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THE NEW PSB MULTIPOLE MAGNET SYSTEM

G. Baribaud, P. Bossard, G. Nassibian, K.H. Reich,
K. Schindl, J. Vlogaert*, F. Völker

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Acknowledgements

References

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*) EA Group, SPS Division.

1. INTRODUCTION AND SUMMARY

A number of correction lenses were provided[1)] as part of the PSB construction. They were considered as experimental tools, anticipating that in the course of running in and optimizing the machine, it might well turn out that more, or differently located units would be needed - or that certain types would not be required at all[2)].

This is what actually happened[3)]; in particular more skew sextupoles were called for with the new working area ($5 < Q_V < 5.5$) in order to compensate the systematic resonance $3Q_V = 16$.

While one could decide from the outset to deal simultaneously with up to seven 3rd and 4th order resonances out of a total of about fifty coming into consideration[4)], there remained the following uncertainties:

- future standard working point
- extrapolation of lens strengths to highest intensities, taking into account the effects of space charge as driving force.

After detailed studies it was decided to combine a sextupole, a skew sextupole, an octupole and a skew octupole into a cylindrical unit (Fig. 1a), and to order eight stacks of four units each[4)]. Four of these stacks were to go into (long) L1 type straight sections as shown in Fig. 2, and four into (short) L4 type straight sections.

As the L4 type straight sections were all occupied by orbit correction or ejection bump dipoles, a different design had to be adopted for the L4 stacks. These units consist (from centre outwards) of a skew octupole, a skew sextupole, a dipole for vertical orbit correction and a dipole for horizontal orbit correction*. Skew sextupoles and octupoles rather than normal elements were chosen because four normal sextupoles and four normal octupoles were already available in each ring. Concentric cylindrical one-layer windings are again used, each function occupying one "shell" (Fig. 1b).

As regards the power supplies, a more restrictive policy was adopted because of the greater possibility of later additions. Only fifty-six supplies were ordered for the ninety-six new lenses, and it was accepted

*) These dipoles are not considered further in this report.

that rearranging the connections between lenses and power supplies could be done manually.

The fifty-six supplies are divided into two sets located in the auxiliary tunnel, each consisting of one rectifier and twenty-eight independently controlled current regulators. This arrangement resulted from an optimization study taking into account the cost of the supplies and of the cable connections between them and the lenses (located around the entire PSB ring).

The controls, status acquisition and equipment monitoring were obviously somewhat complicated on account of the possibility of connecting a given power supply to a number of lenses. Using CAMAC and CIM technology a solution was found which works at present using the IBM 1800 control computer and the MCR maxi-console (as well as the PSB mobile console). Its conversion to the new computer system was also taken into account and should not present too many problems.

The (restricted) experience gained to-date with the new system can be summed up by stating that it seems to meet the specifications.

2. CHOICE OF TYPES, NUMBERS AND LOCATIONS

2.1 General

The first two points have been covered previously[4,5] and are summarized in the introduction. For each ring, "old" and "new" multipoles together give a rather large set of resonance compensation elements; for each type, numbers and locations (per ring) are given in the following table:

Type	Total number	L1 elements in periods "old"	L1 elements in periods "new"	L4 elements in periods (all new)
Normal sextupoles	8	3,8,11,16	4,6,9,12	-
Skew sextupoles	8	-	4,6,9,12	2,6,11,12
Normal sextupoles	8	3,8,11,16	4,6,9,12	-
Skew octupoles	8	-	4,6,9,12	2,6,11,12

(16 zero-harmonic normal sextupoles for chromaticity control and 16 normal octupoles for Landau damping are not listed).

2.2 Criteria leading to the choice of the actual number of lenses

i) For compensating a particular resonance $n_1 Q_H + n_2 Q_V = p$, it is sufficient to have 2 lenses of the proper type, provided the betatron phase difference is near $\pi/2 + k\pi$ (k any integer) with respect to the harmonic p considered. The quite ambitious aim of the new multipole project is to provide tools for compensating any of the 54 3rd and 4th order resonances in the potential PSB working areas $4 \leq Q_H \leq 5$, and $4 \leq Q_H \leq 4.5$, $5 \leq Q_V \leq 5.5$. The harmonics p may take any value between 1 and 22 for these stopbands, so clearly more than two lenses of a given type are needed to satisfy the $\pi/2$ - criterion for all these harmonics.

ii) With a high intensity new linac, the PSB beam - after RF trapping - will cover a very large region in the $Q_H - Q_V$ diagramme, necessitating simultaneous compensation of several resonances, which in turn is only feasible with much more than two lenses.

iii) The working region considered contains several systematic resonances, the most worrying of which is $3Q_V = 16$. It may well turn out that for this very strong resonance more than two lenses are needed (not yet confirmed by experiment).

2.3 Position of lenses

i) Dealing with several resonances of the same type at a time complicates compensation (it is clear that if one tries to compensate just one of them, the other will even be enhanced, since they are caused by the same type of non-linearity). It may be shown[6)] that this can practically only be solved if there are lenses at different betatron amplitude values available (i.e. some in L1 and some in L4). This is the case for skew elements, but there are no normal multipoles in L4; indeed, simultaneous compensation of two normal sextupole or octupole resonances may well turn out not to be feasible; however, there is a way out: in case of absolute necessity, disconnecting one of the 0-harmonic sextupoles (octupoles) located in L3 (same β-values as L4) may be envisaged.

ii) $3Q_V = 16$ again: as the phase difference between L1 section is 2π for the harmonic $p = 16$, skew sextupoles in locations other than L1 are needed. Putting them into L4 results in a phase difference of $108^0 + k \cdot 180^0$ (near enough to 90^0).

2.4 Criteria underlying the choice of the actual locations

i) The position of the "old" normal sextupoles and octupoles;

ii) the available free positions in straight sections L1 and L4;

iii) the relative "effectiveness" of a given position (depending on the β values and their combination);

iv) the given number of new multipole stacks;

v) the PSB stop-band widths and phases computed from measured field maps in all 128 PSB bending magnet and 196 quadrupole gaps[7]. (These computed data turned out to be representative for the real effects, in as much as predicted stop-bands widths - at least for 3rd order resonance - correspond typically within a factor 2 to the measured values[8].)

By "searching" through all possible location patterns, the computer looked for the optimum combinations such that

- pairs of lenses with phase difference $\alpha = \pi/2 + k$ be available for as many of the 54 resonances as possible and 150 A per lens are sufficient to cover the computed stop-bands, even up to 800 MeV, except for a few 4th order resonances which are less harmful anyway.
- All 24 3rd and 4th order crossing-points of equal type resonances be compensated with reasonable multipole currents (again 150 A seem to be sufficient).

The actual location of the old and new multipoles around the ring may be found in Fig. 3.

A report treating this subject more in detail is in preparation[6].

3. MULTIPOLE MAGNETS

3.1 Design and fabrication

These magnets were designed by the MAE (EA) Group. As a number of multipoles designed by them previously had already been installed in the PSB, the first idea was simply to add more of the same design. However, reasons for change soon became apparent.

i) The existing magnets had enlarged bores to accomodate the beam position monitors, an unnecessary feature for the new multipoles[9].

ii) In order to permit rapid field variations, it was considered desirable to have laminated outer shells[10].

iii) As a result of studies on the efficient positioning of the multipoles, it was found that at least some of the new magnets should be placed in positions already occupied by orbit correcting dipoles.

To take account of all these points, a four layer design of two types was worked out, with the following windings[11]

Type A (Fig. 1a)	Normal octupole Skew octupole Normal sextupole Skew sextupole
Type B (Fig. 1b)	Skew octupole Skew sextupole Vertical dipole Horizontal dipole

After careful thought, it was decided[12] to keep the same low impedance coil design as used in the original multipoles, as this gave the best economic compromise, particularly in view of the fact that one would install a larger number of magnet windings than of power supplies.

In addition to carrying out the design and supervising the fabrication, the MAE (EA) group was also responsible for measuring the multipoles, mounting the 32 cylinders in their frames, and fitting all the necessary water and electrical interlocks and connections[13]. The results of the measurements are shown in Table 1.

3.2 Installation[14,15]

The installation of eight multipole stacks in a machine operating ∿ 6000 hours per year presented some problems. In order to reduce the work load for the long shut-downs, five stacks were installed as they became available, using the short shut-downs (ten and two days).

Installation of the four type B stacks in place of the existing dipoles (located between an F and a D quadrupole) was complicated by the fact that a continuous vacuum chamber traversed both the Q_F and Q_D lenses as well as the dipole.

It was thus necessary to

i) cut the 4 chambers
ii) remove Q_F,Q_D and dipole
iii) weld new flanges on the chambers of Q_F and Q_D, align, connect, test, etc.

Installation of the four type A stacks in the long straight sections was in principle simpler, but required the installation of additional supports.

Modification of other equipment was occasionally necessary where the stacks were installed in already partly occupied straight sections.

The installation of the large number of power cables was a substantial undertaking but thanks to good planning by those concerned the awkward schedules were kept.

A large number of man hours was absorbed by the work on the multicore control cables, but as this work could proceed during machine operation no special scheduling problems arose.

4. POWER SUPPLIES

4.1 General

It was clear from the start that the most economical solution would be to use a small number of rectifiers to feed the individual current controllers. As design studies had indicated individual current requirements varying from 25A to 150A, much consideration was, at first, given to the possibility of using current controllers of different ratings. As work progressed, it became apparent that at the low powers involved ($\sim$ 1 kW per multipole shell) the cost of the controls was dominant and for the sake of simplification a single type of current controller, rated at 150 A was chosen.

In order to have sufficient precision in the setting of small currents, a 12 bit measurement and 10 bit control system was specified.

To limit the cost of the power cables, the supplies had to be placed as close as possible to the magnets.

After examining various possible arrangements, it was decided to have two groups of power supplies[16,17], situated roughly diametrically opposite each other in the service tunnel which runs above the PSB ring.

Each group, which occupies eleven standard 19" racks, consists of one main rectifier, 28 (plus spares) power supplies and a patch panel for connecting to any of 48 magnet windings[18].

Each power supply consists of

- the control electronics (three printed circuit boards: control PCB, inversion and interlocks PCB, logic interface PCB)
- a water cooled transistor array
- a remotely operated polarity inverter of the pulsed rotary type
- a current measuring shunt and
- the associated ancillary equipment.

4.2 Power supply specifications

Each power supply must meet the following requirements:

- I_{nom} = 150 A
- Load impedance (including cables) : resistance 79-84 mΩ
inductance 76-210 μH
- Current stability and resolution : 0.1% I_{nom}
- Current rise : 0-I_{nom} in less than 50 ms
- Polarity inversion with intermediate open-circuit position
- Control by any of 14 analogue functions, multiplied by an adjustable factor
- Possibility to connect to any of 48 windings, with automatic identification
- Extensive local fault and operational monitoring and transmission of all relevant information to the MCR.

4.3 Current regulation system[19)]

The general layout is shown in Fig. 4. For each supply, a local memory receives a 16 bit word transmitted via a suitable interface by the CAMAC system.

The bit allocation is as follows

10 bits for the multiplying factor
1 for ON/OFF
1 for polarity.

The power supply is protected by a limitation on I_{max} (which can be set at 50, 100, 150 A) and $(dI/dt)_{max}$, in addition to all necessary interlocks.

The servo control has to work over a range of load impedances. In order to obtain good overall accuracy and stable dynamic response, in spite of the low internal impedance of the transistor bank, a voltage control loop is connected in cascade with the current loop (Fig. 5).

An RC filter ($RC \simeq 0.1$ ms) is added to the input of the transistor power stage to limit noise sensitivity and intrinsic instability at frequencies above 10^5 Hz.

The voltage control loop transforms the transfer function of the power stage and load, as seen by the current control loop, to a single lag, with 12 kHz corner frequency.

The resulting over-all current control open loop response is shown in Fig. 6; T_L is the time constant L/R_L of the load and $T_{(i+L)}$ the composite time constant of load and internal power stage resistance $L/(R_i+R_L)$; T_1 to T_4 belong to the correcting elements of the loop.

4.4 Power circuits

The main rectifier is rated at 25 V, 2000 A_{dc}. A variable motor driven autotransformer feeds two transformers, having star and triangle connected primary.

The secondary windings are star connected and power two rectifiers, in parallel via an interphase choke.

The power diodes are water cooled cells; an LC filter is included in the rectifier cubicle.

The transistor arrays of the regulators consist of 28 2N5885 units; six arrays are mounted on a water cooled copper plate; each of them is capable of delivering 150 A.

The current measuring shunts have a value of 10 mΩ and are also mounted on a water cooled plate.

The polarity changer is of the pulsed magnetic type with four successive positions: normal, open, inverse, open. It is powered by an auxiliary 110 V supply.

Connectors of the "multicontact" type permit to connect a power supply to any of the magnets; identification of the actual connection is done through auxiliary contacts.

The cables to the magnets have four aluminium conductors diametrally connected in parallel pairs to lower the inductance.

5. CONTROLS

5.1 General

The main requirements for the control system can be summarized as follows:

i) allow the new multipoles to be operated in the same way as those already installed, using the IBM with STAR data transmission system;

ii) provide convenient operation, good equipment monitoring and fault finding facilities;

iii) make provision for a smooth change over to the new computer system.

Notable features of the system are automatic identification of magnet to power supply connections, and an analogue observation system linked to the KNOBS control selection[20]. The control and acquisition hardware is built in CAMAC technology.

In addition to extensive status monitoring, an improved varilog facility[21] has been provided, based on a microprocessor in a CAMAC crate acting as an auxiliary controller[22]; provision has been made for control and supervision of up to 72 power supplies, randomly connected to a maximum of 120 magnet windings.

A block diagram of the system is shown in Fig. 7.

5.2 Hardware

Each group of 30 power supplies is controlled by 5 CIM crates, each containing 6 regulator modules. The 25th position in each crate is occupied by the interface unit to the CAMAC dataway. One CAMAC crate is required per group of 30 power supplies. A custom designed crate controller[23] interfaces CAMAC to STAR (Figs. 8 and 9).

Currents from the 30 shunts are processed in a separate CIM crate, where the signals are interfaces to the CAMAC ANALOGUE Acquisition System (CAAS) for transmission both to the computer and to the analogue observation system. Analogue signals are selected in the MCR by automatic link with the KNOBS (Fig. 10). The digital conversion is done for all power supplies once per PSB cycle with a timing adjustable by computer (RTPS04).

In order to keep a check on the shape of the functions produced by the power supplies, the area under the curve is measured. To reduce the volume of data to be transmitted, a microprocessor (Intel 8080) is used to perform all calculations locally and only the 56 values are transmitted to the MCR. Access to the CAAS is through the CAMAC dataway (Fig. 11).

Status monitoring is provided by 64 line surveyors, and precautions have been taken against AC mains disturbances.

5.3 Software

Although it was agreed from the start to have only the minimum of control facilities compatible with effective operation of all multipoles (new and old), a considerable amount of work was still necessary. Extensive modifications had to be made to existing programs, notably for data bank management and KNOBS. New programs had to be written to build the connections table between multipoles and power supplies[24], for status display, currents histogram, LOG and VARILOG. All those new programs and their uses are described in a separate operation note[25].

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H. Kumpfert (DESY)

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New P.S.B. MULTIPOLES

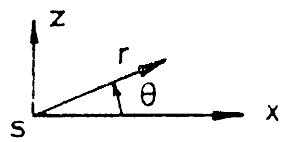
Table 1

Main magnetic parameters. Average of measurments.

Type A

Lense	Nom. current I (A)	n	Derivative of magn. field: G'' or G' or B $\frac{\partial^{n-1}B}{\partial r^{n-1}}\left[\frac{T}{m^{n-1}}\right]$	Derivative of magn. field: $\int G''ds$ or $\int G'ds$ or $\int Bds$ $\int\frac{\partial^{n-1}B}{\partial r^{n-1}}ds\left[\frac{T}{m^{n-2}}\right]$	Multipole coefficient: $a_n\left[\frac{T}{m^{n-1}}\right]$	Multipole coefficient: $\int a_n\,ds\left[\frac{T}{m^{n-2}}\right]$	Magn lenght l(m)
Octupole	270	4	422,81	183,5	17,61	7,64	0,434
Skew octupole	270	4	278,7	109,8	11,6	4,575	0,394
Sextupole	270	3	7,35	2,25	1,22	0,375	0,306
Skew sextupole	270	3	7,56	2,33	1,26	0,388	0,308
Type B							
Skew octupole	270	4	422,81	183,5	17,61	7,64	0,434
Skew sextupole	270	3	8,39	3,0	1,40	0,50	0,358
Vertical dipole	270	1	0,0504	0,0122	0,0504	0,0122	0,242
Horizontal dipole	270	1	0,0585	0,0137	0,0585	0,0137	0,234

Definition of multipole coefficients:

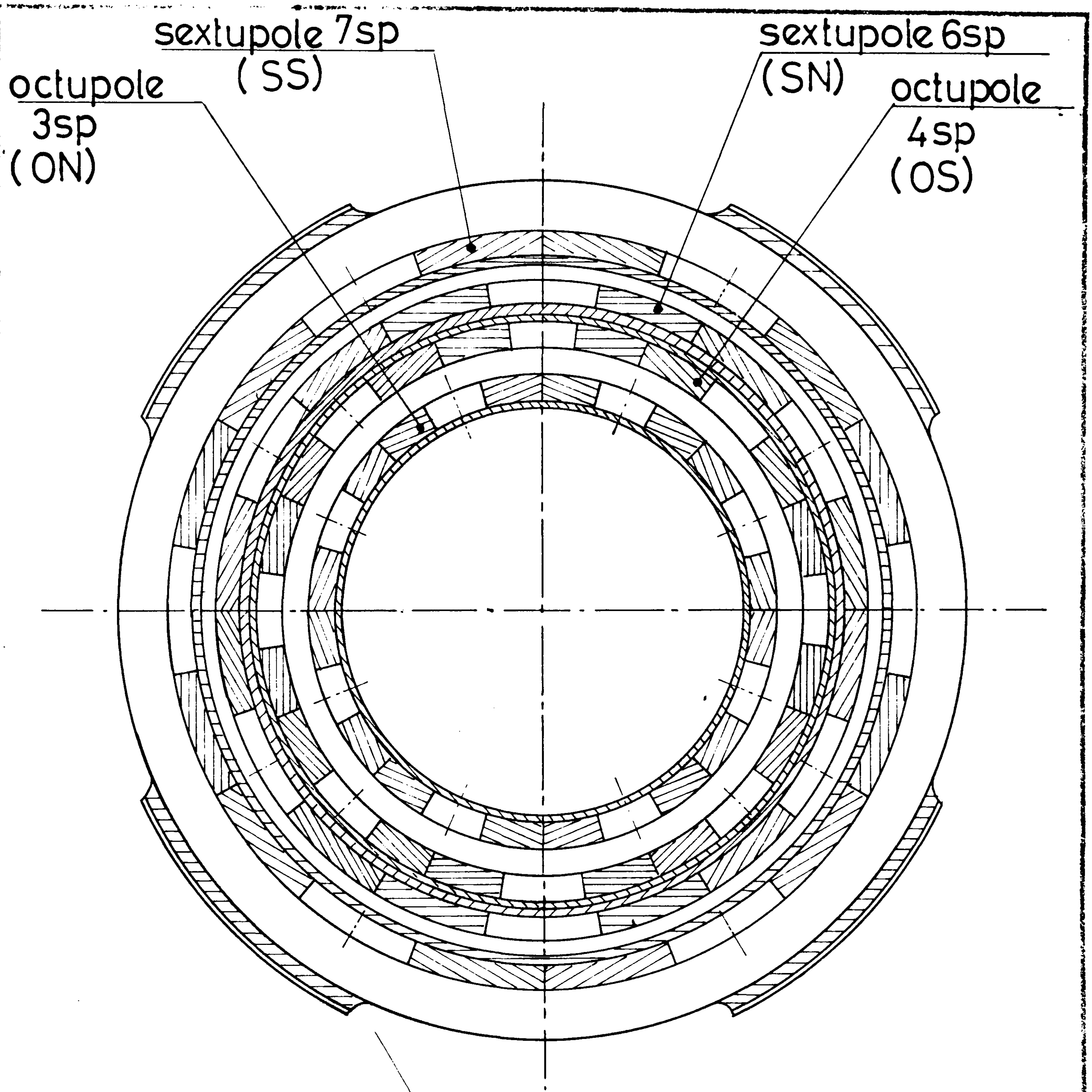


$$B_r = n a_n r^{n-1}\sin n\theta,\quad B_\theta = n a_n r^{n-1}\cos n\theta$$ for normal octupole, sextupole and vertical dipole.

$$B_r = n a_n r^{n-1}\sin(90^\circ - n\theta),\quad B_\theta = n a_n r^{n-1}(-\cos(90^\circ - n\theta))$$ for skewoctupole, skewsextupole and horizontal dipole.

Magnet to magnet fluctuations of G'', G' and B: ± 1‰

Possible rotation of element around S-axis: $\Delta\theta = \pm 0{,}3^\circ$



TRANSVERSE CUT

FIG. 1a

NO / UNITE	DESCRIPTION	POS.	MAT.	OBSERVATIONS

Rugosité VSM 10321 Roughness									
Groupe	∇	∇∇			∇∇∇			∇∇∇∇	
Classe	N 10	N 9	N 8	N 7	N 6	N 5	N 4	N 3	N 2
μm.	12,5	6,3	3,2	1,6	0,8	0,4	0,2	0,1	0,05

Abréviations	VSM 10319
Symboles usinage, traitement	VSM 10320
Symboles de formes	VSM 10324

Tolérances	
0 - 10	± 0,1
10 - 30	± 0,2
30 - 360	± 0,3
360 - 750	± 0,4

REMPLACE

REMPLACE PAR

REDUCTION

CONTROLE

VU

NOM NAME	DATE	ISSUE
		G
		F
		E
		D
		C
		B
		A

ASS. S/ASS.

MULTIPOLE - A -

Echelle
Scale

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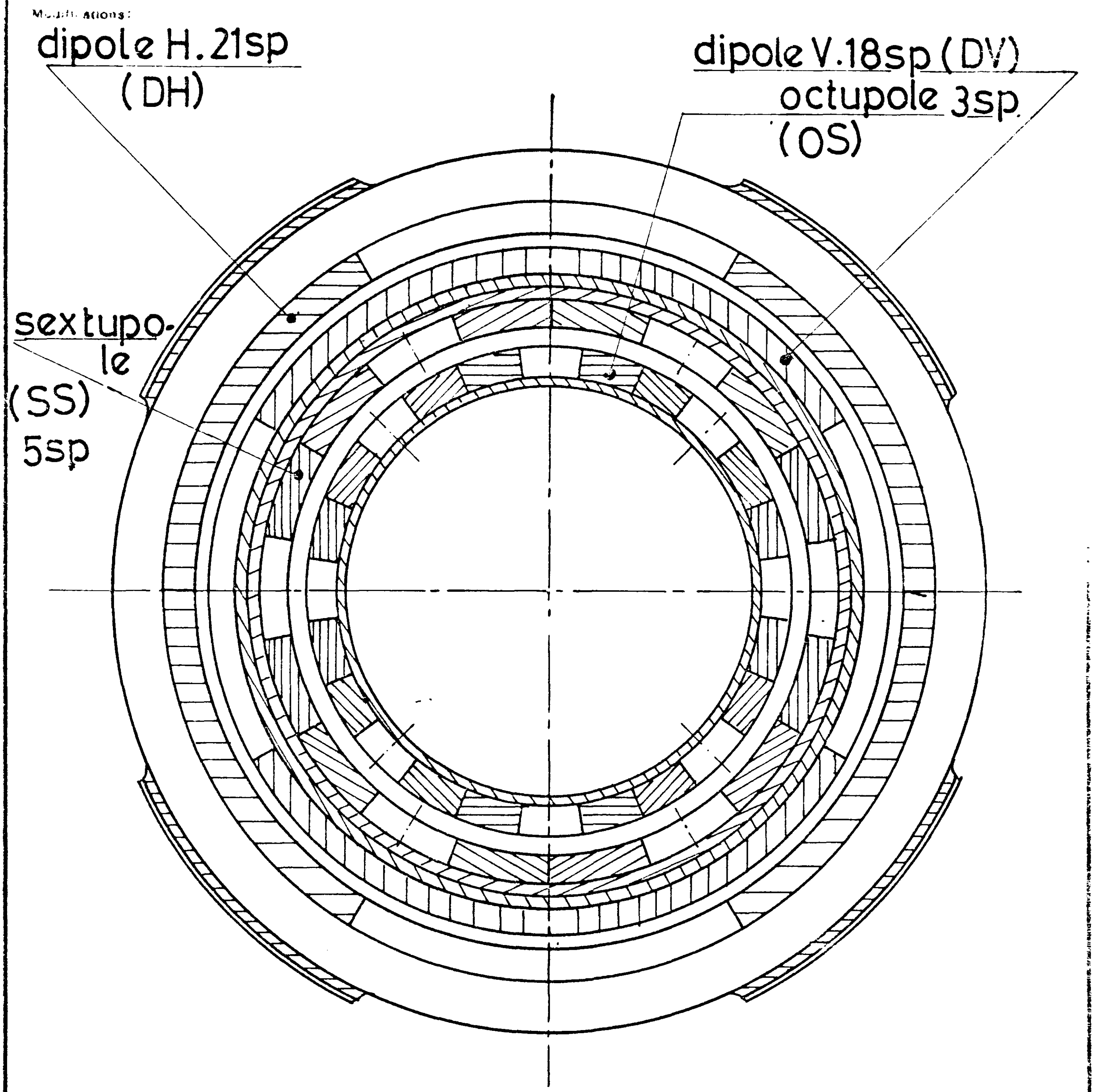

FIG. 1b

TRANSVERSE CUT

First angle projection
Projection Européenne

Ensemble Assembly	S/ensemble S/assembly	Echelle Scale	Nom-Name	Date	Issue
MULTIPOLE -B-			Dessiné		
			Contrôle		
					A
					B
					C

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN LAB CH-1211 GENÈVE 23

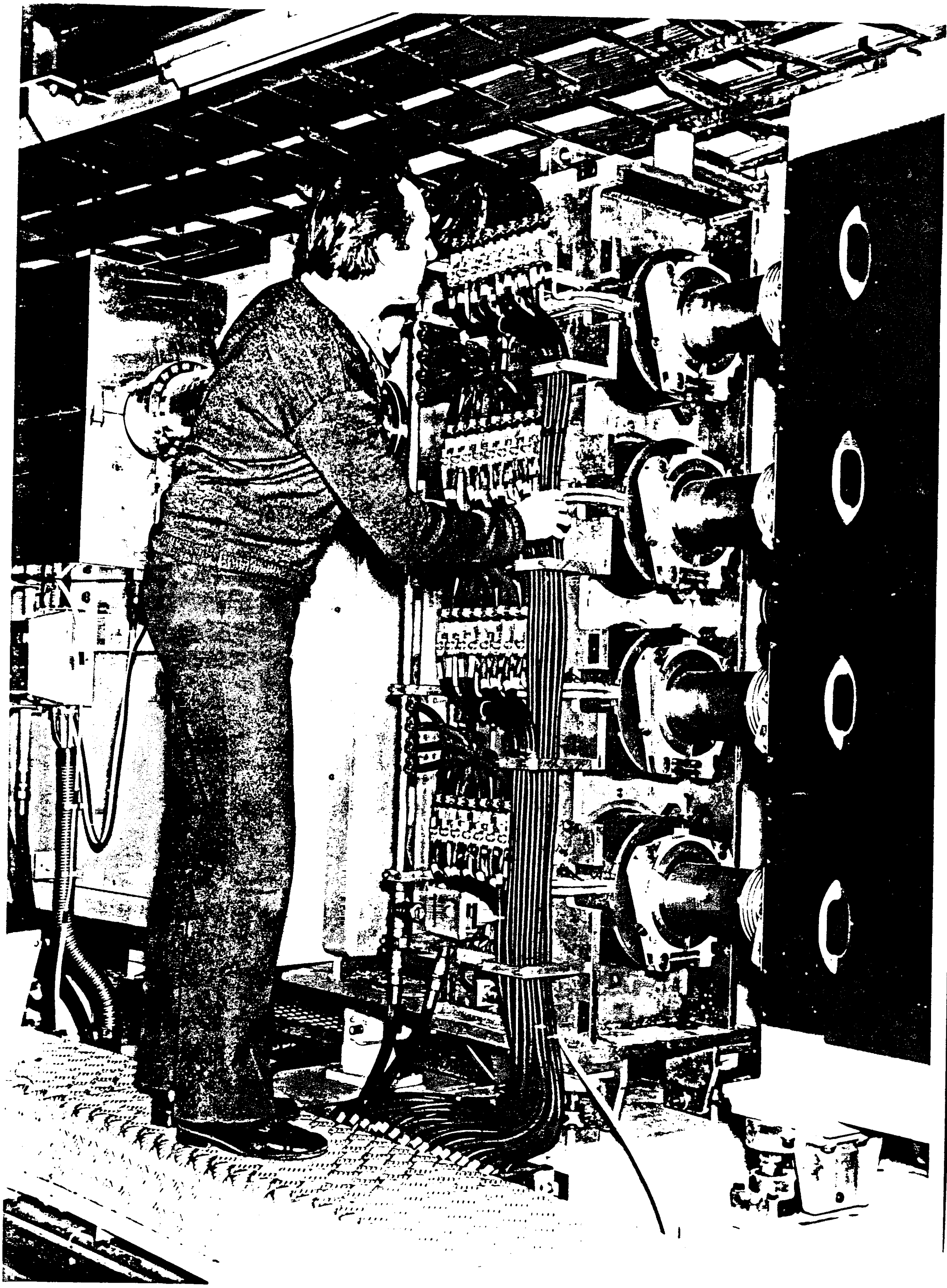

FIG. 2 Stack of 4 multipole cylindrical units, showing power leads and water cooling for the 16 independent shells.

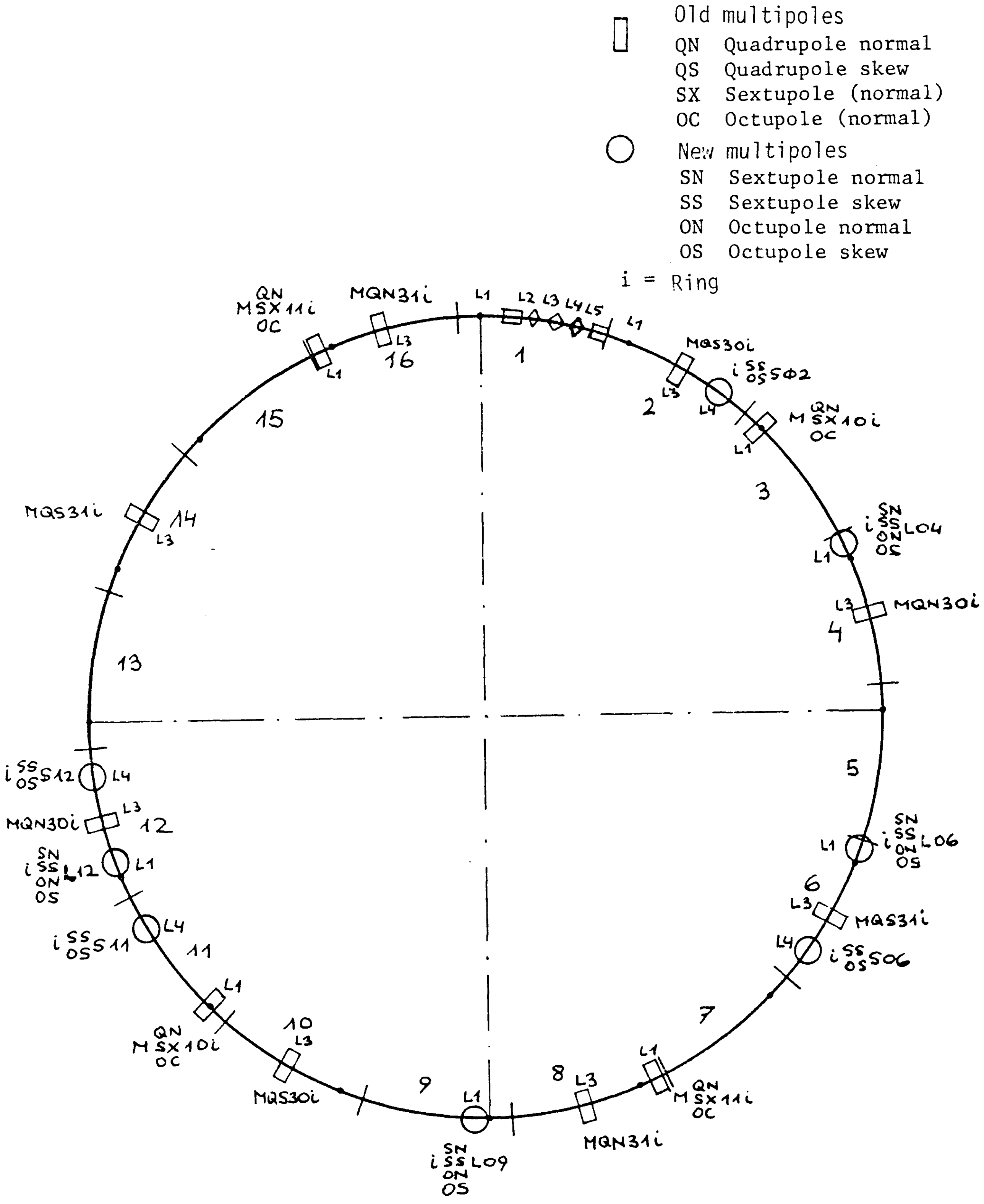

FIG. 3

Positions of harmonic correction multipoles

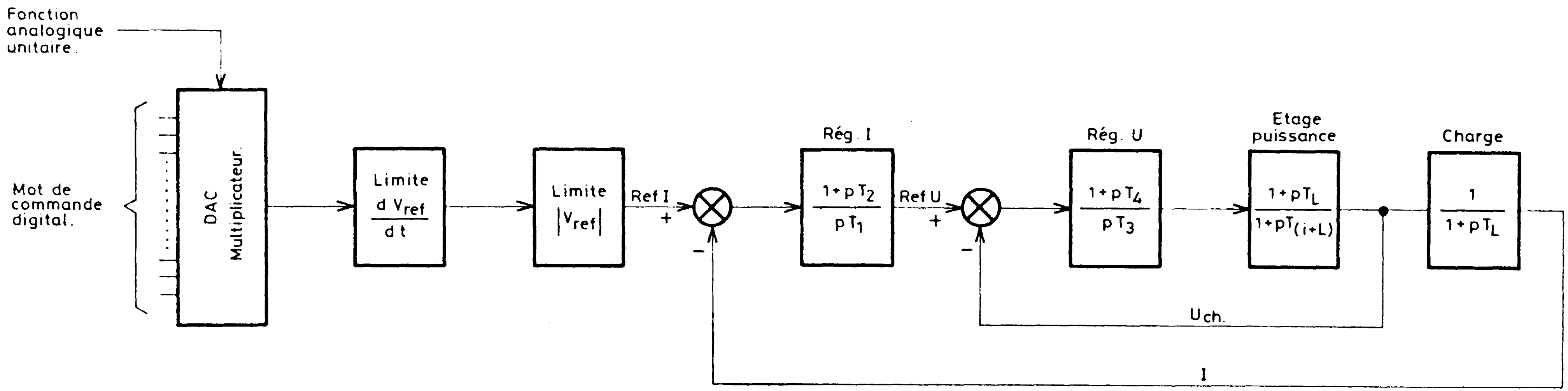

FIG. 5

Block diagram of the current regulation system

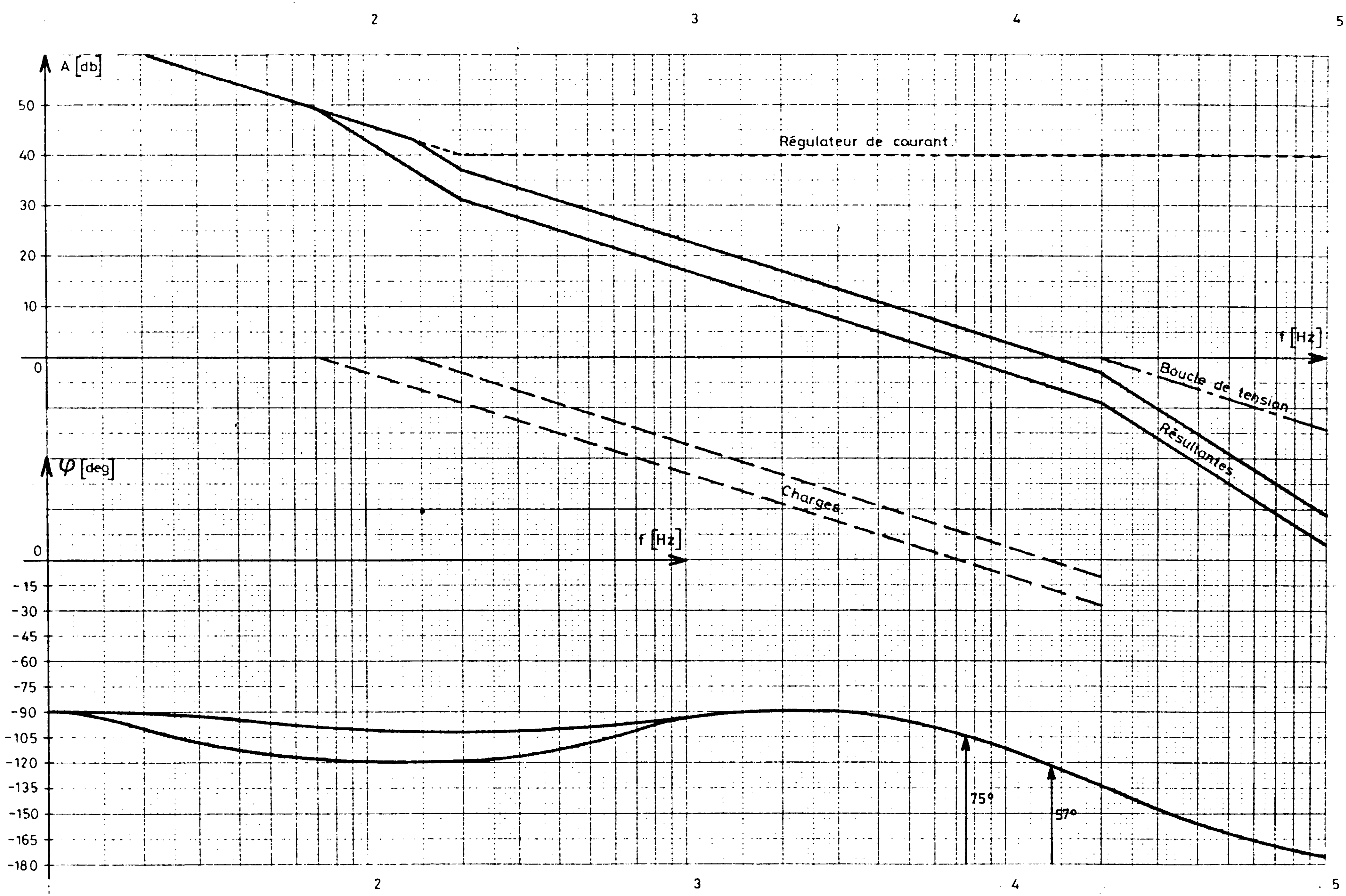

FIG. 6 Over-all open loop response of current control system

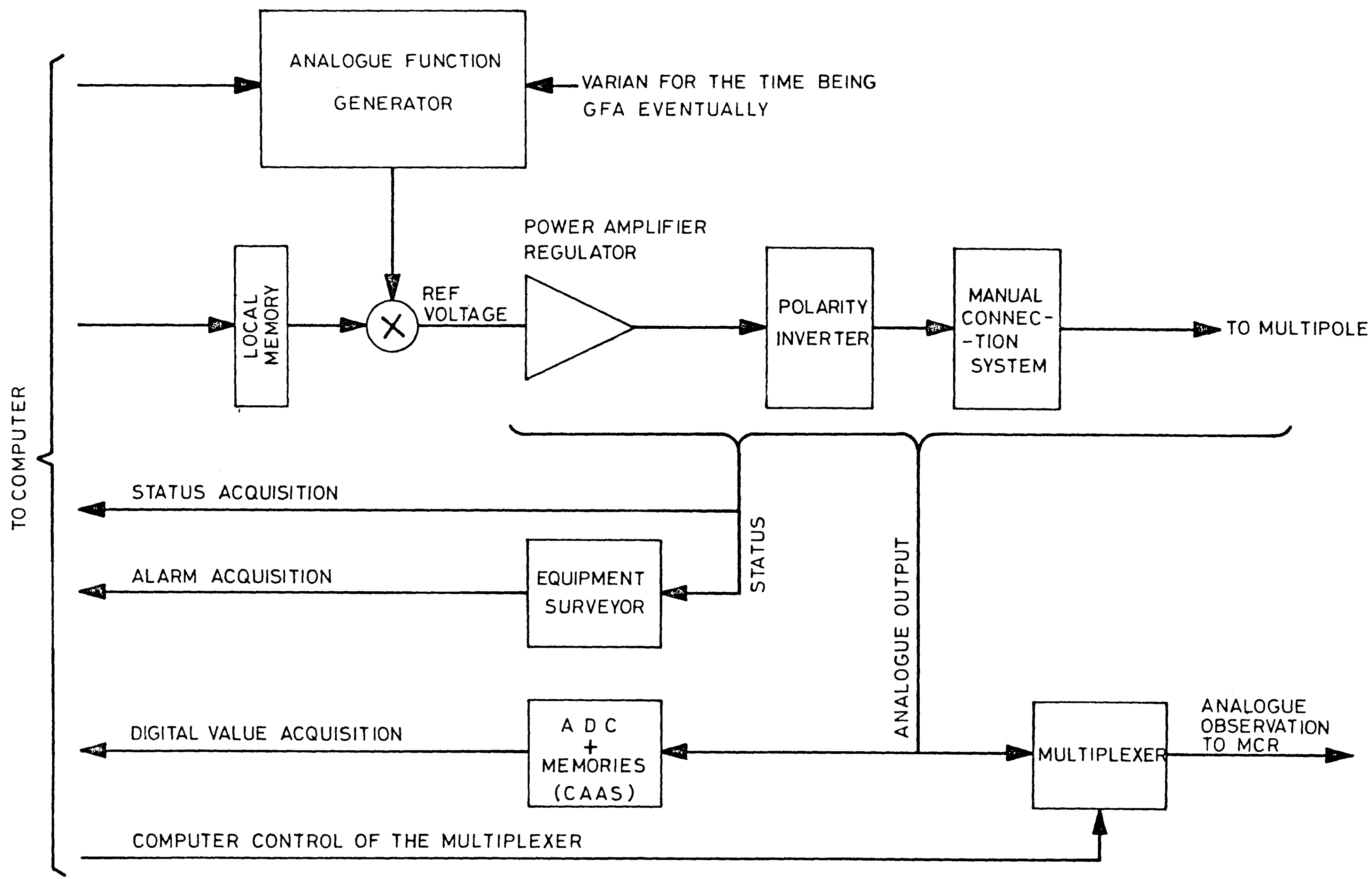

FIG. 7 - CONTROL SCHEMA OF THE NEW MULTIPOLES

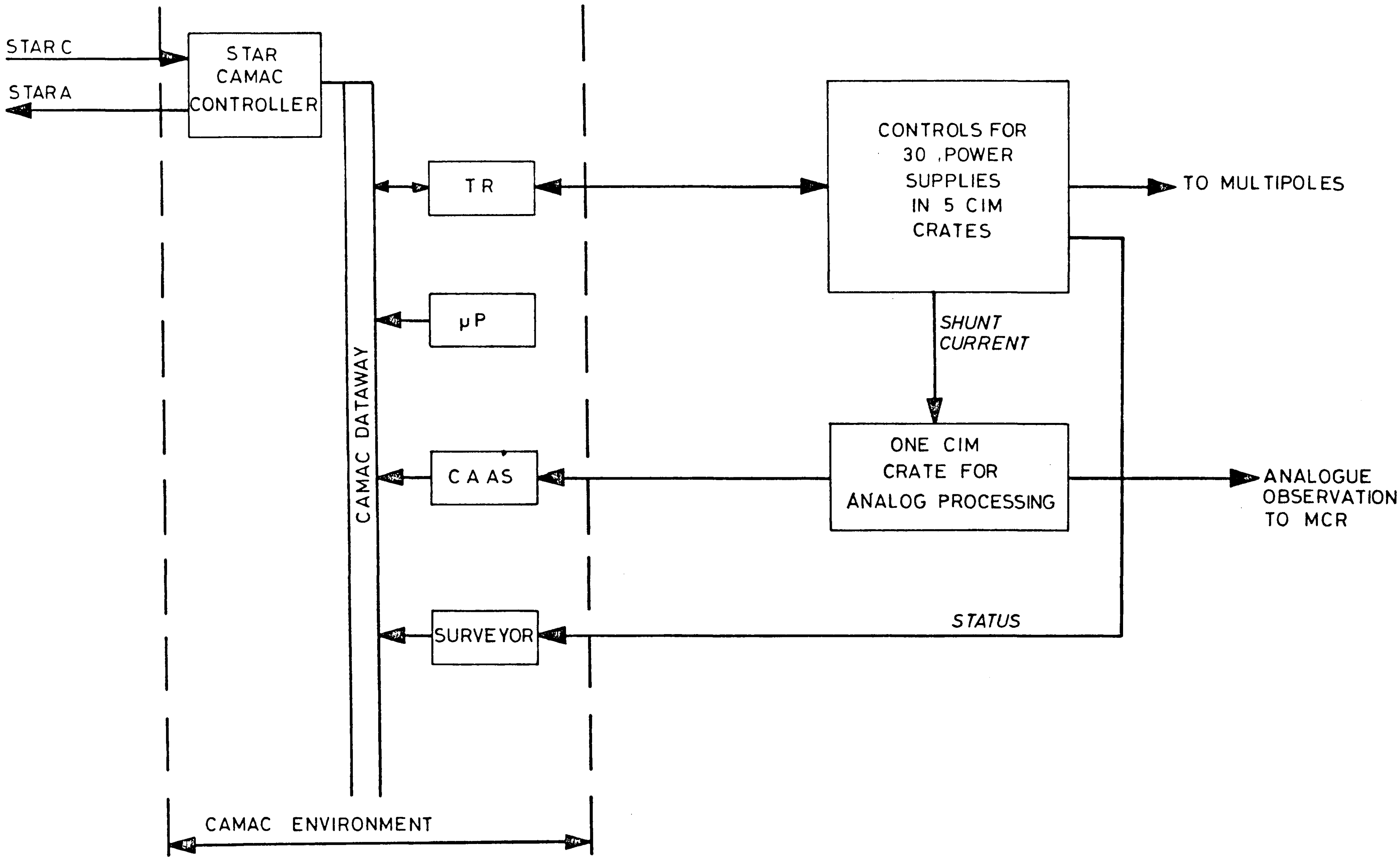

FIG. 8 HARDWARE LAYOUT FOR ONE GROUP

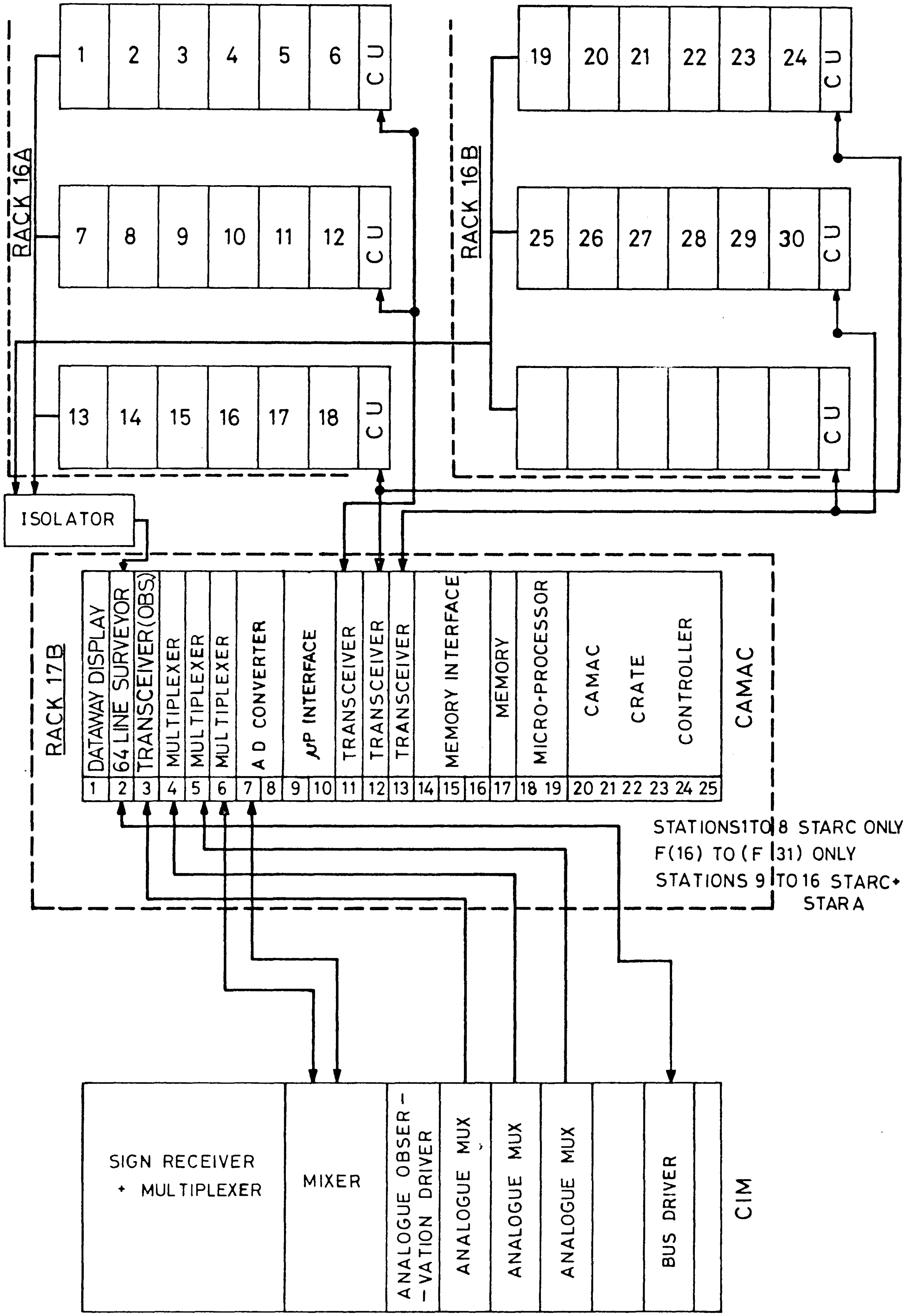

FIG. 9 FINAL LAYOUT OF THE HARDWARE

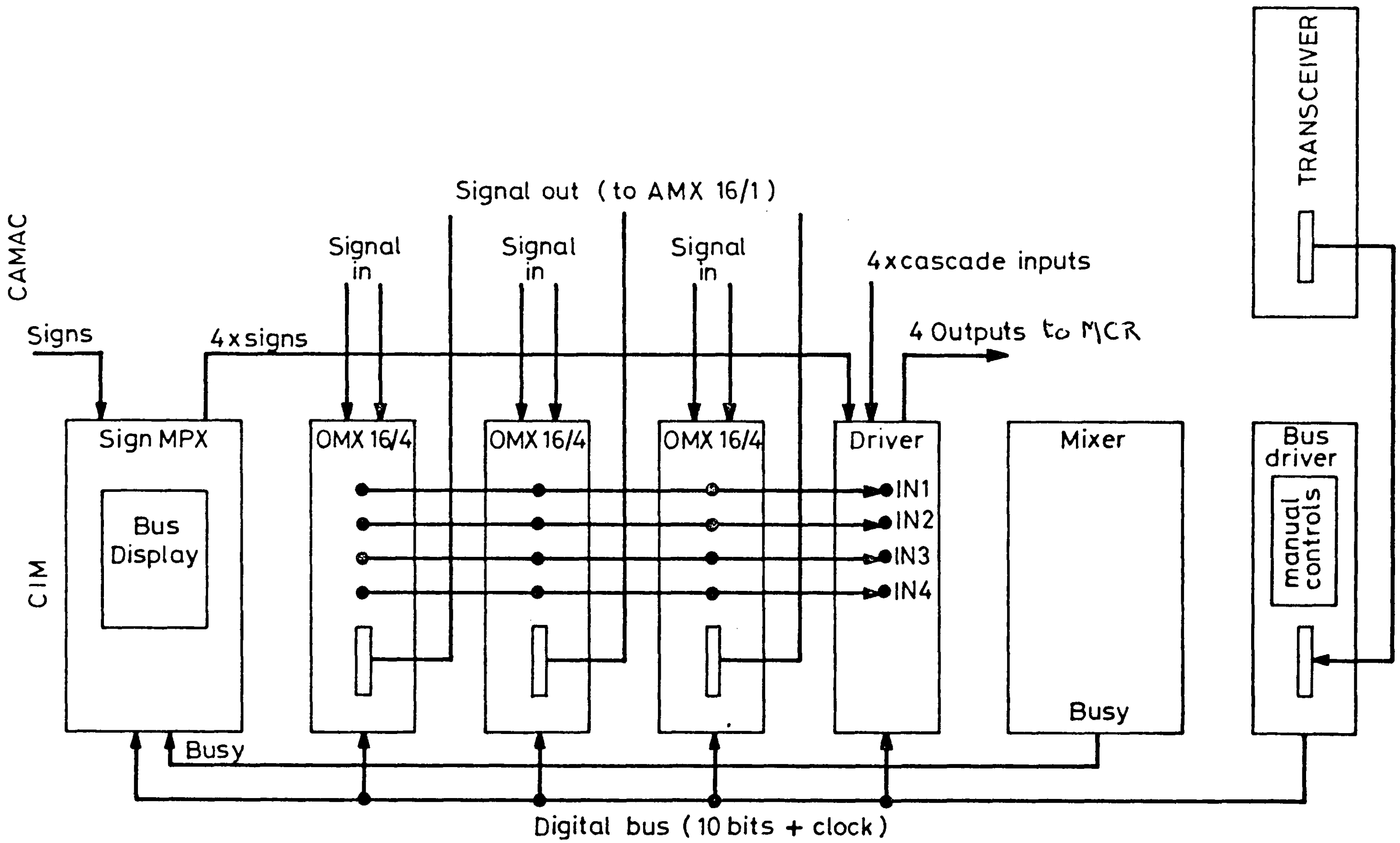

FIG. 10 Analog signal observation layout

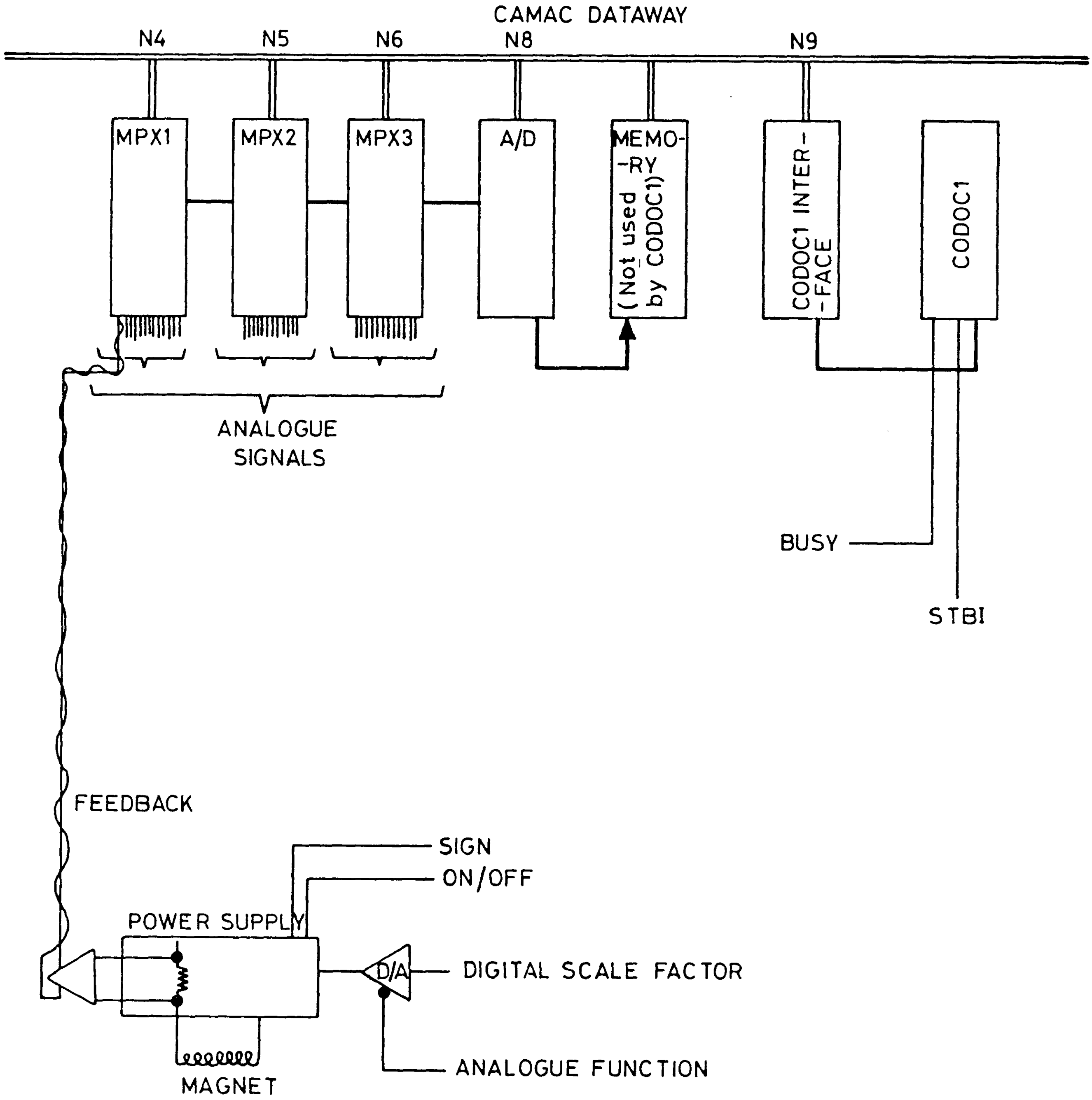

FIG. 11 MULTIPOLE MICROPROCESSOR VARILOG (HARDWARE)

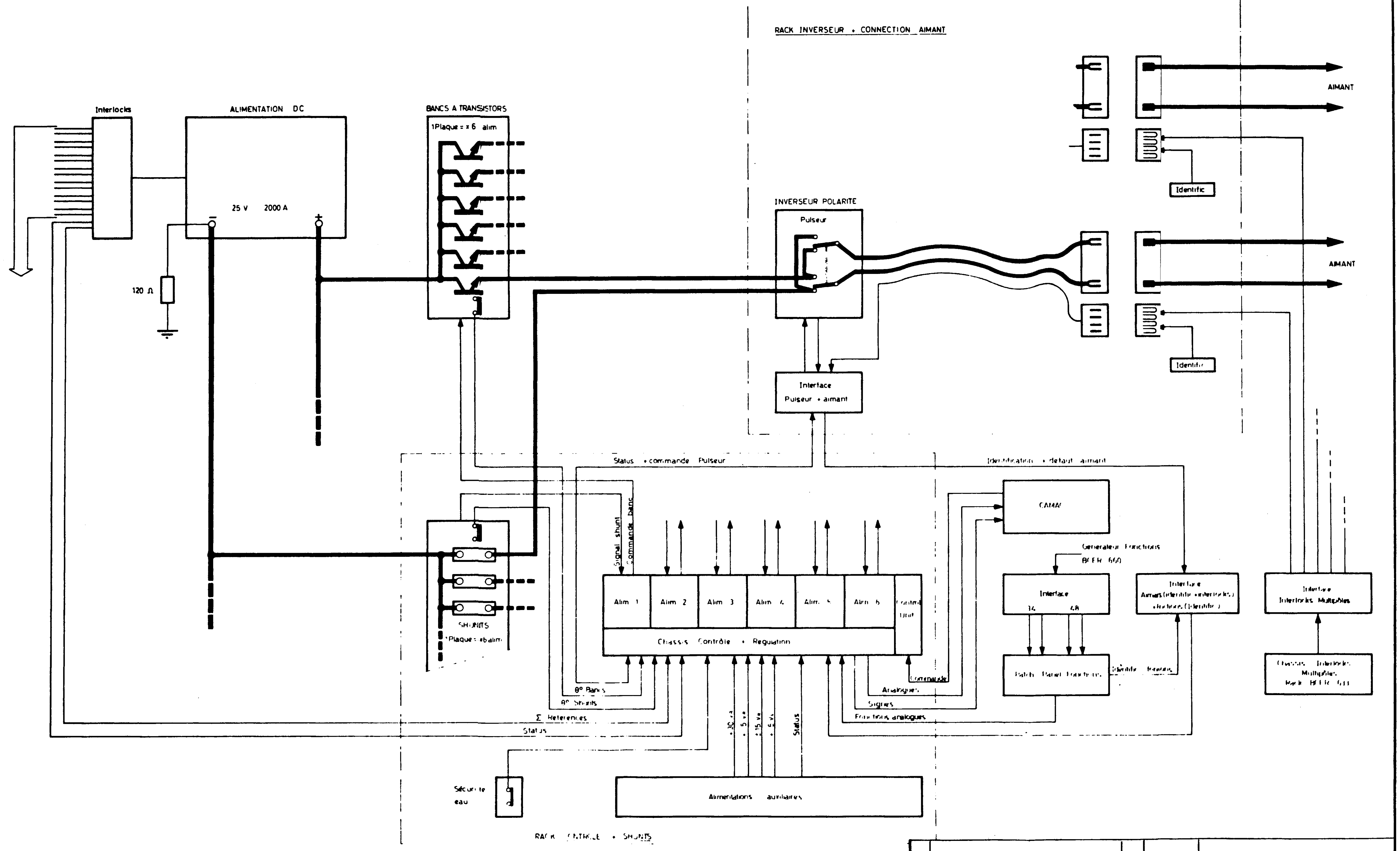

FIG. 4 General layout of current regulation system

DÉSIGNATION	POS.	MATIÈRE	OBSERVATIONS
ASS.	S/ASS.		

NOMBRE DE PIÈCES

NOUVEAUX MULTIPOLES PSB

Schéma général d'une alimentation

ECHELLE			
	DESSINÉ	26.5.76	
	CONTROLÉ		
	VU		
	REMPLACE		
	REMPLACÉ PAR		
	RÉDUCTION		

CERN ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE - GENÈVE

PS/BR 650.00.1005