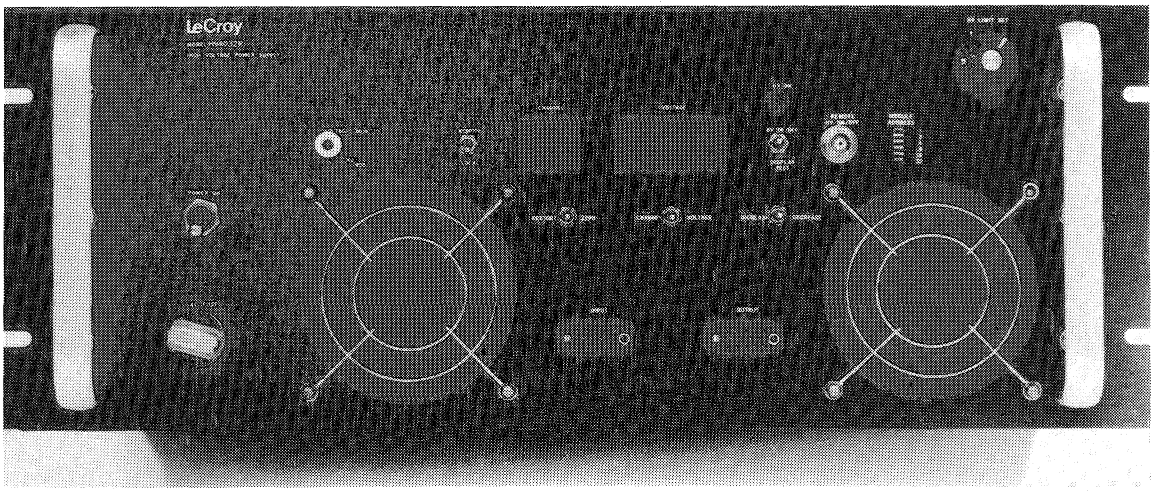


Fig. 16 LRS 4032 multichannel HV supply. 32 independent HV outputs of 0-3 kV, 2 mA each, are contained in a 19 in., 3 unit high cabinet. Exhaustive voltage setting and monitoring is provided by front-panel controls. Remote control of up to 32 units is based on a standard teletype bus.

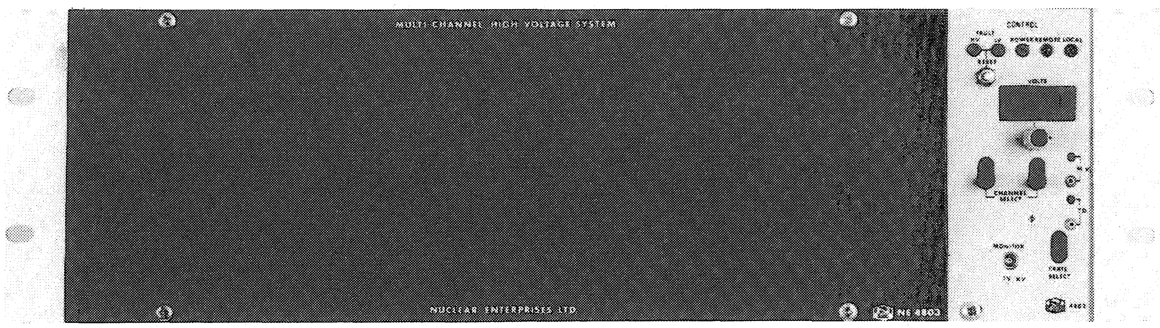


Fig. 17 NE 4550. Multichannel HV supply. Same performances as the instrument in Fig. 16.

The front panel of the instrument is equipped with the usual type of controls required for local operation and monitoring, namely:

- channel address selector and display (1 to 32),
- voltage monitoring output of the selected channel (1 V/kV),
- digital content display of the selected channel, plus increase/decrease switch,
- alarm signal for overloaded or faulty channels,
- maximum voltage limit (common to all channels),
- voltage take-down input (logic signal to decrease all output voltages by a preselected amount).

In addition to the manual control features, the unit is foreseen for remote dialogue, and can be quite simply connected to a teletype terminal and/or to a suitable CAMAC control module. Voltage setting, read-out and the reception of simple diagnostic messages are then feasible with little limitation on distance or number of controlled units.

3.3.3 Other applications

It is possible, and foreseen, to adapt the multichannel HV supply to multiwire proportional chamber or drift chamber operation, by increasing the output voltage capability at the expense of maximum load current.

A special version can be available to provide low-voltage power and control signals to 32 d.c.-d.c. converter PM bases type 4239 (Section 3.2.3).

3.3.4 Performance versus price

The cost per channel of the new systems is shown in Table 5 and compared with some of the traditional systems.

Table 5

Cost per channel of multichannel HV supplies, compared to cost of traditional systems

	SF
Computer-controlled HV supply (Figs. 16 and 17)	350
HV cable (30 m)	30
Dynode booster supply and cable (optional)	60
Total cost per channel without PM base	440
Distributed HV system, without PM base (Fig. 14 and Table 3)	292-512
PM base (with resistor-Zener voltage divider chain)	240
Distributed low-voltage system (Fig. 15 and Table 4), including d.c.-d.c. converter PM base	764

It appears that computer-controlled multichannel supplies offer additional features at no extra cost, although they do not offer a substantial price reduction, as required in very large experiments.

3.4 Low-cost high-voltage systems

It has been concluded in Section 2 that substantial cost reductions are offered by some new PM tubes and by suitable re-design of PM housings. The question to be answered here is whether the HV supply cost can be lowered correspondingly.

3.4.1 Solutions based on available equipment

As mentioned in Section 2, a simple and economical solution consists of choosing a low-current value ($\lesssim$ 0.2 mA) in the voltage divider resistor chain, and powering the largest possible number of PMs ($\sim 10^3$) from a single HV, high-power supply. The counting rate capability can be kept quite good by suitable booster supplies for the last few dynodes. The gain of each PM can be adjusted by a fixed resistor in series, or a small potentiometer associated with it. High-voltage wiring can be minimized by voltage distribution boxes installed near the detector. No voltage read-out system is foreseen, and voltage or gain adjustments depend on the accessibility of the experimental set-up.

A similar, but less crude, solution makes use of the current capability of the new, multichannel HV supplies to power groups of 10 to 16 PMs by each one of the 32 outputs of a unit. These PMs can be selected in groups of approximately equal gain, then gain-trimmed by series resistors or potentiometers as above. The HV setting and reading, the ON/OFF control, etc., cannot be independent within a group of PMs sharing the same HV output. Nevertheless, more control facilities than in the central HV supply system are provided.

The cost per channel of both solutions mentioned is estimated in Table 6, not including the wiring between the PMs and the HV supplies. As can be seen, these are really low-cost solutions, well matched to the most economic PMs and housings.

Table 6

Cost per channel of HV supply, by PM grouping, for a 1000-PM system

	SF	SF
HV, high-power supply (0-2500 V, 250 mA) (one for 1000 PMs)	5.10	
32-channel computer-controlled HV supply (1 channel/16 PMs)		22.00
Medium-voltage (booster) supplies (three for 1000 PMs)	5.20	5.20
HV supply, total cost per channel	10.30	27.20
PM tube and housing (from Section 2.5)	245.00	

3.4.2 *Need for improved solutions*

There can be experiments, or parts of an experiment, where the compromise solutions outlined above do not meet requirements like individual PM gain control, very high rate capability, etc. On the other hand, the solution offered by multichannel HV supplies, at one PM per output, is cost effective only up to some hundred channels. What would be needed is a solution where the features of programmable multichannel systems are obtained at substantially lower cost.

To discuss the feasibility of such a system, it is useful to analyse the factors and choices which contributed to the high price of the multichannel HV supplies described in Section 3.3. These are:

i) The lack of a simple, economical hardware standard to house and control the HV modules. This has forced the manufacturers to design a mechanical and electrical system for the occasion, ignoring the NIM or CAMAC facilities because of them being too expensive. The complexity of this task has clearly restrained the number of possible suppliers.

ii) The choice of a 19 in. self-contained instrument limits the number of channels (32) over which the cost of the low-voltage power supply, controller, and all other features, is distributed.

iii) The choice of the HV regulating device has been restricted to the d.c.-d.c. converter per channel scheme because of luxury requirements in terms of voltage and current ranges.

3.4.3 Guidelines for a low-cost programmable system

To arrive at the lowest possible cost, each of the factors affecting cost mentioned above has to be attacked separately. Hence the guidelines for a new system could be the following:

i) Use of a simplified hardware standard (like the modular card system proposed in Section 4). The design and development of such a standard should not be borne by the HV equipment manufacturers, nor intended for HV applications only.

ii) Centralize power supplies, controllers, and all other features not attached to individual HV outputs. The cost of these centralized features is then distributed over the maximum number of channels.

iii) Search for the simplest HV regulating schemes. Voltage-dropping devices, for instance, can offer attractive solutions if some limitations are accepted. These are:

- limited voltage span (0-500 V below the input HV magnitude);
- no possibility of switching off individual PMs;
- limited short-circuit protection (one or more replaceable components in a channel to act as fuses to interrupt a short-circuit path).

To illustrate these ideas, the diagrams of two simple voltage-dropping and -regulating circuits are given in Figs. 18 and 19. Both are derived from actually built devices and have a basic component cost not exceeding SF 30.- per channel.

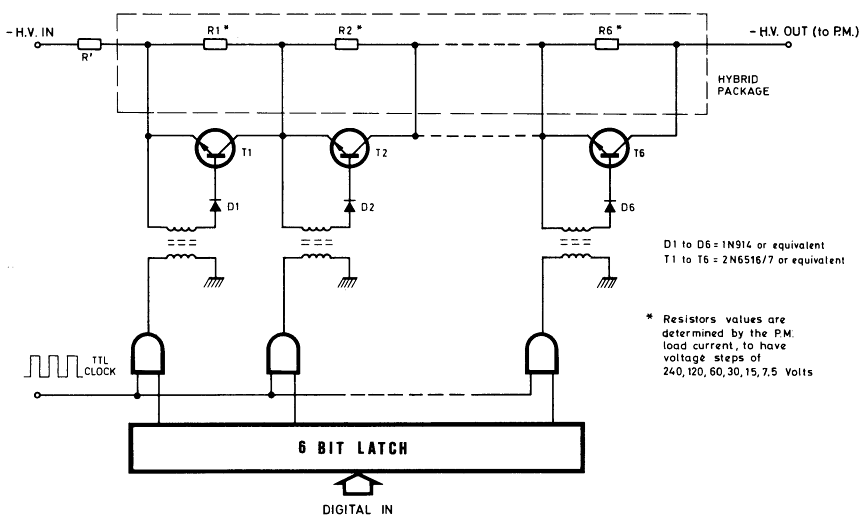


Fig. 18 Electronically controlled PM series resistor. Tight resistor tolerance is assured by hybrid execution. Individual resistors are taken out of the HV path when the parallel transistors are driven into saturation by a transformer-coupled a.c. signal. The voltage setting depends upon the load current, and is entered in digital form. (By courtesy of Pisa team.)

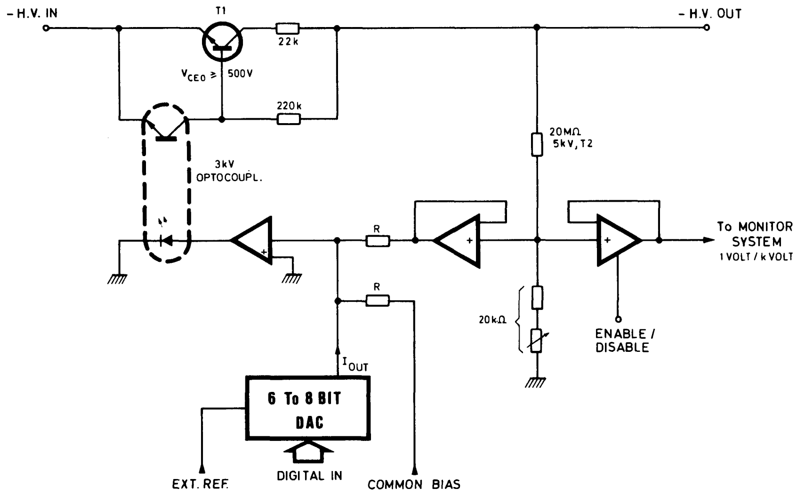


Fig. 19 Series voltage regulator. Digital voltage setting, converted into an analogue voltage, is used as a reference for stabilized HV output, the latter being independent of the load current. Low-voltage monitoring is built-in. (From J. Berbiers' design.)

By use of a judiciously selected and designed system, a final cost of some SF 100.- per HV output is not out of reach. An artist's view of this system is given in Fig. 20. Note that the circuit in Fig. 19 also allows the powering of groups of 16 or more PMs by each HV output.

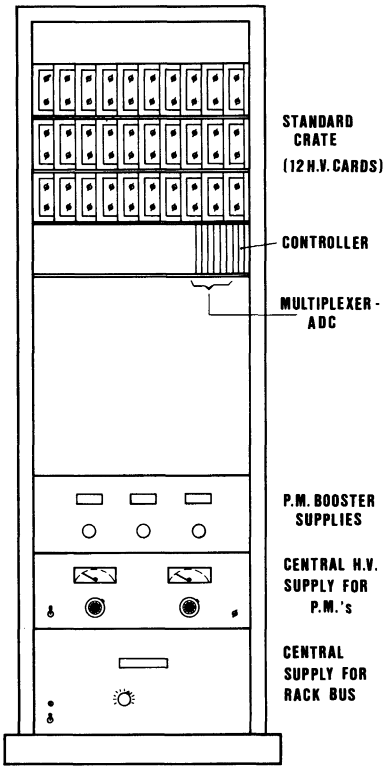


Fig. 20

Card-mounted HV supply system. The low-voltage power sources, the voltage-monitoring section and the digital controller are shared by a number of channels, which are not limited by the system structure. Adding or replacing HV channels is easy. The HV cards can be manufactured without control system know-how.

4. ELECTRONICS

4.1 General

The very large number of PMs or other signal sources -- several thousand -- required in certain experiments to be carried out in the near future will call for some very careful considerations of the associated electronics. In fact, cost will become a much more dominating factor than in the past. It is with this in mind that the following study of a low-cost electronics system has been carried out.

The possibility of simplifying an existing system, such as NIM or CAMAC, has not been retained. The reason for this is that if one wants to lower the cost by simplifying and still keep the compatibility with the system, not very much can be gained. If, on the other hand, the modifications are extensive enough to be worth while from the point of view of cost, so little of the original system will be left that one is better off by working out a completely new one.

Ideally, all the links of the signal-handling chain, from the PM and up to the computer interface should have their prices reduced in the same proportion. However, PMs, their housings and their HV supplies have until now not been the subject of very intensive cost-reducing efforts. One can, therefore, expect very good results, as seen in Sections 2 and 3. The situation is quite different for the electronics, which has for a long time benefited from industrial and commercial competition. Margins for price reductions are therefore much smaller and the means to obtain them will have to be more drastic.

In order to realize the sought-for economies it has been unavoidable to sacrifice such considerations as the user's convenience, a wide range of applications and, to a certain extent, mechanical ruggedness. In other words, the user is asked to put up with such inconveniences as mechanically flimsy but electrically adequate cable connectors, modules that ask for great care in handling when out of the crate, no front panels on which to stick labels, etc. It is thought that this could be acceptable in a maximum economy system which, once set up, would remain essentially untouched for long periods.

The electronics system proposed here is intended for use in:

a) decision-making electronics (fast logic),

b) data handling, including wire chambers,

c) HV supply systems.

The system is derived, where mechanics is concerned, from an industrial (DIN specified) card system: the Eurocard. This is manufactured by many firms in Europe and is used extensively by industry, which guarantees the easy availability of the components. It is flexible enough to allow good adaptation to our needs.

The following pages describe the proposed system, which comprises (see Fig. 21):

a) self-supported circuit-card modules,

b) crate with card holders, dataway and power distribution,

c) twisted-pair cables and connectors for fast module interconnections and system input/output,

d) forced cooling units,

e) central power supply and vertical (rack) power distribution bus.

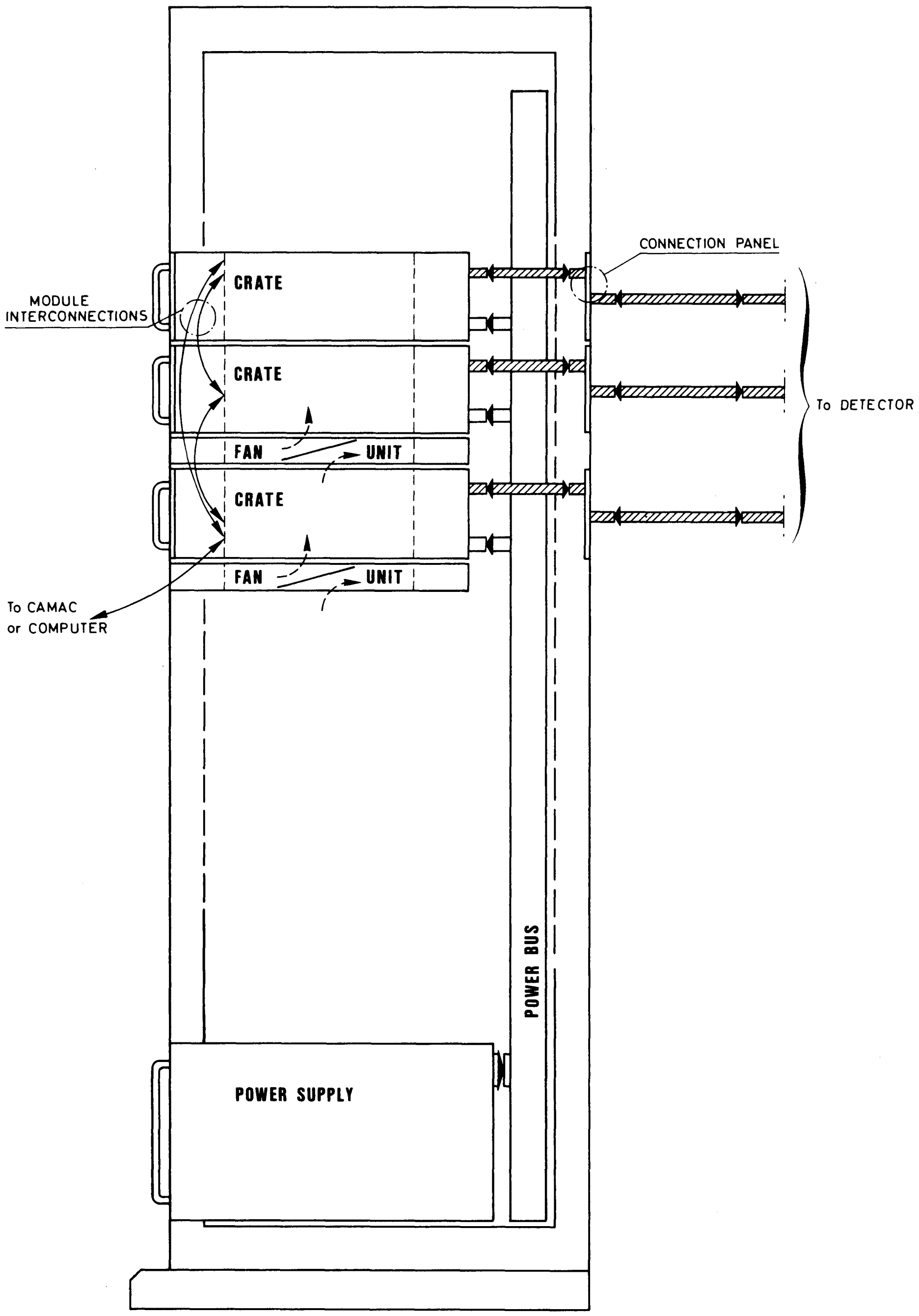


Fig. 21 Rack with crates; ventilation and central power supply

4.2 Crate and card mechanics (see Figs. 22 and 23)

4.2.1 Modules (see Fig. 24)

The modules consist of simple, self-supporting circuit cards with an integral edge-connector. Circuit components that must be accessible from the front (cable connectors, switches, signal lamps, etc.) can be mounted directly on the card if there is no front panel.

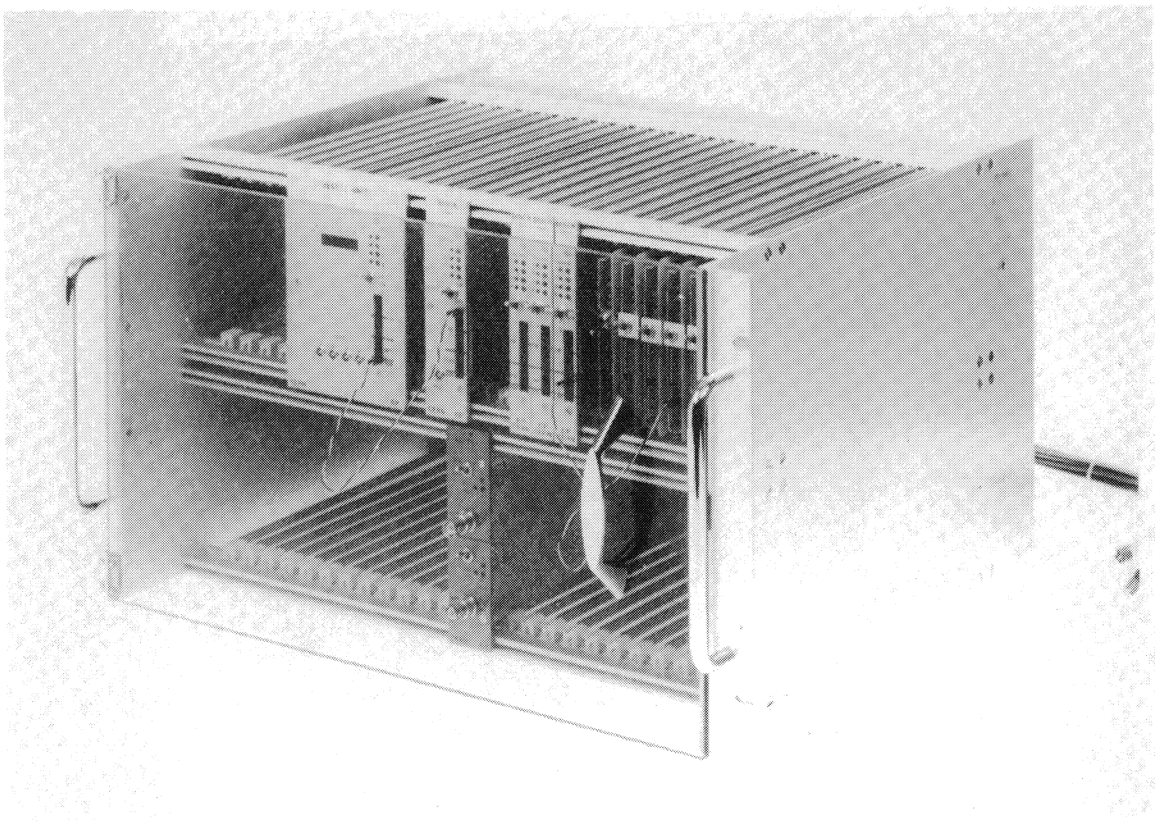


Fig. 22 Front view of a double-row version of the electronics crate. Behind the transparent door can be seen some different types of plug-in modules and twisted-pair interconnection cables.

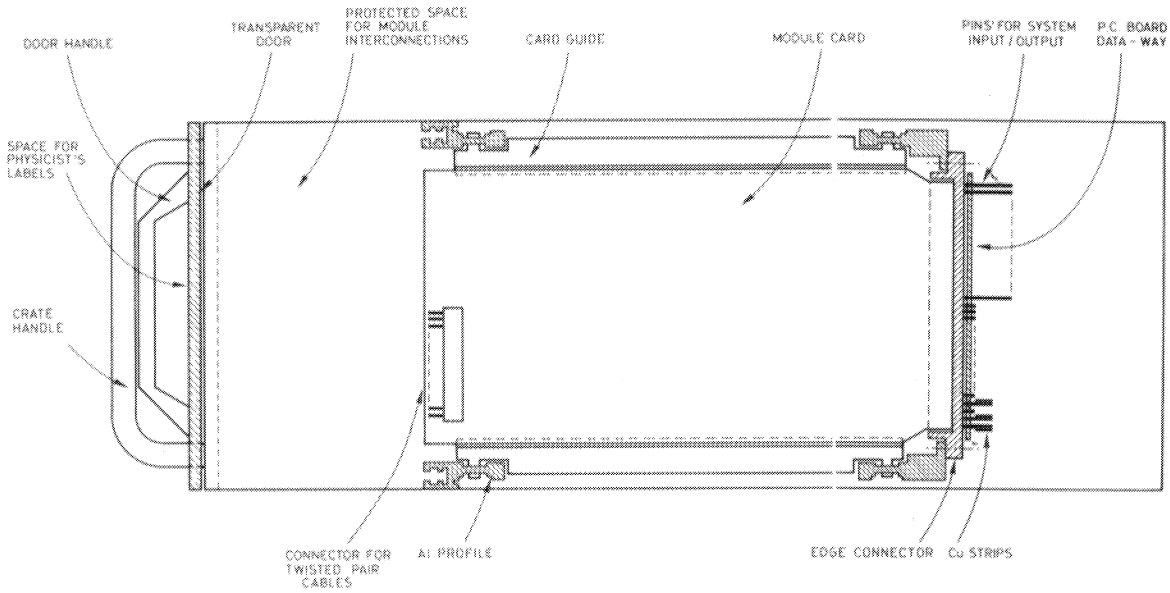


Fig. 23 Crate with module

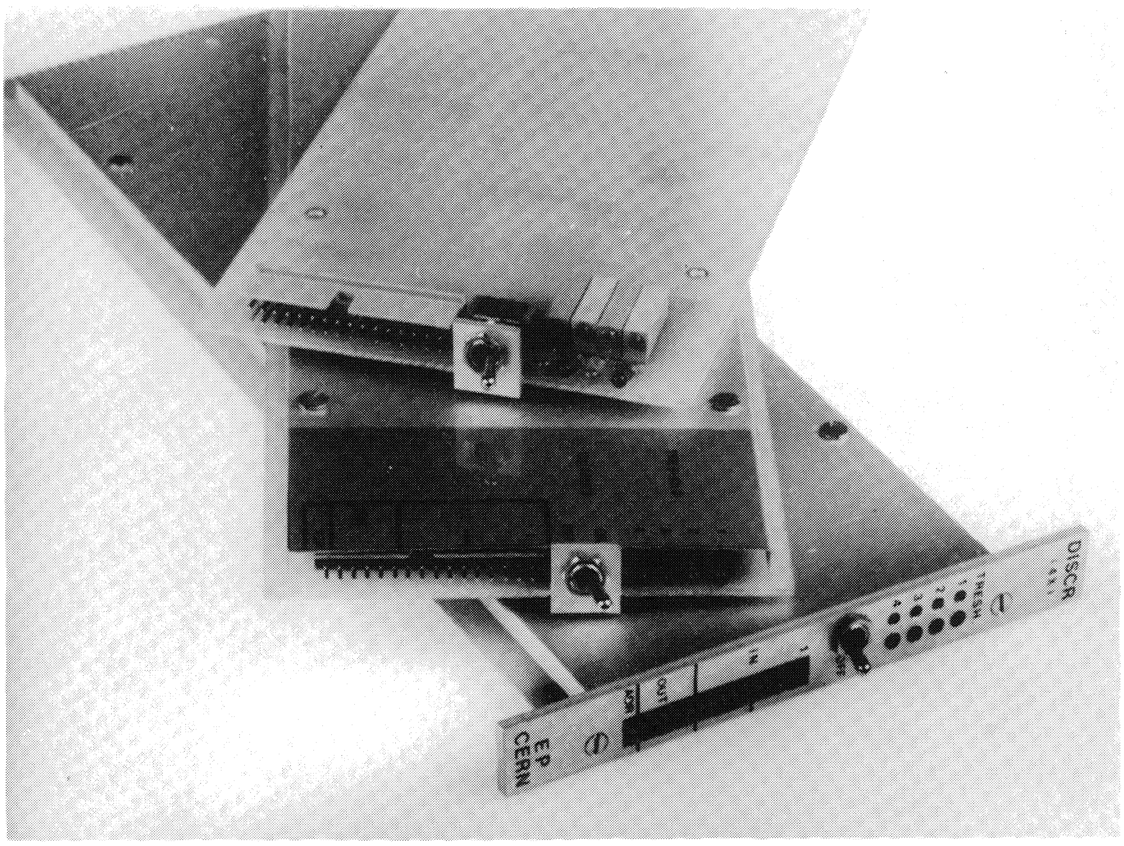


Fig. 24 Front ends of modules, showing connector pins for fast interconnections with twisted-pair cables and various possibilities for mounting components and labels

4.2.1.1 Printed circuit board

The card height is 100 mm, conforming to the Eurocard standard. The card depth has, somewhat arbitrarily, been set at 280 mm, in order to allow the optimum use of the available rack volume. Although this is a deviation from the mechanical standard, the cost penalty is small, since the only non-standard parts are the crate side panels, and these will have to be made to order also for other reasons [space in front of the cards, see Section 4.2.2, point (ii)].

If the front edge height of 100 mm is not considered sufficient for mounting the needed components, the next standard height, 144.5 mm, should be chosen. It is, of course, not possible to mix the two, so one or the other must be decided on.

The possibility of having cards of double height (200 mm or 289 mm) exists (see Fig. 25). Special crates would have to be used, but they would be made of the same basic components as the standard crates, except for the side panels.

The rear edge-connector is of the direct type (see Fig. 25), i.e. the contacts are printed directly on the circuit board. It has 2 × 35 contacts with a pitch of 2.54 mm (= 0.1 in.). It fits in a standard card edge-connector, available from several manufacturers and is chosen as a compromise between a sufficient number of contacts for the foreseeable needs and a reasonable insertion/extraction force.

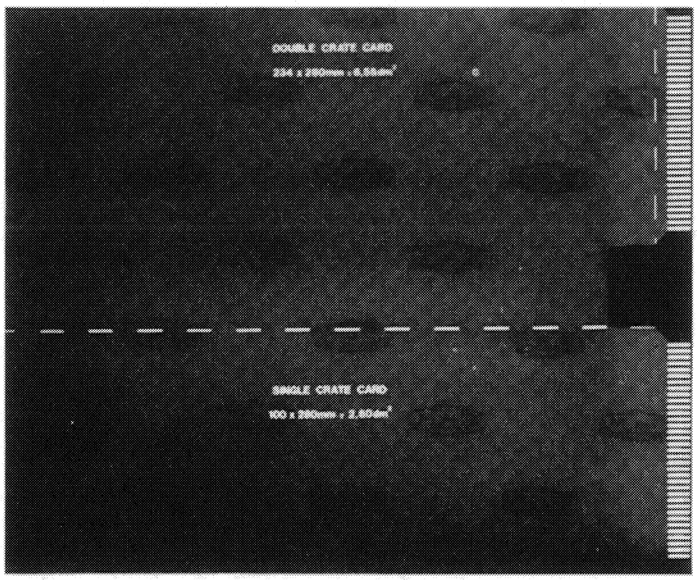


Fig. 25 Some possible dimensions for module cards

The lower part of the rear edge-connector is used for a printed board dataway and power distribution. The remaining pins are left free for use as system input/output (see Section 4.4.1).

4.2.1.2 Front panel and component shielding

The front edge of the cards holds such components as must be accessible to the user, in particular the connectors for the module interconnections. They should normally be mounted directly on the card or, if needed, on mounting brackets or a front panel.

A front panel is not normally required. It is possible to fit one if considered necessary for providing space for labels or indications, or for electrical screening and/or protection.

The same is true for side panels. Where needed for protection and screening they can easily be fitted, but since they are not used for guiding or holding the module in the crate, they are not obligatory.

Modules can be one unit (= 15.24 mm) or several units wide.

The mechanical stresses on the cards are low enough to make a locking device unnecessary, the rear edge-connector providing enough friction. However, a small handle may be needed for easy extraction of the module.

4.2.2 Mechanical layout of the crate

The crate contains one row of cards, joined by a dataway with power distribution, but no power supply. Industrial standard card guides and aluminium profiles are used for holding up to 26 module cards per row (see Fig. 22). The separation between cards is 15.24 mm (= 0.6 in.).

In order to protect the relatively delicate twisted-pair cables used for module interconnections (see Fig. 22), the cards are mounted so that their front edges fall about 8 cm behind the crate front. The space that then becomes available for cables can, if desired, be further protected by a transparent door.

The crates have neither top nor bottom covering plates. The reason for this is twofold (see Fig. 21):

- to provide a path for crate interconnections,
- to allow the easy flow of air for forced-air cooling.

The rear edge-connectors should normally not need any special protection, since they are well recessed from the crate rear (see Fig. 23). However, in the case where the crate is used for housing a HV supply system, a protection panel, covering the whole crate rear, can be installed. This panel can also be used for mounting the HV input/output connectors (see Fig. 26).

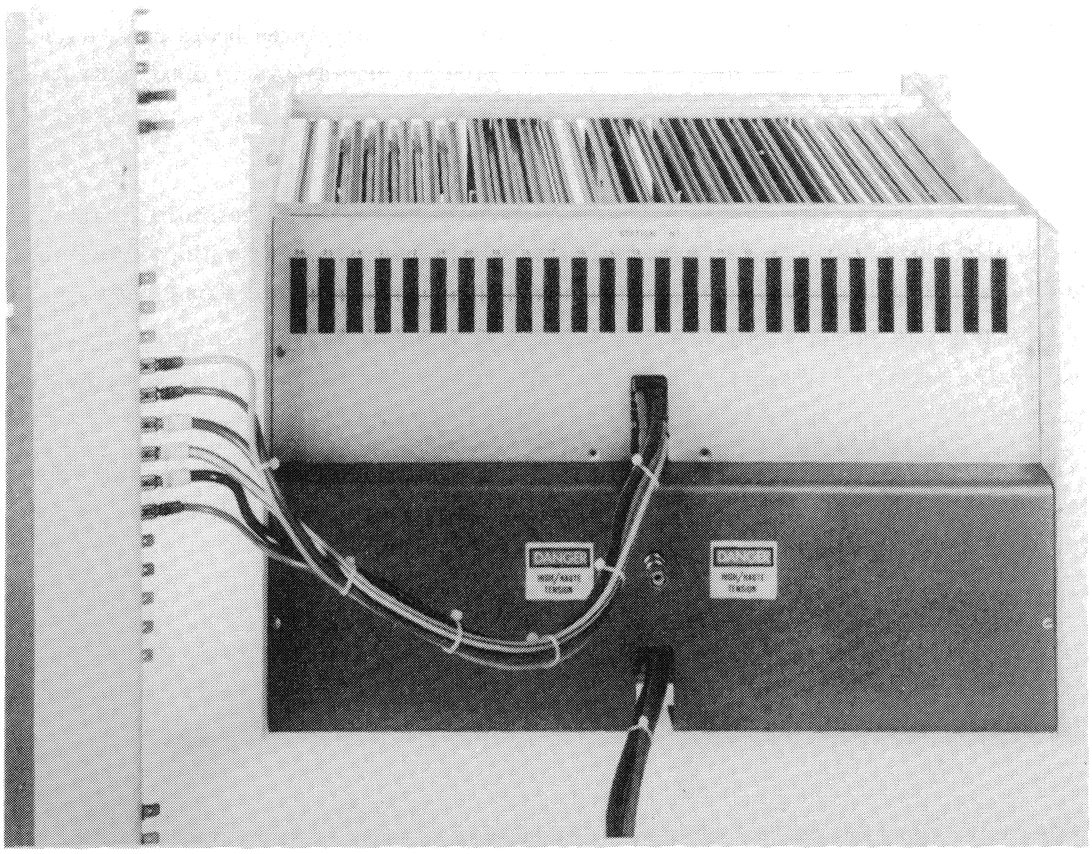


Fig. 26 Rear view of the crate in Fig. 22. Upper part shows connectors for system input/output. Below can be seen a protection panel for HV applications. The Fast-on connectors to the left are for power from the rack-bus.

4.3 Power and cooling

4.3.1 Power supply requirements

The crates are powered from a central power supply, common to the whole rack. A vertical rack bus (see Fig. 21) distributes the power to the horizontal bus in each crate. The number of voltages distributed is, for economy reasons, limited to four: ±5.2 V (for TTL and ECL) and ±15 V (for MOS and analogue circuits). The possibility of distributing a special purpose voltage exists.

The maximum power dissipation in a crate is estimated to be 250 W, corresponding to an average dissipation of 10 W per card, a value which is very unlikely to be exceeded even on a very dense card. The edge-connector does not constitute a limitation of the available power, since the maximum allowed current in one pair of contacts is 6 A, corresponding to 30 W at 5 V.

The six crate buses have the following assignments:

+5.2 V,
-5.2 V,
+15 V,
-15 V,
ground
spare (clean ground or non-standard voltage).

4.3.2 Power distribution

The connections between the crate buses and the rack bus can preferably be made with "Fast-on" connectors, which are easily available and combine a low price with good reliability (see Figs. 26 and 29).

The crate buses consist of 1 × 6 mm copper strips. All buses are soldered to two card contacts (one for each side of the card) for better contact and easier mounting (see Fig. 27).

The bus dimensions are such that when all cards have a maximum allowed dissipation (10 W), the total voltage drop on the supply bus and the ground bus is less than 50 mV.

The stability and ripple specifications of the power supply should be adapted to each particular case (logic, analogue, etc.), keeping in mind that over-specification can be expensive.

The power supply must have an overload cut-out, preferably with an adjustable trip level. This will provide the necessary protection for the power supply itself, but not for the electronics on the cards, since it is impossible to adjust the trip level with enough accuracy to react to a local fault on a card. Each module must therefore have its own fuse for each voltage used. The fuse can eventually take the form of a resistor of suitable value and size.

As a further means of protection, it is recommended to insert a voltage status module at some convenient place in a crate. Such a module will give an alarm when any supply voltage is outside the tolerances, or temperature becomes too high.

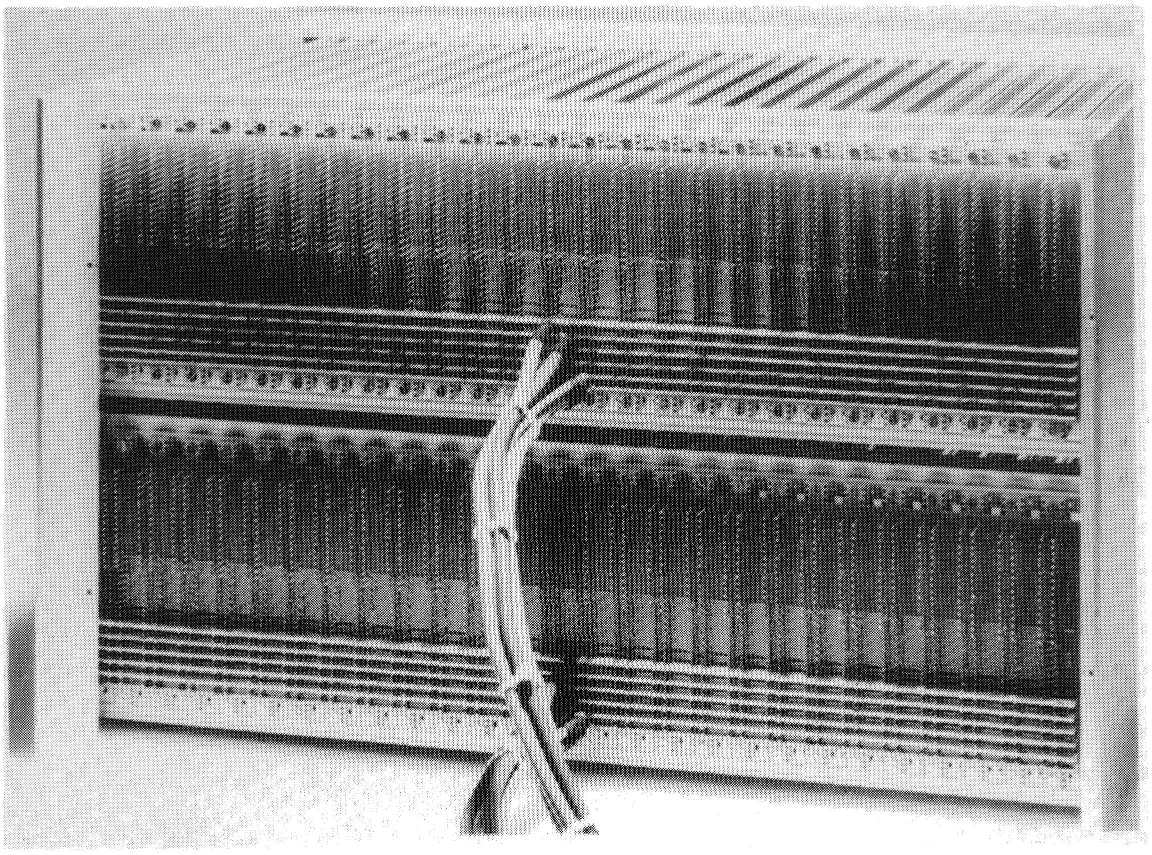


Fig. 27 Two rows of dataway with free pins for input/output, data handling lines and power buses soldered to the pins

4.3.3 Crate cooling

The crates will, in many cases, have to have forced cooling. For this purpose, separate fan units can be mounted adjacent to the crates, providing a vertical air flow with an air intake at the front and the exhaust to the rear (see Fig. 21). The crates are open at top and bottom to permit the air to flow freely. Depending on the dissipation involved, one or several crates can be serviced by one fan unit.

4.4 Inputs and outputs of the system

The inputs and outputs of the system are the connections with devices outside the system described here, for example, PM, MWPC, NIM and CAMAC modules, etc.

The input and output connections can be located either at the front of the module or at its rear, via the free pins on the edge-connector (see Fig. 28). The latter alternative is preferred, since it keeps cables that seldom need to be handled out of the way and simplifies the signal flow on the circuit card.

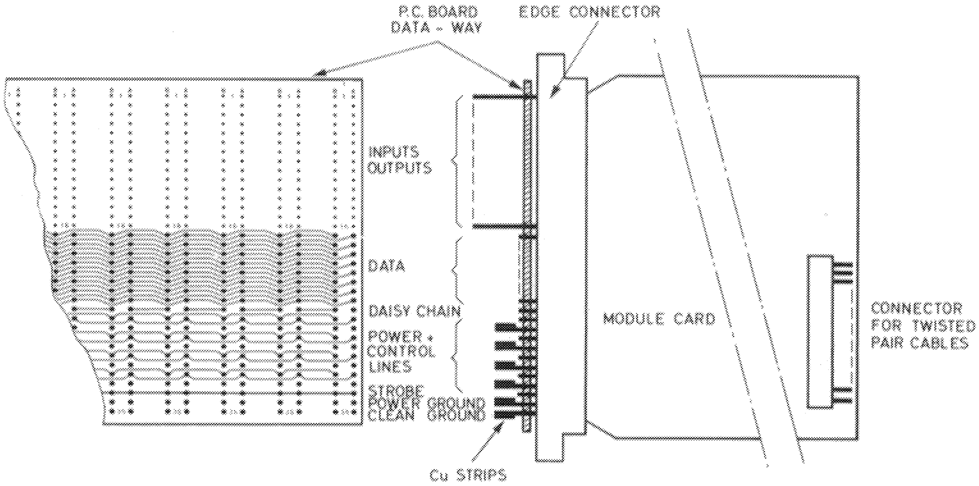


Fig. 28 Rear-edge connector and P.C. board dataway with power distribution

4.4.1 Input/output connector panel

Cables from external devices, such as PM, etc., arrive at a connector panel mounted at the rear of the rack (not the crate -- see Fig. 21). The type of connector used on this panel is left to the user's discretion and depends on the type of cable used: twisted-pair or coaxial. Where coaxial cables are used, considerable economies are possible by avoiding coaxial connectors and replacing them with either "Fast-on" (see Fig. 29) or screw connections. The losses due to mismatch in the connector would in most cases be negligible.

Connections from the connector panel to the modules are made with twisted-pair cables. The cables are connected to the rear edge-connector with twisted-pair connectors fitting on

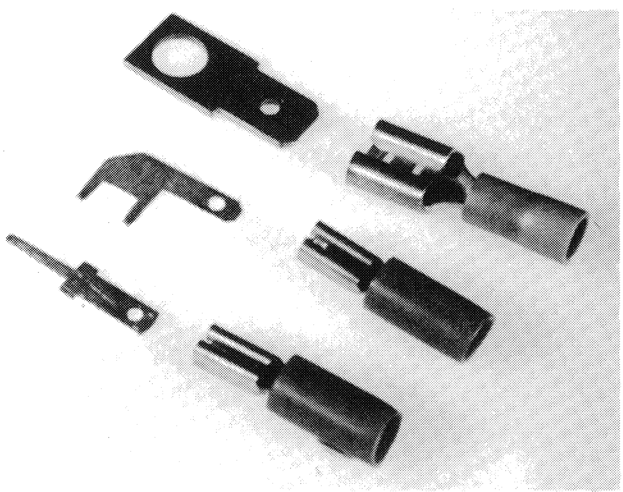


Fig. 29 Fast-on connectors of various dimensions

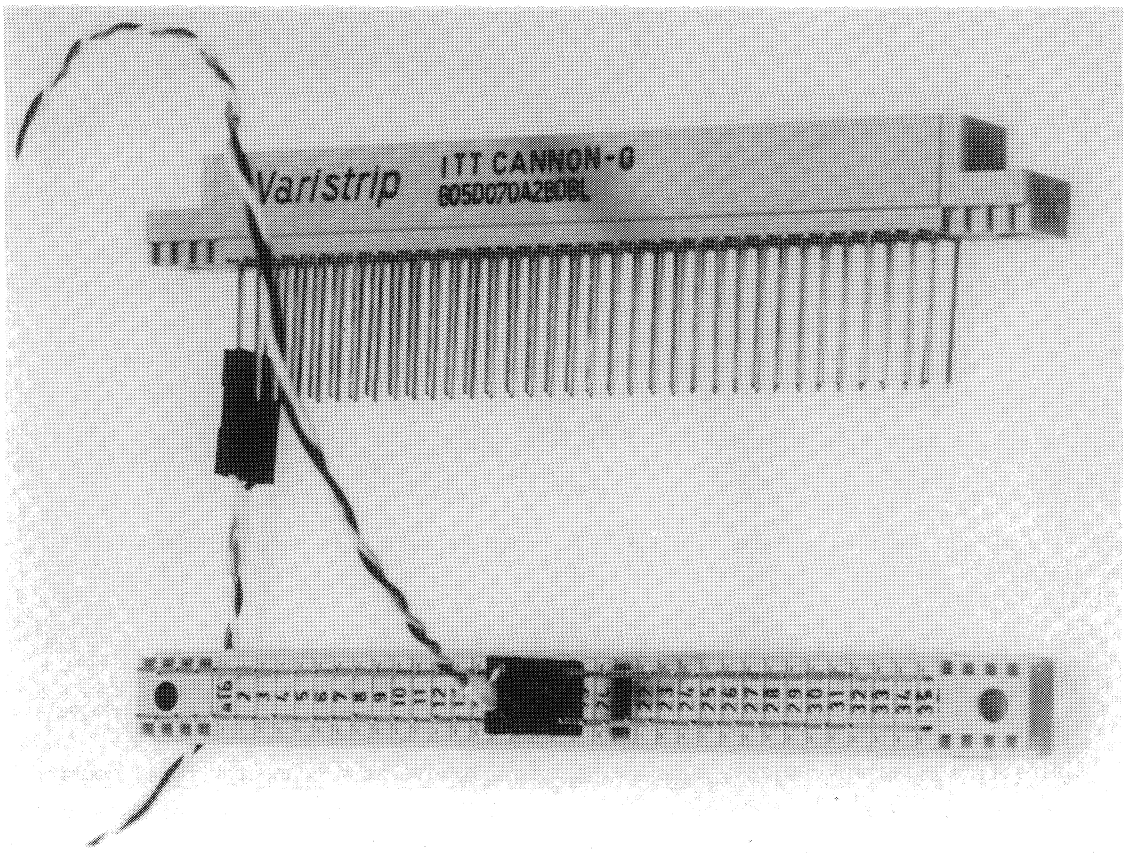


Fig. 30 Rear-edge card connector and twisted-pair cable

the miniwire-wrap pins (see Fig. 30). Such twisted-pair connectors are obtainable either for a single pair or several pairs grouped together.

Outputs to other systems or devices (NIM, CAMAC, computer interface, etc.) can be located either at the rear, via the connector panel (Section 4.4.1), or at the front. In the latter case, suitable connectors (e.g. LEMO, BNC) are mounted on the module card directly.

4.4.2 *High-voltage outputs*

When the crate is used for housing a HV supply system, a protection panel is installed at the rear, covering all the rear edge-connectors (see Fig. 26). This panel can also be used for holding the HV connectors, unless it is preferred to locate them at the front of the modules. Front panels must be mounted on HV modules for protection.

4.5 Fast signal interconnections

A substantial cost reduction can be achieved by replacing the LEMO or BNC type cables now used with twisted-pair cables and corresponding connectors.

4.5.1 *Cable*

The electrical quality of twisted-pair cables is essentially as good as the thin coaxial cables now in use for short distances, although the impedance is higher -- about 110 Ω.

The disadvantage of the twisted-pair cables is their mechanical fragility. However, since the fragility is immediately visible to the user, it will hopefully inspire him to take proper care. Furthermore, once installed, the cables are protected by the transparent door covering the crate front (Section 4.2.2).

4.5.2 *Connector*

The twisted-pair connector consists of two pin receptacles in a plastic housing (see Fig. 31). Such connectors are made by several firms, but there might be incompatibility problems between them.

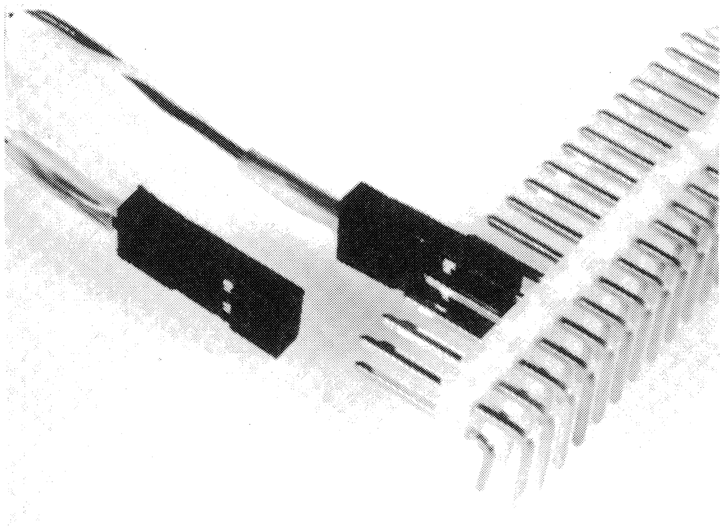


Fig. 31 Twisted-pair connectors for card front-end

The twisted-pair connector is symmetrical, but the polarization is indicated by the colour of the wires.

The connector at the module front end consists of two rows of pins, compatible with the cable connector mentioned above. The distance between the rows and between the pins is 2.54 mm (= 0.1 in.) (see Figs. 24 and 31).

The number of pins (pin pairs), as well as the pin assignation, depends on the needs of each particular module.

4.5.3 *Logic type and signal levels*

Logic signal levels at the module front edges are to be compatible with ECL 10,000 series integrated circuits. This standard is different from NIM or CAMAC signal standards, but the transformation is relatively simple. NIM levels should not, however, be introduced, except where really needed.

The two pins of an output pair are driven with balanced signals, i.e. one pin carries a normal signal, the other a complementary one. This will ensure the best noise immunity and also permit the easy realization of the complementary function by turning the cable connector by 180°. A convention for polarity indication will have to be agreed on.

Inputs to modules may be balanced (e.g. line receivers) or simple (most logic blocks). In all cases both the connector pins are used in order to have a proper impedance matching. The use of simple inputs will give some worsening of the noise immunity.

4.5.4 Terminations

For fast logic applications it is necessary to match the cable impedance, which is about 110 Ω. This can be done in different ways. The two most suitable arrangements are shown in Fig. 32. They cannot be mixed; one or the other will have to be chosen. The series termination (Fig. 32a) has the slight advantage of providing some protection (by the series resistors) of the output integrated circuit.

The parallel termination (Fig. 32b) makes it possible to mount the output pull-down resistors (R_e) in the receiving module, thereby eliminating the power consumption in unused output stages. The bias current of an output stage in either termination arrangement is of the order of 2 × 10 mA.

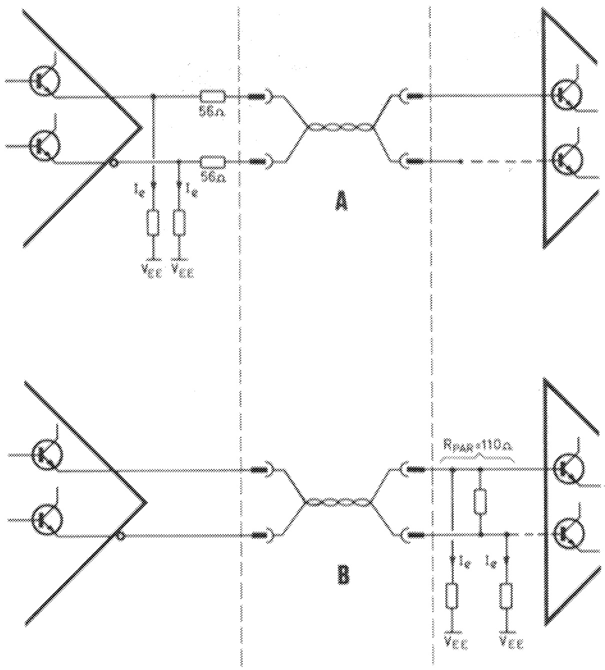


Fig. 32 Twisted-pair cable termination
A: series termination,
B: parallel termination.

4.6 Data transfer

4.6.1 The dataway

The dataway consists of a printed board, soldered to the rear edge-connectors (see Fig. 28). Apart from the power lines (Section 4.3.2) and the 16 pairs of free pins for the inputs and outputs of the system (Section 4.2), it has the following distribution:

8 control lines,
16 data lines,
1 daisy chain .

The daisy chain can be used for serial addressing and/or data transfer, or for block transfer addressing. The number of dataway lines has been chosen to be as small as possible, compatible with the requirements for a simple, but practical, data-handling system.

In addition to the lines mentioned above, one pair of pins at the module front should be considered as being part of the data-handling logic. It is intended for a twisted-pair hardware address wire, installed where required.

4.6.2 Signal levels

Signal levels or control logic on the dataway are not defined; TTL, MOS or ECL are all possible. The layout of the dataway printed board permits relatively high speeds when ECL logic is used. It is very likely to achieve Read or Write cycle times below 100 nsec, even with complex ECL electronics such as decoders, multiplexers, priority encoders, etc.

4.6.3 Controller

Since all stations in a crate are identical, the crate controller or interface can be placed in any location. Furthermore, the use of individual, user-connected address wires makes the layout of the system independent of the physical position of each module. In this way one physical controller may be used to act on any number of physical crates (within one rack), to form one "logical crate".

An important condition is, though, that all single dataways (each crate) concerned have to be coupled together in a suitable way (if there is one-way or two-way communication), either in the form of

a) a unibus chain, or

b) a vertical data highway.

In case (a), the same type of dataway signals must be used, whereas in case (b) one could think of mixing any logic level in each crate (Section 4.6.2) onto the common data highway. In this case each crate (or group of crates) has to have its own dataway interface.

4.7 Cost considerations

The cost of any electronic system can be evaluated only when the system features are exactly specified. However, in a modular standard, the cost of a station, or "slot", is determined by the mechanical and electrical hardware of the crate (including the power supply), and must be paid for by the user independently of what type of device is built into each module.

The sales prices of NIM and CAMAC main parts are nowadays well known, whilst for the card system described above only the prices of some bits and pieces can be quoted. However, a comparison of the slot costs is necessary to show that the target of finding a low-cost extension of the available standards has not been missed.

The comparison is given in Table 7, in the following way: for each of the three systems, the true material cost, from which the manufacturer will calculate his sales price by applying a suitable multiplication factor (usually between 2.2 and 2.5) is indicated.

Table 7

Hardware cost per station in NIM, CAMAC and proposed standard

Item \ Station	NIM 1/12	CAMAC 1/25	New 1/26	Unit
Available surface on printed-circuit board	3.6	5.2	2.8	dm^2
Average power dissipation	10	12	6	W
Module mechanics	29	15.50	-	SF
Front-panel finish	10	10	8 a)	SF
16 fast logic connections on front panel b)	65	107.50	4.50	SF
Module rear connector	16	-	-	SF
Printed-circuit board drilled (∿ 150 holes/dm^2)	60	103	53	SF
Assembly work	50	10	5	SF
Total hardware of a module	230	246	70.50	SF
Bin mechanics, dataway and ventilation (material only)	58	49	21.50	SF
Total hardware per station (materials only)	288	295	92	SF
Cost to the user, per station (sales price)	∿ 635	∿ 700	∿ 200	SF
Power supply, assembled and installed	100	108	20 c)	SF
16 external cables for fast signals	225	225	56	SF
Total cost per fully equipped slot d)	960	1033	276	SF

a) Optional.

b) With Lemo RPL 00250 and ODU 254-1, respectively (Fig. 31).

c) Based on a single power supply per rack.

d) The module is still empty!

Both a single-width empty module and the corresponding station in the bin are taken into account. The module is supposed to have:

a) all required standard mechanical parts;

b) printed-circuit board finished and mounted (no components referring to a specific application);

c) all standard power voltages available on the printed-circuit board;

d) 16 fast signal connections between front panel and printed-circuit board.

Finally, the cost of the power supply and of some external fast signal interconnections is quoted.

Note that the comparison is made between, on the one hand, two general-purpose systems (NIM and CAMAC) as they are commercially available today, and, on the other hand, a system adjusted to a specific task (i.e. electronics for very large PM systems).

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