CORRECTION MAGNET SYSTEM OF NAL MAIN ACCELERATOR

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Abstract

Several different types of correction magnets have been installed in the NAL Main Accelerator. Approximately 100 horizontal and 100 vertical correction magnets are used to correct injection field, which is affected mostly by the remanent field variation of main bending magnets. These magnets are independently controlled from the control room with individual dc power supplies. About 200 air core sextupole magnets are used to correct sextupole field in the main bending magnets due to remanent and eddy current fields. These magnets are controlled simultaneously through three pulsed power supplies. Thirty-six trim quadrupole magnets and thirty-six iron core sextupole magnets will be used to correct high harmonic resonances. Twelve air core skew quadrupole magnets will be used to compensate coupling between horizontal and vertical motions.

Introduction

The correction magnets presently installed in the Main Ring to correct magnetic field imperfections of the main bending and quadrupole magnets include horizontal and vertical dipole correction magnets, air core sextupole magnets, iron core sextupole magnets, trim quadrupole magnets, and skew quadrupole magnets. Figure 1 shows pictures of these magnets.

The horizontal and vertical correction magnets were used since the beginning of accelerator operation to correct the variation of the remanent field of bending magnets, effects from misalignment of the main quadrupole magnets, and earth magnetism. A 100 GeV beam was attained using only these correction magnets. Later the air core sextupole magnets were used to achieve acceleration up to 200 GeV to correct sextupole fields in the bending magnets during injection. The use of these two types of correction magnets has been essential in maintaining a stable accelerated beam.

The iron core trim quadrupole magnets and sextupole magnets will be used to correct higher resonances at and just beyond injection. The skew quadrupole magnets will be used to correct roll error of the quadrupoles.

At present, all correction magnets except the air core sextupole magnets are controlled independently by individual modular power supplies controlled from the control room. Presently the air core sextupole magnets are powered in series by three different power supplies, each supply controlling one third of the magnets.

Horizontal and Vertical Dipole Correction Magnets

Dipole correction magnets are used to steer the beam horizontally and vertically in order to maintain the beam orbit near the center of the vacuum chamber during injection. Large radial deviations of the beam are present due to variations in the remanent field of the bending magnets. The measured rms deviations in remanent field are 1.3 G and 0.9G, corresponding to the average remanent fields of 17 G and 13 G for the B1 and B2 magnets, respectively.[1] Radial orbit deviations due to the remanent field are estimated to be about ±5 cm. Radial deviations due to horizontal misalignment of the main quadrupole magnets are roughly ±1 cm and less important. The effect of earth's magnetic field in the long straight sections is small.

On the other hand, vertical deviations are caused by vertical misalignment of the quadrupole magnets and roll of the bending magnets. These effects are particularly important during injection when the beam size is largest. The estimated vertical deviation is smaller than ±1cm.

About 100 horizontal and 100 vertical dipole correction magnets are being used. A horizontal correction magnet is placed immediately following a horizontally focussing quadrupole magnet. Since at the horizontal focussing quadrupole the beam is narrow vertically, the horizontal correction magnet can be made with a narrower gap. The same thing can be said for a vertical correction magnet.

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At both ends of the six long straight sections, a pair of horizontal and vertical correction magnets are installed. These correction magnets have wider magnetic gaps to accommodate a larger vacuum chamber (2" x 5" as compared to 1.5" x 5" or 2" x 4"). The important parameters of the dipole correction magnets are given in Table I.

Trim Quadrupole Magnets

Trim quadrupole magnets can be used for independent fine tuning of horizontal and vertical tunes (ν_x and ν_y) and for excitation of the 41st harmonic with changeable amplitude and phase to cancel the half integral stopband at $\nu = 20.5$.

Thirty-six iron core trim quadrupole magnets are installed in the Main Ring. This system provides a tune shift of ±0.5. The magnets are 12 in. long and have a gradient range of ±4 kG/m. A quadrant coil consists of 81 turns of #13 square conductor.

Skew Quadrupole Magnets

Coupling between horizontal and vertical motions can be caused by skew quadrupole field. Sources of this coupling field are mainly roll error of the main quadrupole magnets, vertical displacement of the beam in sextupole field in the main bending magnets and correction sextupole magnets, and unpaired inner-coil ends of the main bending magnets. The largest contribution may be due to the roll error.[2] This coupling will cause beam loss during injection when the beam size is largest and will also reduce resonant extraction efficiency.

Twelve air-core skew quadrupole magnets are built and installed in the Main Ring in order to compensate possible coupling field at the injection. Each magnet is 24 inches long and consists of four identical coils of 40 turns each. Due to spatial limitations, the magnet is designed with a radius of 5 in. and mounted over an air-core sextupole magnet. A gradient range is ±2 G/cm for a current range of ±5 A. The internal gradient as measured along one axis at ±2 in. varied by less than 3%. The magnet parameters are summarized in Table II.

This system of the twelve skew quadrupole magnets can compensate an rms roll error of 5 mrad in the main quadrupole magnets at the injection.

Air-Core Sextupole Correction Magnets

Sextupole correction magnets are used to compensate remanent sextupole fields in the main bending magnets during injection and also to compensate sextupole fields due to eddy currents in the vacuum chamber and conductors of the main bending magnets at the beginning of the acceleration.

The sextupole components in the remanent fields of the B1 and B2 bending magnets have been measured to be $B'' = -0.64$ and -0.56 kG/m^2. The sextupole field components due to eddy currents for the B1 and B2 magnets have been measured to be $B'' = +0.6$ kG/m^2 and $+0.4$ kG/m^2 respectively for the maximum field changing rate during the ramp of 6 kG/sec (sextupole due to eddy currents are proportional to the field changing rate). It can be seen that the sextupole fields nearly compensate each other when dB/dt is a maximum.

Originally, 190 air-core sextupole magnets were installed in the Main Ring in order to remove strong non-linear behavior arising from the sextupole fields described above. In general, one air-core sextupole magnet is distributed for every four main bending magnets (which includes two B1 and two B2 magnets). Each is 24 in. long and has a field strength of 10 G at one inch for a maximum dc current of 40 A ($B'' = 31$ kG/m^2). The magnet parameters are summarized in Table II.

Some of the air-core sextupole magnets have been removed from the mini-straight sections to install various types of extraction equipment. At present, about 160 air-core sextupole magnets remain at diagonally symmetric locations in order to avoid a possible 61st harmonic resonance.

About 30 of the air-core sextupole magnets in each superperiod (the Main Ring consists of six superperiods) are connected in series, making a loop. Two sextupole loops corresponding to two superperiods are connected in parallel to one of three pulsed power supplies.

The present arrangement cannot provide simultaneous correction of horizontal and vertical tunes as a function of momentum. However, the sextupole current wave form shown in Fig. 2 was found to give an adequate and satisfactory correction. The decrease in current from 40 A to 20 A is necessary to correct for the eddy current sextupole component due to a field changing rate of about 3 kG/sec, which occurs during the earlier part of the acceleration cycle, shown in Fig. 2.

Iron-Core Sextupole Correction Magnets

Thirty-six iron-core sextupole magnets are installed in the Main Ring. They are 6 in. long and have a maximum field gradient of $B'' = 280\ \mathrm{kG/m^2}$ at a current of 5 A. The central two pancake coils have 20 turns and the remaining four coils have 140 turns each. (See Fig. 1E) The magnet parameters are summarized in Table II.

They will be used for fine tuning of horizontal and vertical tunes and for compensation of a possible 61st harmonic resonance.

Production Processes

In order to reduce the effect of remanent field in the iron-core correction magnets, silicon steel laminations with low coercive force are used. ARMCO Steel A6, Gauge 26, is used for dipole magnets, and M22, Gauge 22, is used for sextupole magnets and trim quadrupole magnets. The laminations were punched and assembled by reversing every inch. The outside of the core is TIG welded with several tie bars under pressure to keep the exact shape and to prevent fanning out of laminations. About a dozen of the welded half-cores were pressed again on a flat table to retain the dimensions and soaked with a thinly diluted epoxy, curing overnight. The supports which are welded to the top half-core have register notches that allow them to be mounted quickly and accurately in place (Fig. 1). The other half-core is brought up from beneath the vacuum chamber, and is fastened with four bolts to the former. The half-cores are prevented from shifting with respect to each other by a round key which fits in the backleg.

The coils of the horizontal and vertical correction magnets were wound randomly on special coil winding frames using AWG #13 round wire with polyimide insulation. Then the coils were overwrapped with 7 mil glass tape, pressed into molds, and vacuum impregnated. The epoxy formulation contains 100 parts by weight of resin 204E, 100 parts of MNA, 1 part of accelerator DMP30, and 50 to 100 parts of alumina filler. A small amount of carbon black die was also added to give a uniform appearance to the coils. They were heated to 120°F to facilitate the epoxy flow and then cured at 220°F for a minimum of 4 hours.

The coils for trim quadrupole magnets and iron-core sextupole magnets were made with AWG #13 square conductor insulated with a polyimide coating. These coils were layer wound to achieve maximum copper density and fully vacuum impregnated. The epoxy formulation is similar to the above but without black dye.

The finished coils were glued to the cores. The coil resistance to core is checked and an induction test is performed which compares all coils to a standard. Also, the field tests were done.

The air-core sextupole magnets were wound with AWG #7 square conductors with polyimide insulation. The coils were ground wrapped with a layer of half overlapped adhesive glass tape. The six coils were clamped to a specially shaped bakelite form which was mounted on the vacuum tube, as shown in Fig. 1F.

The skew quadrupole has coils wound with AWG #13 round conductor which were simply wrapped with adhesive glass tape to keep the turns in place.

Control System

The control system for the correction magnets is a part of the integral Main Ring control system which also handles beam position detectors, radiation loss monitors, beam observation flags, and so on. A block diagram for this system is shown in Fig. 3. The principle of the system, consisting of the console and XDS $\Sigma 2$ computer is described in a paper which describes the control system of NAL 200 MeV Linac[3]. The mini-computer (a Lockheed MAC-16), Main Ring cabling system, and House Logic Unit (HLU), are described in a paper related to the Main Ring control system[4].

Related information, such as the device name, location, and setting, are converted into digital form and sent out to the service building through MAC-16 mini-computer and transmission cable. The digital information is received by the related HLU, which forwards the setting information to the specified power supply controller. There the digital data is converted into an analogue value, and the magnet current is changed accordingly. The output voltage across a standard resistor, which is proportional to the current, is sent to a multiplex analog-to-digital converter (MADC). It changes the signal into a digital form and sends it back to the console through the same communication system around the Main Ring. In case of a malfunction, the system can be checked locally at the HLU or at the unit power supply using a specially made digital box.

Operation

By entering the designated name of a

correction magnet, e.g., HA-11, on a TV display through a keyboard, the present setting of that magnet appears automatically on the screen. A single control is provided for setting device values such as magnet currents. These functions are handled by the $\Sigma 2$ computer.

There are display pages where all of the settings or readings of the current value of all the magnets of a kind can be displayed simultaneously on a Tektronic 611 display unit. A typical display is shown in Fig. 4. In the lower part of that display, the setting of all magnets is shown in analogue form. If there is a difference between the set value and the read value beyond a specified amount (usually 3 or 4), there appears a darkened square, which is indicative of a malfuntioning device. The setting of all the correction magnets can be stored and retrieved within seconds by pressing a special button.

All the magnets can simultaneously be set to a specified value which is done to check them for malfunctioning. In addition, the magnet settings can be changed bit by bit automatically and simultaneously to check malfunctioning of individual bits.

Three or four magnets in sequence can be ganged in a specific manner to make a bump in the beam orbit. All of the magnets of the same type (about 50 for horizontal or vertical magnets) can be ganged to produce 20th, 21st, or other harmonics, and can be changed simultaneously.

Power Supplies for Individual Magnets

All correction magnets except air-core sextupole magnets have individual power supplies and can be controlled from the Control Room. There are twenty-four service buildings around the Main Ring. Each building has two power supplies, each of which contains six modular units as shown in Fig. 5.

The unit power supply is a bi-directional constant current supply with a maximum current of 5 A and can be controlled in the range of ±128 units (1 unit corresponds to about 40 mA). The current ripple is less than 0.1%. The maximum available output voltage is about 30 V. Darlington type power transistors MJ4032 and MJ4035 are used for output transistors.[5]

The power supply has a high frequency response. But when it is used for a dipole correction magnet, its response is intentionally slowed down by putting capacitors at several places in the circuit. Otherwise, the transient voltage exceeds 100 volts and in some instances, the power transistors were blown out. Also, a pair of bucked Zener diodes are connected at the output terminal of the power supply to cut transient voltage. For a magnet with less inductance, this precaution is not needed. Thus the rise time of the magnetic field in horizontal correction magnets is about 100 ms, but that of an iron-core sextupole is about 20 ms. To reduce heat dissipation in the power transistors, resistors are included in series with the trim quadrupole magnets and iron-core sextupole magnets, thus r raising their impedance to better match the power supplies. If it is needed, the power supply can be programmed and current setting can be changed during a ramp of main ring pulse.

Acknowledgements

The authors wish to extend their sincere thanks to the many colleagues for their consultation and assistance during this project.

References

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3. R. W. Goodwin, "NAL Linac Control System Software," Proceedings of the 1970 Proton Linear Accelerator Conference (1970), p. 371.
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TABLE I Parameters (I)

Types of Magnets	Horizontal Dipole	Vertical Dipole
Effective Magnetic Length	10.0 in.	9.1 in.
Aperature (height and width)	1.9 x 5.4 in.^2	2.4 x 4.2 in.^2
Maximum Field (± 5 A current)	± 680 G	± 430 G
Maximum Bending Angle (8 GeV)	± 0.58 mrad	± 0.34 mrad
Maximum Deviation (8 GeV)	± 2.2 in.	± 1.3 in.
Resistance per magnet	3.6 Ω	4.4 Ω

TABLE II Parameters (II)

Type of Magnet	Trim Quadrupole	Skew Quadrupole	Air-Core Sextupole	Iron-Core Sextupole
Length	12"	24"	24"	6"
Aperture	$xy = 2\ \text{in.}^2$	5" in radius	3.5 " in radius	2.4" x 5"
Maximum Field Gradient	3.9 kG/m at 5 A	0.20 kG/m at 5 A	$B'' = 32\ \text{kG/m}^2$ at 40 A	$B'' = 280\ \text{kG/m}^2$ at 5 A
Resistance per magnet	1.5 Ω	1.2 Ω	0.10 Ω	1.6 Ω

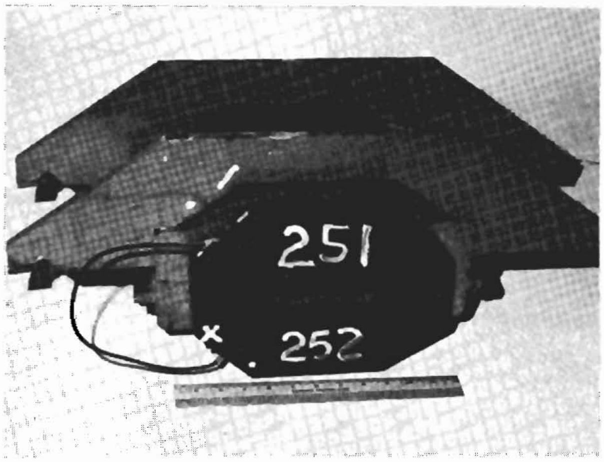


Fig. 1A Horizontal Dipole Magnet

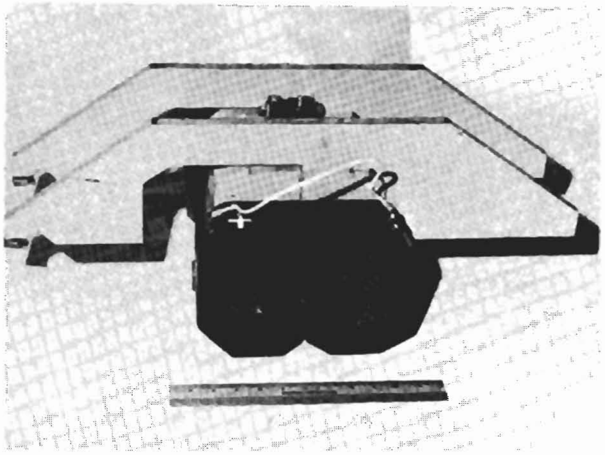


Fig. 1B Vertical Dipole Magnet

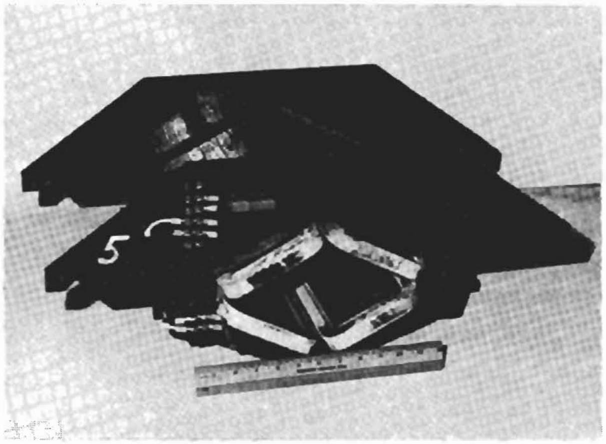


Fig. 1C Trim Quadrupole Magnet

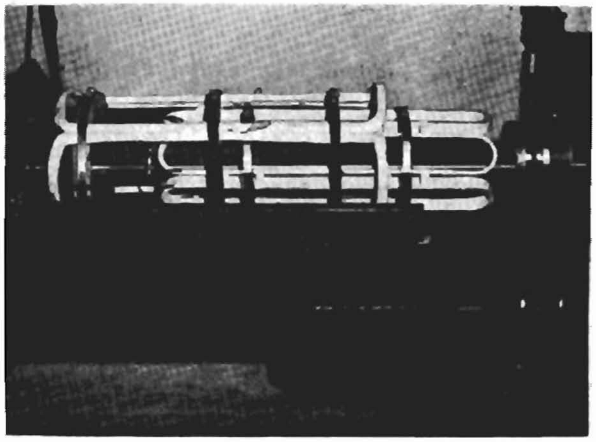


Fig. 1D Skew Quadrupole Magnet
Mounted on Top of Sextupole Magnet

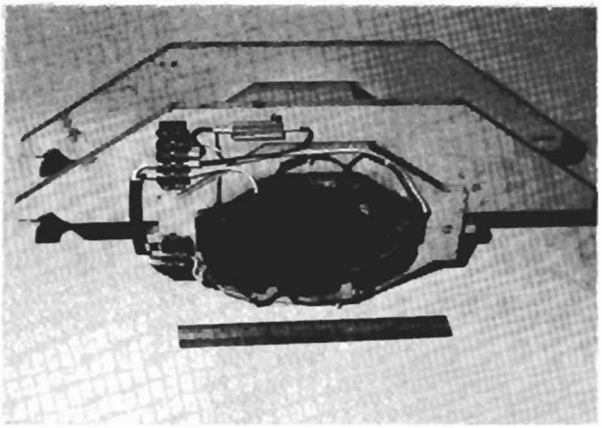


Fig. 1E Iron-Core Sextupole Magnet

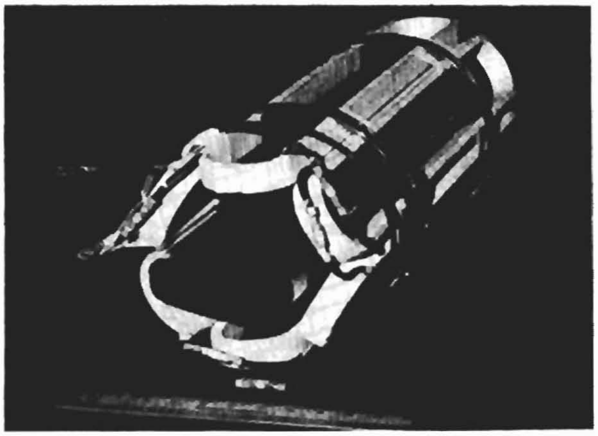


Fig. 1F Air-Core Sextupole Magnet

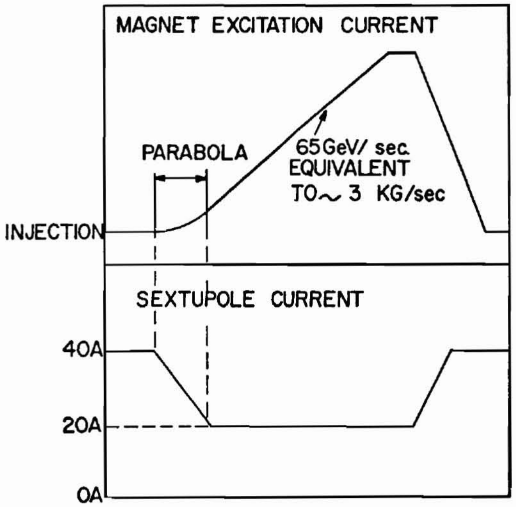


FIG. 2 ACCELERATION CYCLE OF SEXTUPOLE MAGNETS RELATIVE TO MAIN MAGNET EXCITATION CURRENT

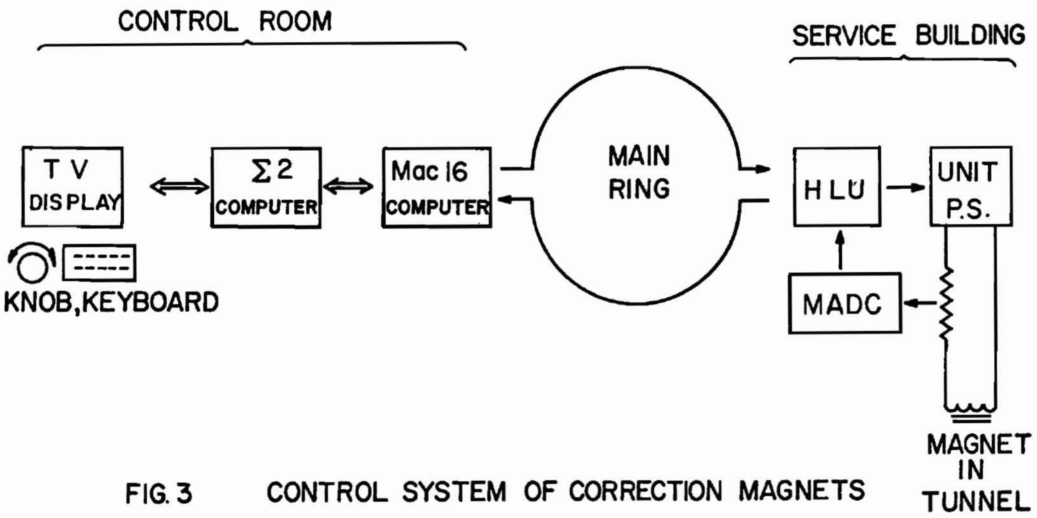


FIG. 3 CONTROL SYSTEM OF CORRECTION MAGNETS

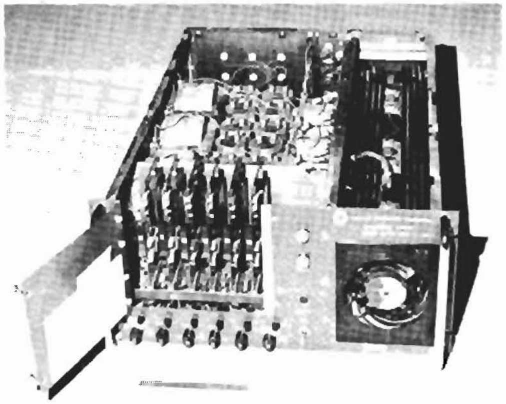
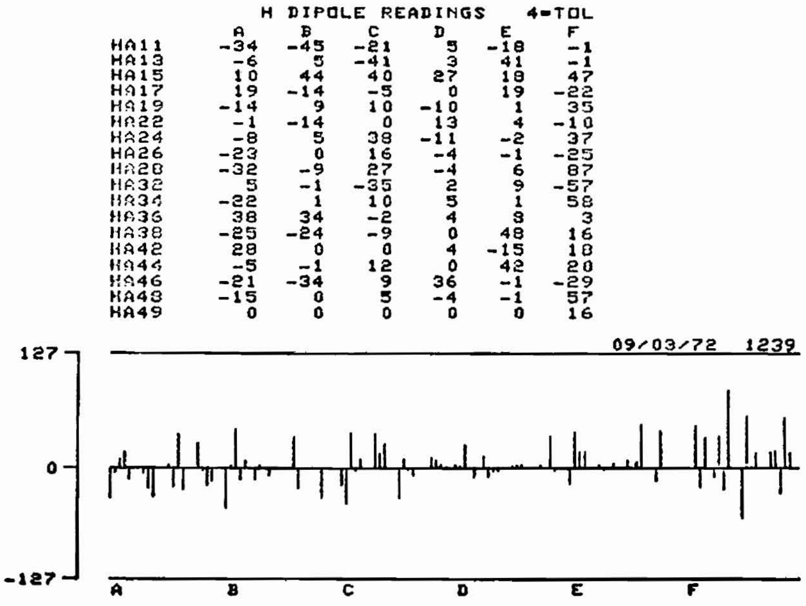


Fig. 5 Modular Unit Power Supply



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                H DIPOLE READINGS    4=TOL
           A     B     C     D     E     F
HA11     -34   -45   -21     5   -18    -1
HA13      -6     5   -41     3    41    -1
HA15      10    44    40    27    18    47
HA17      19   -14    -5     0    19   -22
HA19     -14     9    10   -10     1    35
HA22      -1   -14     0    13     4   -10
HA24      -8     5    38   -11    -2    37
HA26     -23     0    16    -4    -1   -25
HA28     -32    -9    27    -4     6    87
HA32       5    -1   -35     2     9   -57
HA34     -22     1    10     5     1    58
HA36      38    34    -2     4     8     3
HA38     -25   -24    -9     0    48    16
HA42      28     0     0     4   -15    18
HA44      -5    -1    12     0    42    20
HA46     -21   -34     9    36    -1   -29
HA48     -15     0     5    -4    -1    57
HA49       0     0     0     0     0    16
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FIG. 4 DISPLAY OF DIPOLE MAGNET CURRENTS