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DESIGN OF THE MAIN COILS POWER SUPPLY AND CURRENT DUMPING SYSTEM FOR THE MILAN SUPERCONDUCTING CYCLOTRON

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1.- INTRODUCTION

The magnetic field for a heavy-ions superconducting cyclotron is obtained by superconducting coils fitted around the poles above and below the median plane.

The coils which form a variable high inductive load (the inductance decrease roughly 15-20 times as the iron saturates) must be properly energized and protected in order to achieve coils safeguard and the expected performance of the cyclotron.

This paper is intended to give a report on the design and construction of the main coils power supply and current dumping system for the Milan superconducting cyclotron.

2.- POWER SUPPLY AND DUMPING SYSTEM GENERAL FEATURE

The physical characteristics of the superconducting coils which is the load for the power supply are largerly determinated by the magnetic field isochronism requirements(1).

The coils are splitted in two sections labelled in the following α and β; their characteristics are listed in Table I.

The operating diagram of the cyclotron in the plane I_α, I_β is given in Fig. 1 where I_α, I_β are the excitation currents of the α and β sections respectively. The self and mutual inductance of the coils are shown in Fig. 2. In Table II are listed the specifications for the power supply required to energize the superconduting coils

The supply consists of two identical d.c. supplies with common controller and protective circuits. Likewise in the Table III are listed the specifications for the dumping system.

A simplified interconnecting circuit of the power supply, discharge current circuit and superconducting coils is proposed in Fig. 3.

TABLE I

	α Section		β Section
Winding technique		Double pancake	
Superconducting conductor :			
Copper matrix (Cu ETP) dimensions)		13 x 3.5 mm^2	
Superconducting insert		1.8 x 3.6 mm^2	
Internal radius (room temperature)		1000 mm (997 at 4.2°K)	
External radius (room temperature)		1165 mm (1161 at 4.2°K°)	
Height	364 mm		252 mm
Layers	2 x 13		2 x 9
Turns/pancake		2 x 38	
Critical current (at 5 Tesla)		2700 A	
Maximum nominal current		1944 A	
Maximum M.M.F.		6.5 x 10^6 At	
Self inductance (at 6x10^6 At)	8.7 H		3.7 H
Mutual inductance (at 6x10^6 At)		3.7 H	
Maximum stored energy	24 Mj		14 Mj

TABLE II - Specification apply to each α and β sections.

Output voltage	Variable 0-20 V
Output current	Variable 0-2000 A
Regulation modes with controller selection :	
- Output voltage regulation	
- Output current regulation	
Stability :	
- Output voltage regulation mode	± 20 mV (for all range)
- Output current regulation mode	± 20 mA (for all range)
For :	
- A.C. main line	380 V ± 10% 3 phases 50 Hz
- Room temperature	**25°C** ± 5°C
- Cooling demineralized water	20°C ± 2°C
- Cooling water pressure	5 Bar
Voltage ripple (6th armonic)	≤ 100 mV p-p
Efficiency at full load	≥ 75%
Power factor	≥ 0.95
Interlocks :	
- Personnel safety	
- Current dumping system	
- Quench detection system	
- Cryostat and magnet	
Controls :	
- Local with panel meters, digital thumb-wheel switches for test and maintenance	
- Remote via computer	

TABLE III

Dumping switches :	
- Opening time at 2000 A d.c.	≤ 100 msec
- Maximum nominal current	2500 A d.c.
- Maximum nominal voltage	600 V d.c.
Dumping resistors :	
- Maximum temperature free air cooling at maximum dissipable energy	300°C
- Rd α coil	Variable 0.15-0.3 OHM with 4 steps
- Rd β coil	Variable 0.125-0.177 Ohm with 4 steps
- Inductance negligible	

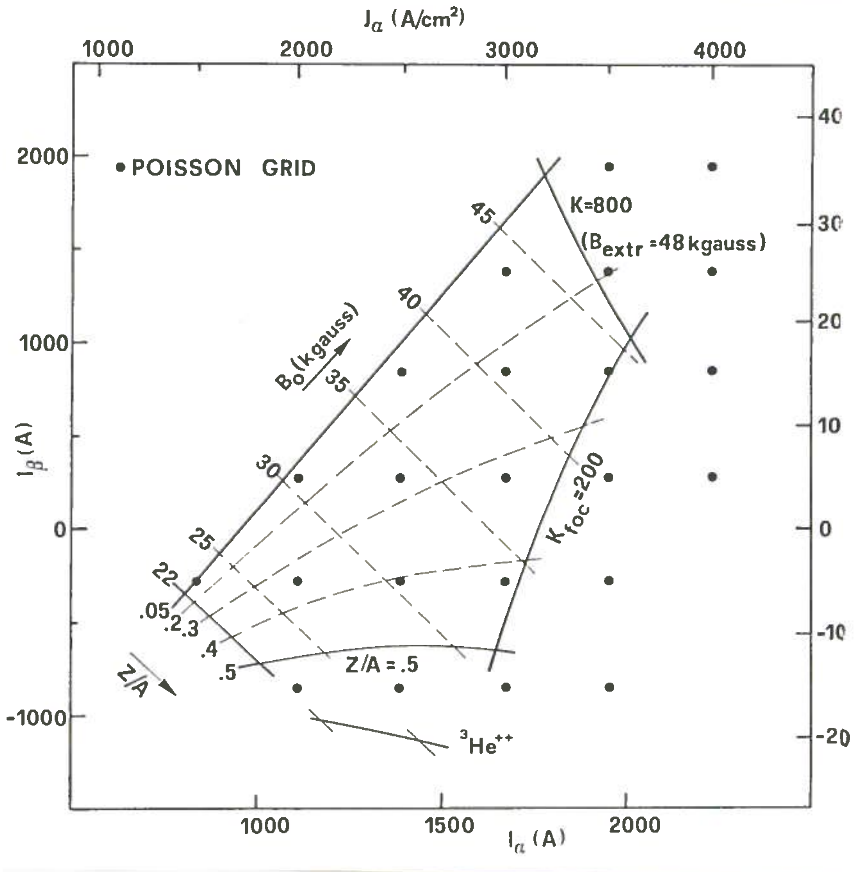

Fig. 1 - Operating diagram of the superconducting cyclotron I_α, I_β plane.

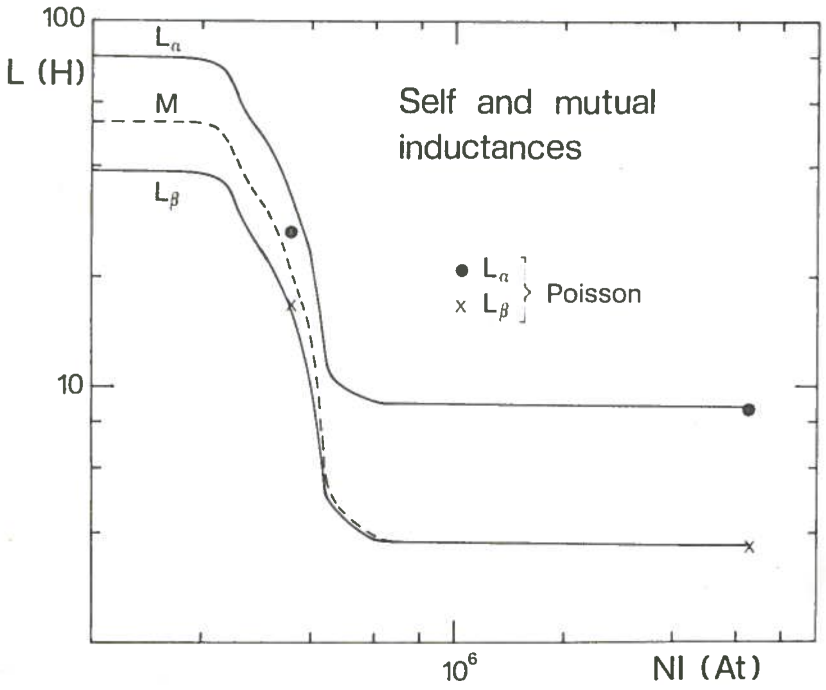

Fig. 2 - Self and mutual inductance variations of superconducting coils.

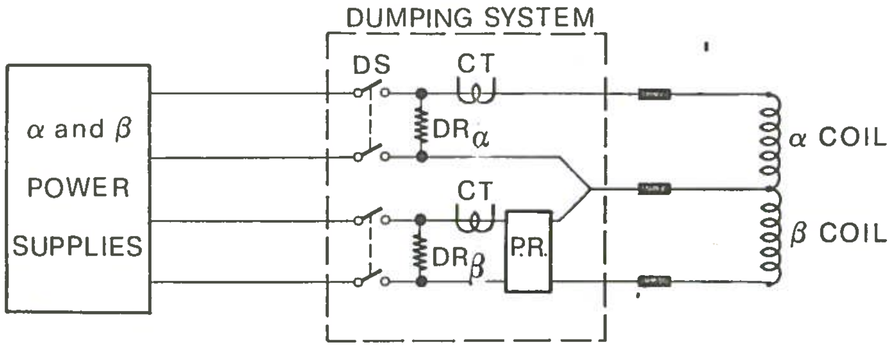

Fig. 3 - Interconnection scheme between power supply, dump system and coils.

The coils are connected internally so that only three leads out of the cryostat are necessary for independent excitation of the α and β coils. The protection resistors DR are permanently connected across the coils and the magnet discharging is accomplished by opening the dump switches DS. A polarity reverser PR allow to energize the coils with opposite currents in the two sections. The current sensors CT are positioned so that only the current that flows in the coils can be monitored.

3.- POWER SUPPLY (ALE 20 V 2 KA)

The most important considerations in addition to the specifications, for the power supply design have been the following :

a) High reliability (with a number of components as low as possible

b) Best components at the present state of the art;

c) Good cost/performance ratio.

We can see now in detail the justification of the choices for the following components respectively:

1) A.C. Regulator and Rectifier;

2) D.C. Regulator;

3) Current sensor;

4) Error Amplifier and Reference.

Fig. 4 shows in schematic form the interconnecting diagram between the above mentioned components for each of the α and β identical sections of the power supply.

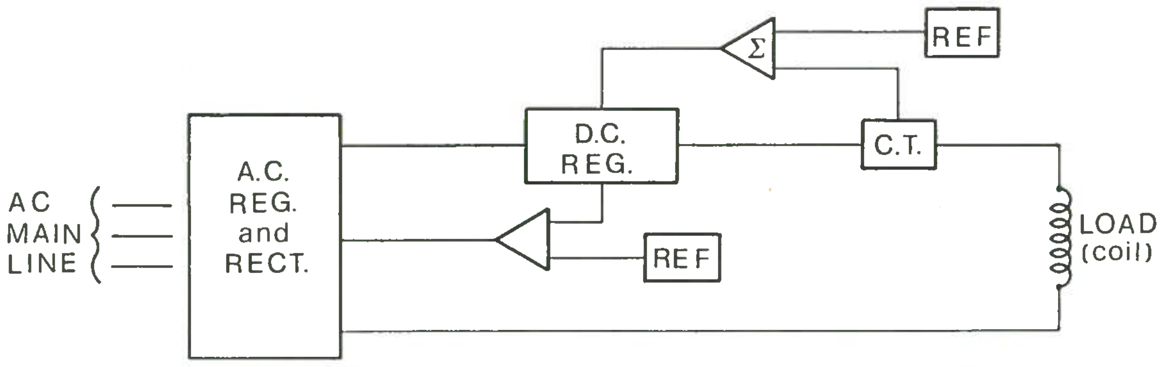

Fig. 4 - Block diagram of the regulating loops.

3.1.- A.C. Regulator and Rectifier

The high inductance of the load does not require the construction of an LC passive filter if the output ripple of the rectifier circuit is sufficiently low.

Three different solutions have been taken in account :

a) Three phase half wave;

b) Three phase bridge;

c) Hexaphase half wave with double secondary transformer and interphase coil.

After a careful cost-performance analysis among the different solutions, a three phase bridge rectifier has been chosen.

The diodes of the rectifier bridge type SWO4 CXC 935 are double side water cooled with 4.5 liter/ /minute; the rectifier can supply 2500 A continuosly (Max. 3800 A).

Slow mains voltage and load variations may be dealt by means of an A.C. regulator(2). Since it is clear that there is no one ideal circuit configuration to meet all needs, three actual system are discussed below. The major classes of device which have been considered for an A.C. control are :

- Regulating transformer;
- Semiconductor controlled rectifier;
- Magnetic transductor.

The major parameters to be considered in the choice of the regulating element are compared in Table IV.

TABLE IV

ITEM	Regulating transformer	S.C.R. without filter	Magnetic transductor
Relative cost/Kilowatt	1	1 to 1.5	0.8 to 1.2
Power range	Few kW to MW	Unlimited	Unlimited
D.C. output current	Unlimited	Price increase in kA range	Unlimited
D.C. output voltage	Unlimited	Price increase above 700 V and below 20 V	Unlimited
Voltage range at full load current	0 to 100%	30 to 100%	20 to 100%
Speed of response	10% per second	Inversely proportional to loop gain, in closed loop	Inversely proportional to loop gain, in closed loop
Ripple on rectified voltage	6% thro' the range	24% at 90 firing angle	24% at 90 firing angle
Efficiency	90 to 96% losses increases with current only	85 to 95% losses increases with increasing current or decreasing voltage output	85 to 95% losses increases with increasing current or decreasing voltage output
Power factor	0.95 at all loads	0.8 to 0.85 at full load	0.8 to 0.85 at full load

Our choice has been for the regulating transformer which on almost every aspects except speed of operation scores over the static rivals.

The regulator is a motor driven variable autotransformer, waveform distortion is negligible and rectifier ripple contents remains a constant percentage of the output voltage, throughout the whole range.

The machine had been constructed under our specifications by Ocem Company (Milan). The particular interconnecting circuit between the variable transformer and the transformer is shown in Fig. 5. It is justified by the reduction of the size of variable transformer while keeping the same regulation sensitivity and by the reduction of the short circuit currents. Fig. 6 shows the control loop and motor driver electric diagram of the A.C. regulator.

3.2.- D.C. Regulator

As the A.C. regulator with slow speed and great dynamics counterbalances the A.C. main line and the load variations,so the D.C. regulator is dedicated for its own characteristics at the fast changes.

Fig. 4 shows, among other things, the simplest conceivable closed loop control scheme for a D.C. regulator in which the load current, derived from a rectifier, is controlled by a D.C. regulating element

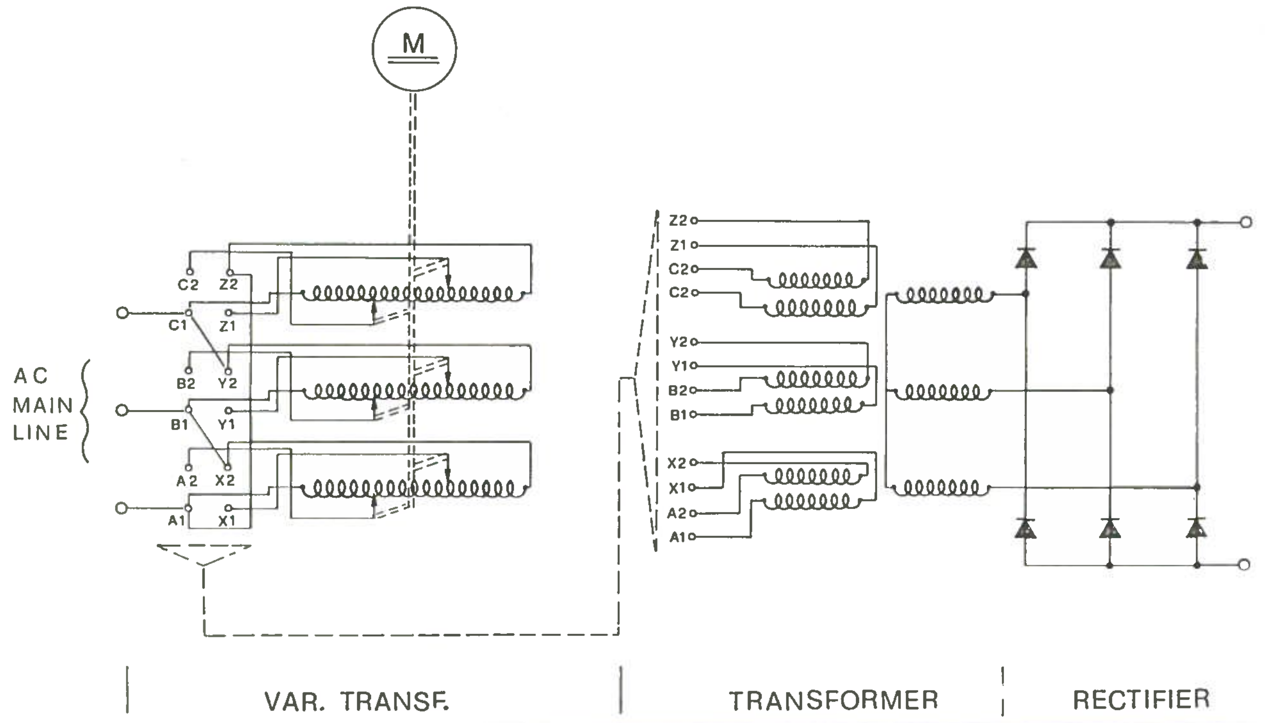

Fig. 5 - Electric diagram of the variable autotransformer, transformer and rectifier.

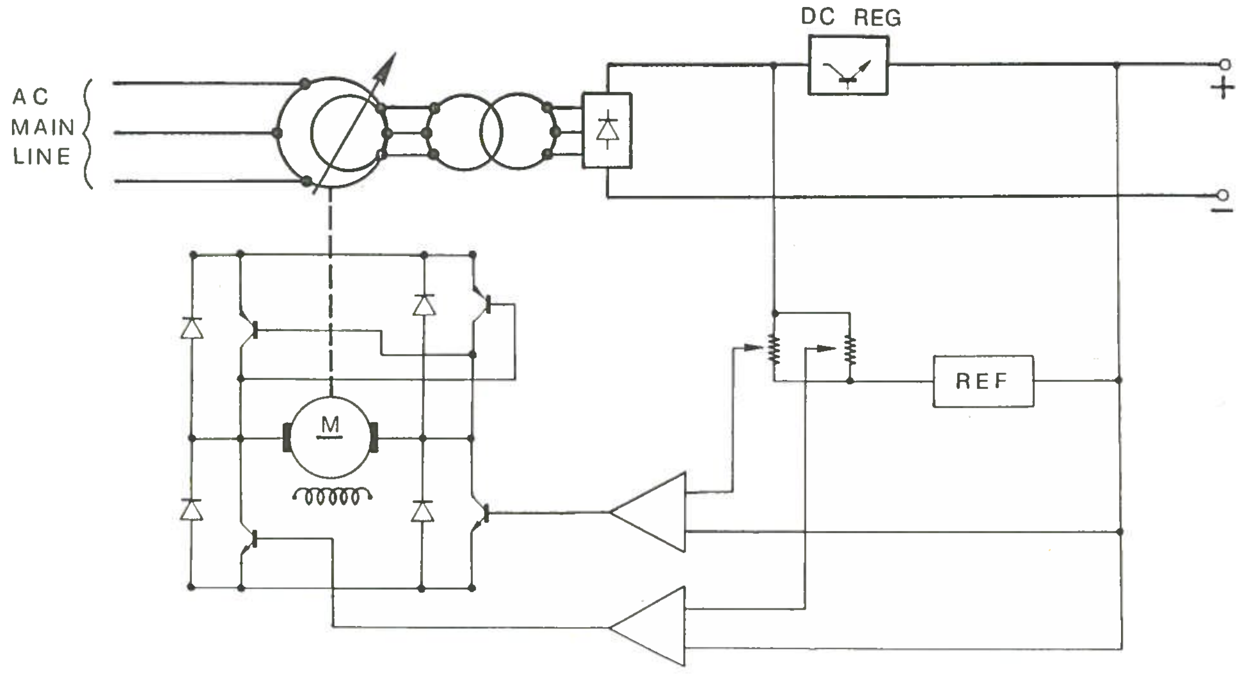

Fig. 6 - A.C. regulator control loop and motor driver.

which receives its control signal from a current sensor in series with the load and a fixed references voltage V_{ref}. The error signal is amplified in the D.C. amplifier, Σ, to give the overall low frequency loop gain GA.

The most succesful D.C. regulators are the power transistors, which apart from their thermal overload capability and limited dissipation show the best performance.

In the design of our D.C. regulator we have taken into account that silicon transistor with collector dissipation of 800 W and saturation collector current up to 250 A are easily available (type WT4433

Westinghouse), see Table V for details. The gain cut-off frequency is adequate for the suppression of the residual ripple components.

A linear series regulator capable to control 500 A has been assembled and tested. The good results allowed us to the construction of a 2000 A D.C. regulator.

Twenty-five transistors are in parallel with current sharing emitter resistor. The other three identical transistors are connected in Darlington configuration with the formers. All the twenty-eight transistors are bolted to a copper, water cooled, heathsink; a picture of the transistor-bank is shown in Fig. 7.

TABLE V

Collector to emitter voltage sustaining	80 V
Collector current cont.	250 A
Total power	830 W
Maximum junction temperature	150°C
H_{fe} at I_c 250 A	20
Collector to emitter voltage saturated	1.05 V
Base to emitter voltage saturated	2 V

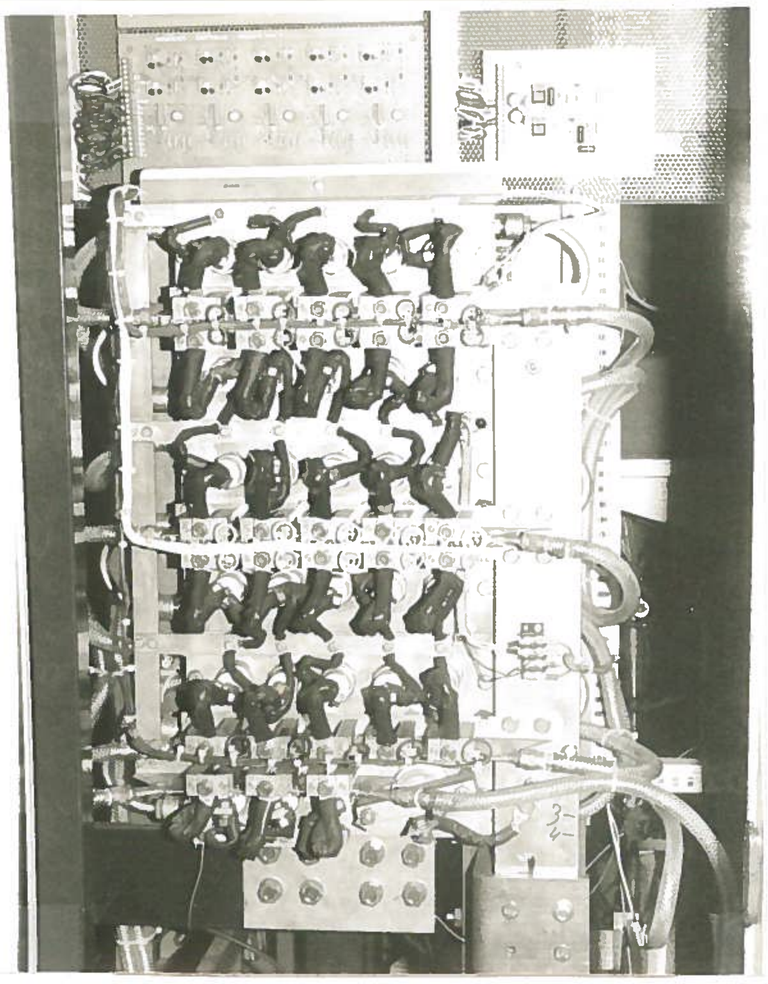

Fig. 7 - D.C. regulator.

The linear series regulator operates at a collector to emitter voltage of about 4 V, adequate to handle the total coarse deviation of the A.C. regulator plus the total excursion of the ripple components in the D.C., and without exceeding the permissible device dissipation.

Since the thermal overload capacity of the transistors is small, it is very important to protect them against overcoming the bounds of the safe operating area. In Fig. 8 is shown the electric diagram of the series regulator and the protective circuit of each transistor. The overcoming of the above mentioned limits is pointed out on the control panel and it switches-off the A.C. main line.

The D.C. regulator is also protected against reverse voltage with a fast recovery diode connected between collector and emitter to carry the total current of 2000 A.

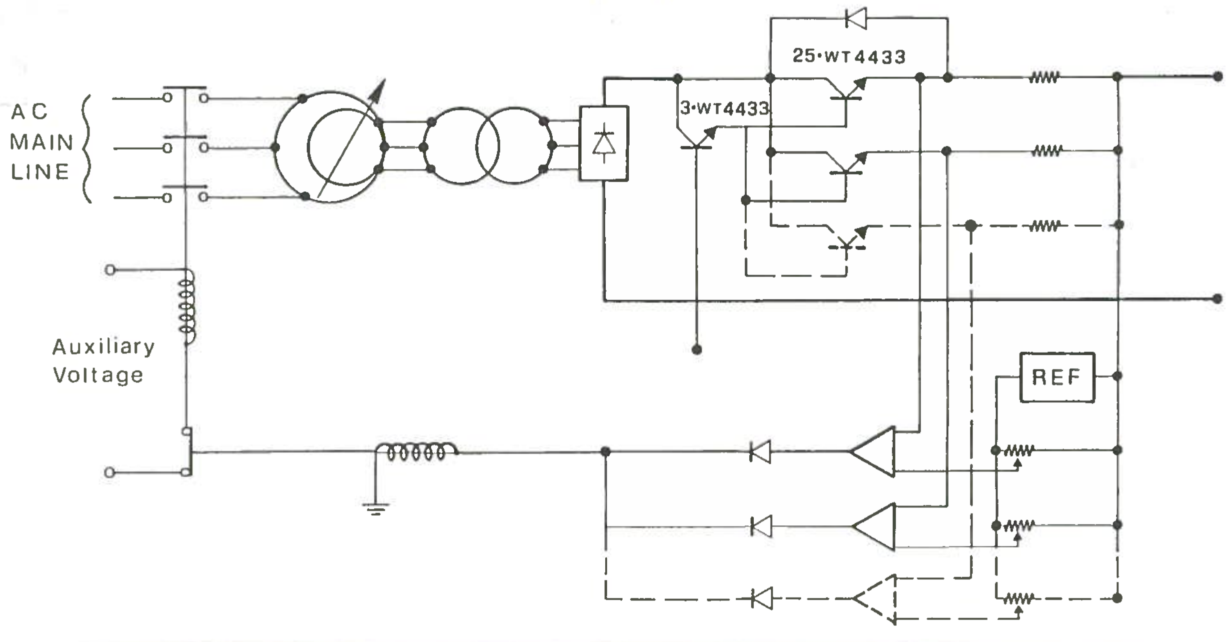

Fig. 8 - D.C. regulator overcurrent protection.

3.3.- Current sensor

Since the required stability makes the current control loop more important than the voltage control loop, an adequate current sensor is required.

The simplest current sensors are the standard resistors or shunt manufactured with manganin annealed and aged to stabilize their characteristics. Voltage drops across their terminals are about 1 Volt, at the maximum load current, typically. The electrical losses increases sharply with a load current of some hundred amperes and it is necessary to provide an adequate cooling system.

Due to the particular position of the current sensor, see Fig. 4, in case of a fast discharge of the coils current, the voltage between current busbars can rise at some hundred volts, so it would be better to fit up a contact-free device.

At current higher than some thousand amperes, it becomes interesting another current sensor called "Direct Current Transformer" or "Zero Flux Current Transformer". With a price similar to that of a precision shunt it offers the following benefits :

- Standard Resistor Precision;
- High output voltage with four terminal precision;
- Contact free sensing with high isolation level (Typ. 2500 V);
- Low power consumption;
- Extremely low ripple and noise.

The principle of operation of "Zero Flux Current Transformer"(3) as shown in diagram of Fig. 9, comprises a magnetic integrator and a second harmonic modulator. The current-carrying conductor is surrounded by three thoroidal cores. A sensing winding W2 on core T1 provides the flux rate feedback to a power amplifier A which drives the ampere-turn compensating current through a common compensating winding W1. The cores T2 and T3 operate as a second armonic modulator to establish zero flux operation and ensuring a perfect temperature-indipendent current balance. A burden resistor BR of high precision and thermal stability, converts the compensating current into a voltage signal which is amplified to give 10 output Volts at maximum load current.

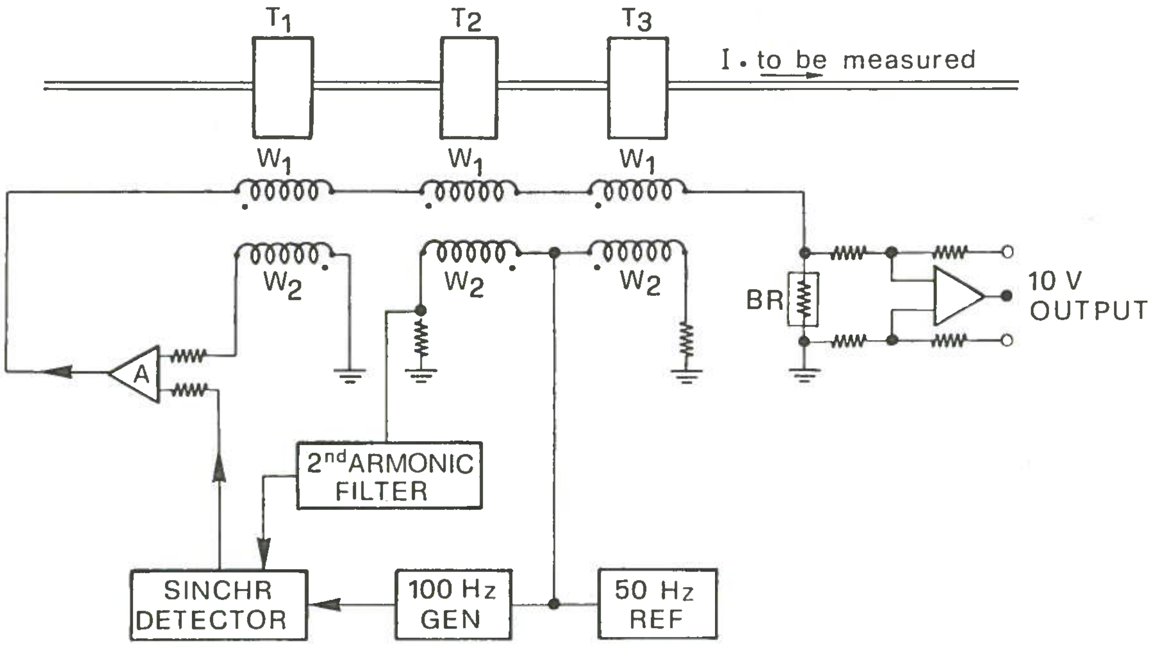

Fig. 9 - "Zero flux current transformer" simplified diagram.

The "Zero Flux Current Transformer" (DCCT) system comprises a core assembly and an electronic module, the standard interconnecting cables lenght is 2.5 m. The device that we have chosen is supplied by Holec Machine & System Group Hengelo, The Netherlands, and the main performance data are listed in Table VI.

The initial ratio and offset errors can be eliminated by a on site calibration.

TABLE VI

Nominal primary current	± 2500 A
Output voltage at I nominal	± 10 V
Maximum output current	2 mA
Output impedance	1mOhm
Bandwidth, small signal	10 kHz
Test isolation voltage (50 Hz 1 Min)	2500 V
Noise voltage (rms)	10 ppm of F.S.
Ratio errors :	
Initial	100 ppm of F.S.
Vs temperature	1 ppm/°K
Vs time	1 ppm/month
Linearity error	5 ppm
Offset errors :	
Initial	10 ppm of F.S.
Vs temperature	1 ppm/°K
Vs time	1 ppm/month
Ambient temperature range	15-35°C
Power consumption at I nominal	150 VA
Supply voltage	220 V 50 Hz 1 Phase

3.4.- Error Amplifier and Reference

The current control loop requires, in addition to the current sensor, a precision high gain amplifier or error amplifier and a voltage reference of a very high stability.

For a load current stability of about 10^{-5} a loop gain of at least 10^{6} will be required, since the transistor bank and the driver have a gain of about 10^3 an error amplifier of a open loop gain of 10^4 will be necessary. High gain solid state amplifier are available at low cost, with the typical characteristics described below :

- Open loop gain	10^5
- Passband	0.5 MHz
- Offset Voltage + Long term variation	5 μV
- Noise rms	5 μV.

We have designed a printed circuit in which it is possible to fit up a low cost, type μA 714, error amplifier or if it will be necessary, a chopper stabilized high gain amplifier as AD 235, TP 7201, etc.

If the amplifier errors including noise is to be 10^{-5} of the full signal, a reference voltage of $10\ \mu V \times 10^5 = 1\ V$ is required. For safety reasons, a voltage reference five ten times higher is usual.

The reference voltage is supplied by a digital to analog converter with 18 bits linearity and precision type AD 1138 K, see Table VII for more details. This choice makes possible the control of the power supply by a controller μProcessor based[(4)].

TABLE VII

Resolution	18 Bits
Magnitude of 1 LSB	38 uV
Output range voltage mode	0 to ± 5 V; 0 to ± 10 V
Rated output current	4 mA Max
Noise rms 10 to 100 kHz	38 uV Max (10 V)
Accuracy (LSB) :	
Differential linearity error	± 0.2 (± 0.5 Max)
Integral	± 0.3 (± 0.5 Max)
Temperature coefficient (ppm/°C):	
Differential linearity	0.4
Integral	0.3
Gain	1
Offset	0.5
Operating temperature	0 to + 70°C

A simplified block diagram of the computer control is shown in Fig. 10.

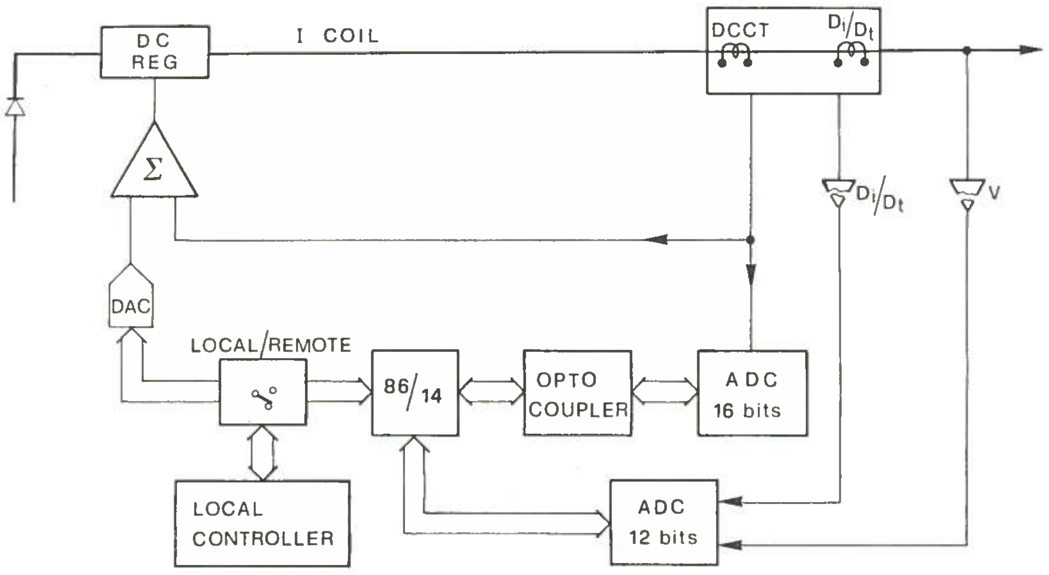

Fig. 10 - Block diagram of the computer control module.

The output voltage control loop of the power supply is very similar to the current control loop, the only difference is in the lower required stability, the change of the control mode is achieved by the controller.

3.5.- Protective circuits

A protective system which automatically interrupts the main A.C. line of both supplies in the event of any of the following conditions in either supply has been designed :

- A.C. interruption (Fuses, Thermomagnetic relay intervent);
- Loss of balance in main transformer secondary current;
- High temperature of : main transformers, rectifiers, D.C. regulators;
- Low flow of cooling water;
- Output : current, voltage, dI/dt limits exceeded;
- Auxiliary voltage failure;
- Regulators and control circuits failure;
- Interlocks (Personnel safety, Quench Detection System, Current Dumping System, cryogenics, and so on).

The trip of the protection circuits is detected and memorized in order to achieve a fast diagnosis of the troubles.

A summary of failures is also monitored on the local control panel and sent to the computer control system.

3.6.- Local/Remote controls

Test and maintance of the supply are possible in "Local" operation mode throw a suitable panel which allows :

- Local/Remote choice of operation;
- ON/OFF commands;
- Current set (Thumbwheel-switches five digits);
- Charge rate change (Four selectable rates);
- Analog control of major electrical parameters (Panel meters) .

Normal working procedure is "Remote" position of the key-switch which forbids the possibility of local control/commands with these exceptions :

- Emergency cutoff;
- Current display;
- Panel meters.

Remote controller shall provide signal for :

- ON/OFF commands;
- Current and voltage references (DAC);
- Choice of regulation "mode";
- Analog regulation loop supervision;
- Failure diagnosis.

3.7.- Housing

The two sections of the power supply are contained, with the control station and the DCCT electronic modules, in a cabinet composed of two identical parts easily detachable for transport and building installation problems; the outline dimensions are :

- Width	2 mt
- Depth	2 mt
- Height	2.2 mt.

The total weight is about 3 tons.

4.- CURRENT DUMPING SYSTEM

The superconducting coils behaviour in case of a quench has been carefully studied. The specification listed in Table III are a compromise between :

a) Temperature rise of superconductor in fast current discharge condition;

b) Voltage build up, when the dump switch opens, at the coil terminals.

The current settings I_α and I_β for a fixed dump resistor value are plotted as a function of the time during a quench in Fig. 11. The same figure shows also T_{max} i.e. the maximum coil temperature for differents quench acquisition time between zero to ten seconds.

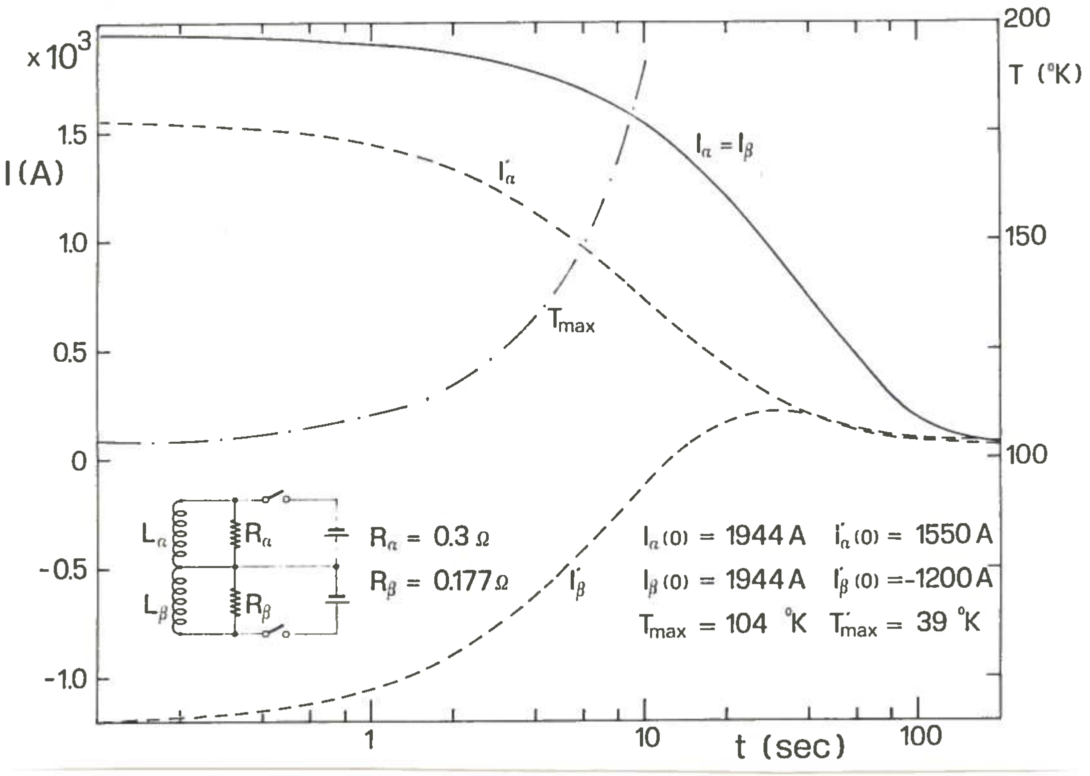

Fig. 11 - I_α , I_β variation, with fixed dump resistors, during a quench, T_{max} of the coils with different quench acquisition time.

4.1.- Dumping switches

The choice of these components is not very difficult, in fact the current and voltage ranges are very similar to those of high power D.C. motors. Italian industry has a good experience in their design and construction.

In our case working conditions are better than in D.C. motor control because of the negligible inductivity of the dumping resistors.

We have chosen and installed two electromagnetic bipolar switches type 331.9 supplied by CGE Company, Milan. In order to increase the opening speed and voltage performances the two poles of the switches are connected in series, a particular opening circuit was installed.

The main characteristics of the device are listed in Table VIII.

TABLE VIII

Maximum continuous current In	2750 A
Maximum voltage	700 V
Breaking power (700 V)	8000 A
Opening time maximum (8000 A; 700 V)	30 msec

A test series were performed on a switch of this type, electrical diagram and typical recording are shown in Fig. 12.

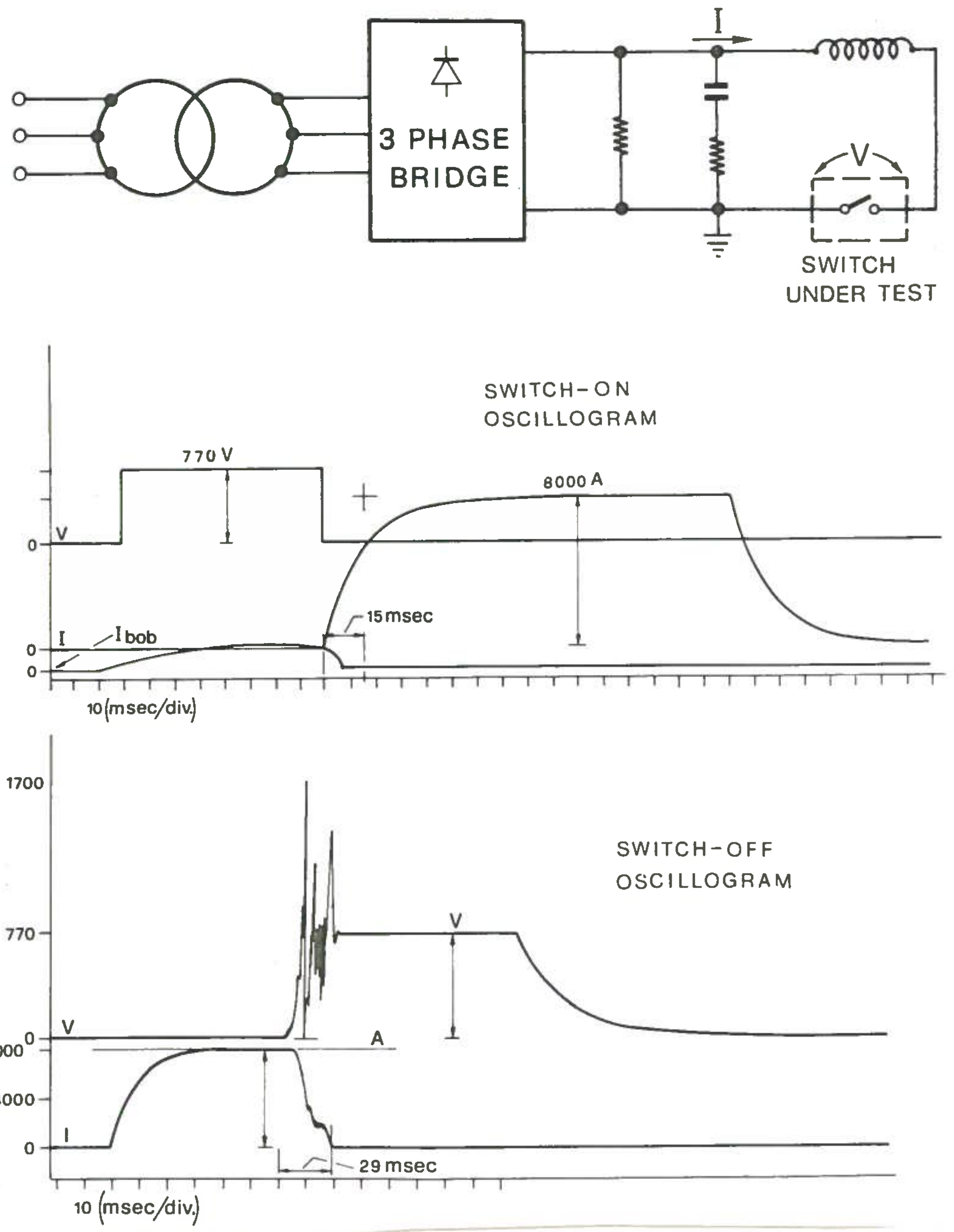

Fig. 12 - Test circuit and test recording of the dump switches.

4.2.- Dumping resistors

A basic consideration is essential in the choice of this component : is it better water or air cooling?

The minor complexity of free-air cooling system, even if the former is cheaper and lighter, persuaded us that this is more reliable. A good suggestion in this direction is a dump resistor water cooled failure at M.S.U. K 500 Cyclotron$^{(6)}$.

Design criteria are the following :

- Resistance value in order to give:

Maximum voltage at 2000 A across α terminals	600 V
Maximum voltage at 2000 A across β terminals	350 V;

- Maximum temperature rise of 300°C when all stored energy in the coils is dissipated (adiabatic condition);
- Inductance as lower as possible, to prevent voltage build up when operating dump switches.

The basic element of the dump resistors is a patended GF2 alloy of high resistivity, high heat capacity and negligible variation of resistivity at full load.

The physical characteristics of the basic GF2 element are listed in Table IX. Worse conditions than those plotted in Fig. 11 have been simulated in preliminary tests. The results obtained on four parallel GF2 A3 elements are shown in Fig. 13.

TABLE IX

Resistance (20°C)	0.02 Ohm
Resistance (450°C)	0.023 Ohm
Heath capacity	580 Kjoules
Surface	0.13 m^2
Length	2.258 m
Weight	2.450 Kg
Resistivity	2 Ohm/mm^2/Mt
Continuous duty current strenght	135 A (530 A at 5%)
Overload capacity	2.7
Maximum temperature	800°C

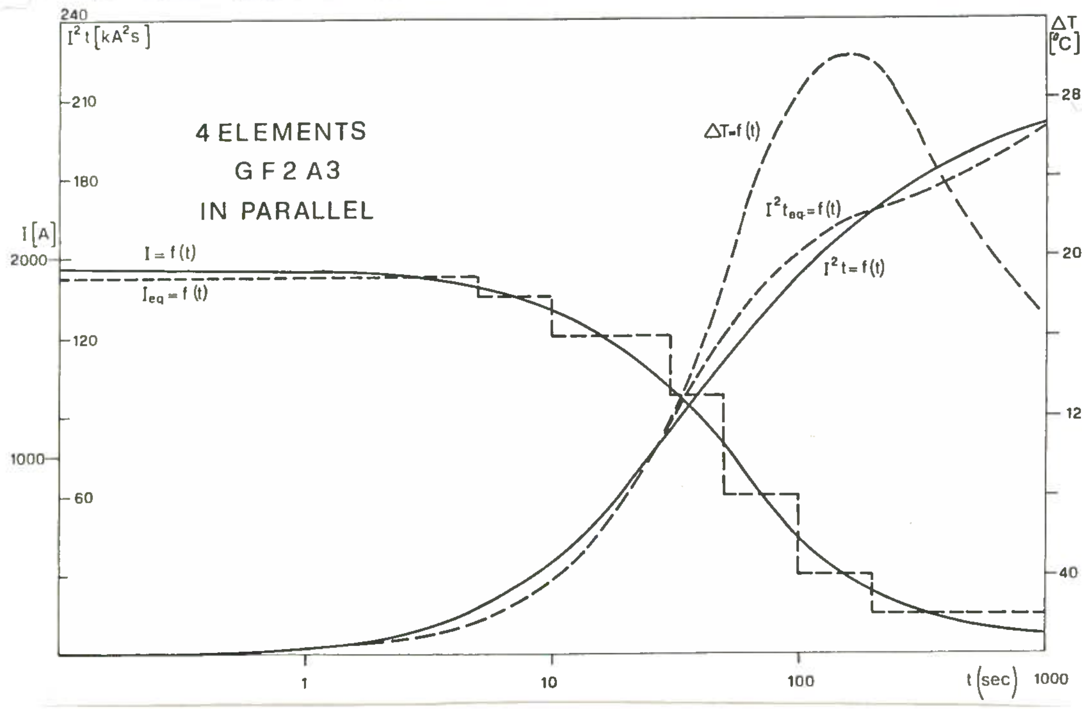

Fig. 13 - Plot of the results of preliminary test on GF2 A3 elements.

The dump resistor DR_α is assembled with 160 elements, the dump resistor DR_β is assembled with 96 basic elements.

A cabinet of the same size of the power supply contains the dump resistors, dump switches, current sensors and polarity reverser of β coil current. See picture of the two cabinets in Fig. 14.

Tests have been carried out in the resistors assembled and installed in the cabinet for the cases of about 32 Mjoule and 20 Mjoule on the dump resistors of the α and β coil respectively. Test circuit and temperature variations are plotted in Fig. 15.

5.- CONCLUSIONS

The construction of the power supply and dumping system started in 1982 and was completed at the beginning of 1984. The interconnecting circuit between the two cabinets positioned as in building is also completed. Test are now in progress in order to verify the expected performances as :

- Long term current stability;
- Voltage ripple and noise of the power supply;
- Thermal heating of the main components;

on a resistive dummy load. A few other are programmed in next months for the computer controller.

6.- ACKNOWLEDGEMENTS

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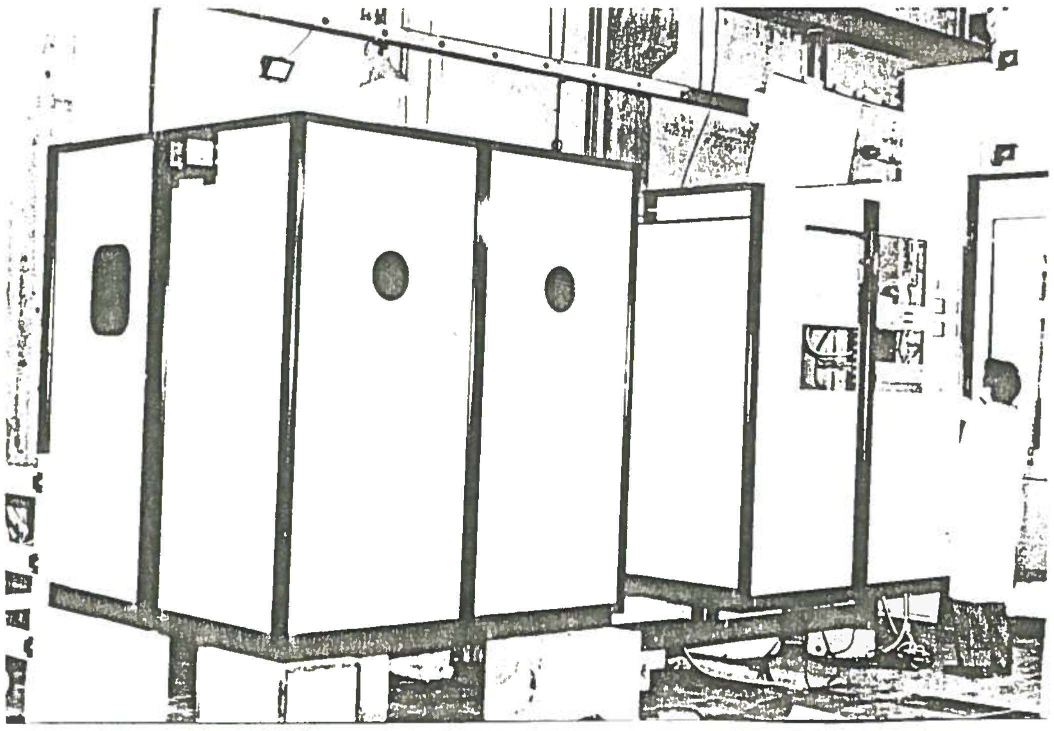

Fig. 14 - Power supply and dumping system cabinets.

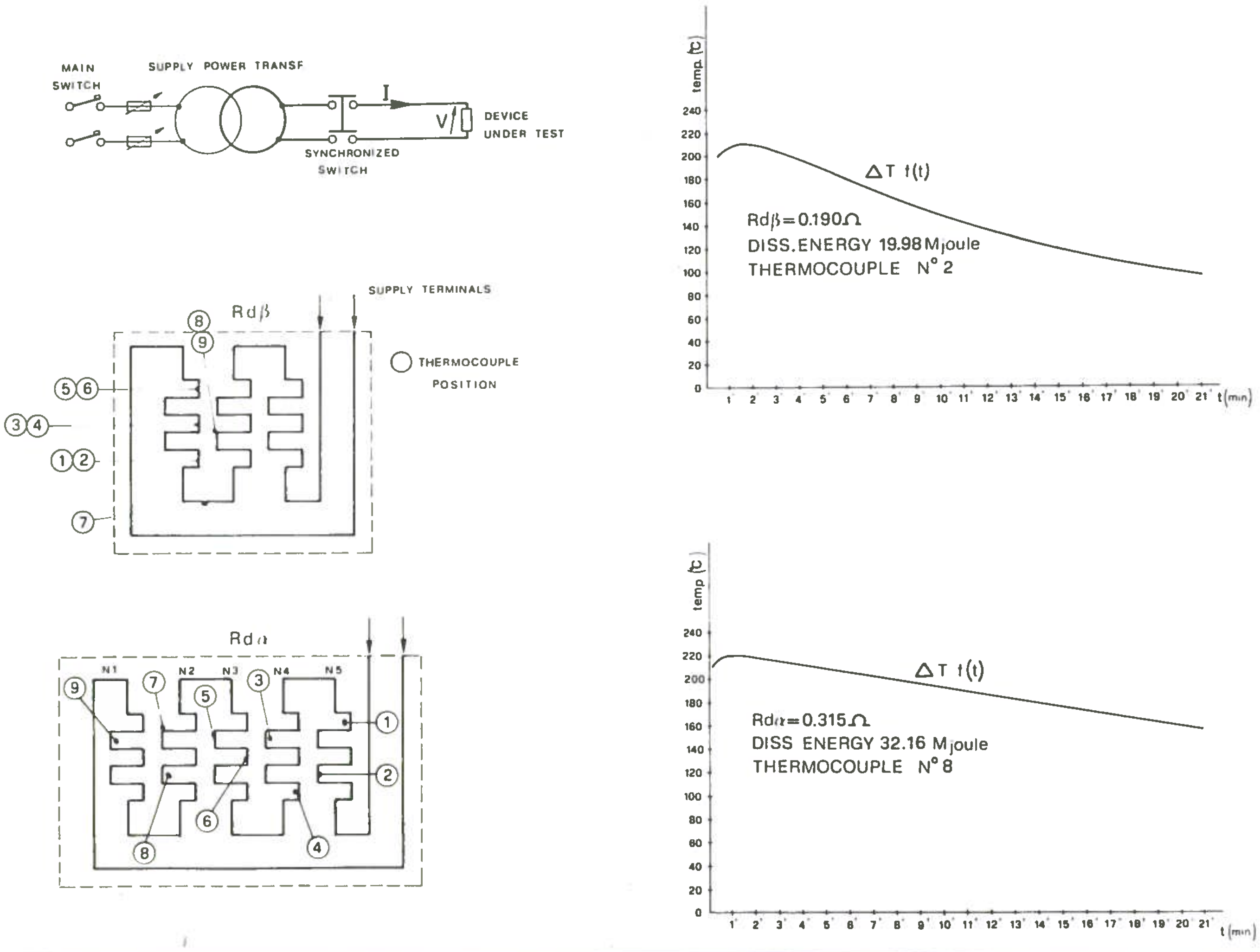

Fig. 15 - Test circuit and temperature curves of the dump resistors.

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