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TABLE OF CONTENTS

I. Introduction

II. Discussion of the field measuring instruments

a.) Nuclear magnetic resonance device

b.) Electron magnetic resonance device

c.) Flip coil - Integrating method

Miller integrator

Voltage to frequency converter

d.) Gated integrator for the pulsed magnet

e.) Hall device

III. Probes

a.) NMR probe

EMR probe

Flip coil assembly

IV. Cables

V. Proposed system

MAGNETIC INSTRUMENTATION FOR THE BEAM SWITCHYARD

I. INTRODUCTION

In order to use effectively the electron beam from the Stanford two-mile linear accelerator, an elaborate beam switchyard is needed. The magnets in this switchyard will provide the 12° and 24° deflections necessary to allow the various experimental areas to be reasonably well shielded and separated from each other. Two basic components will constitute the switchyard: a switching magnet and a deflecting magnet system. Figure 12 shows the switchyard schematically.

The switching magnet will serve to divert the beam into the deflecting magnet system; it is designed for pulsed operation. This provides the capability of switching only occasional pulses into the experimental areas. The pulsing rate for switching magnet is 360 cycles per second. The magnet pulser is able to pulse the magnet with an accuracy of 1% and repeat the operation in less than 2 1/2 milliseconds. The magnetic field in the magnet rises sinusoidally and has a peak value of 2070 gauss. (For 25 BeV beam).

The deflection magnet system, a dc system containing several individual magnets, will bend the beam, momentum analyze it, and direct it toward the end station. This system should be of the zero-dispersion type because one may wish to conduct the beam several hundred feet from the deflection system to an experiment. To conform with current beam parameters the electron energies were assumed to lie in the range of 5-25 BeV, while the angular divergence was varied from 10^{-3} to 10^{-5} radians. Bending magnets with a field strength of 18,000 gauss and quadrupole magnets with a 2,000 gauss/cm gradient were taken as the building blocks of the system.

The purpose of this report is to present a possible instrumentation for these magnets which can measure the magnetic field intensity with the required accuracy.

The accuracy required for the field measurements vary from ±1% in the pulse magnet to .01% in the bending magnets (see Table 1). In the following we would like to list the different measuring methods which can be used in the various magnets in the beam switchyard.

TABLE I

BEAM SWITCHYARD INSTRUMENTATION

Magnets	Field Measuring Instrument	Accuracy
Pulsed Magnet	Electron Magnetic Resonance	1%
	Gated Integrator	1%
Quadrupoles	Compensated Nuclear magnetic resonance	.01%
	Flip coil + integrator	.01%
Bending Magnets	Nuclear magnetic resonance	.001%
	Flip coil + Integrator	.01%

We would like to divide this note into the following sections:

II. Discussion of the instruments

III. Field measuring probes in the magnets

IV. Cables

V. Proposed system

II. MAGNETIC INSTRUMENTATION FOR THE BEAM SWITCHYARD

a. Nuclear Magnetic Resonance (NMR)

The nuclei of certain atoms have a net intrinsic angular momentum which, because of their charge, gives rise to a net dipole magnetic moment. The interaction of this dipole moment with a radio frequency field in the presence of a dc magnetic field is called nuclear magnetic resonance. The frequency f at which resonance occurs is directly related to the dc field Ho by the following formula:

$$F = \frac{\gamma_n}{2\pi} Ho \quad \text{where } \gamma_n \text{ is the "gyromagnetic ratio" for the nucleus}$$

Values of $(\gamma_n/2\pi)$ for various nuclei are given in Table 2. Thus, an NMR device converts the problem of measuring magnetic field to one of measuring frequency, which can be done to one part in 10^8. The accuracy of the measurement, then, is the accuracy with which γ is known, usually about .001%. NMR measurements have the advantage of high accuracy, but suffer from slow speed, and the requirement for a fairly homogeneous field. The slow speed results from the complexity of the adjustments which must be made to the NMR gaussmeter to make the measurement. Also, the "relaxation time" (the time required for the dipole moments to respond to the rf field) is of the order of 0.1 - 1.0 seconds for NMR, so fields that vary at rates greater than 60 gauss/sec or so give very weak signals and are difficult to measure.

b. Electron Magnetic Resonance (EMR)

This phenomenon is directly analogous to NMR, except that the interacting dipole moment arises from the intrinsic angular momentum of the electron. Certain materials, called paramagnets, have an electron population that exhibits this net electron "spin," and thus a net dipole moment. Because of the much smaller mass of the electron, however, the value of the gyromagnetic ratio is much larger. For free electrons, $\frac{\gamma_e}{2\pi} = 2799.31$ kc/g.[1] For electrons in a crystal lattice, this ratio is modified by the crystalline field and by nuclear moments, and for the paramagnetic material D P P H (1,1 - diphenyl 2, picryl hydrazil),

$$\frac{\gamma_e}{2\pi} = 2804.62 \pm 0.1 \text{ kc/g} \quad (1,3,4,5)$$

TABLE II

$\gamma/2\pi$ FOR VARIOUS NUCLEI

NUCLEUS	GYROMAGNETIC RATIO $/2\pi$
Proton in H_2O	4.25776 ± 0.0001 kc/g
L_i^7	1.65461 ± 0.0001 kc/g
Deuteron in D_2O	6.53637 ± 0.0001

The same disadvantage of complex adjustment still exists, but since the relaxation time for D P P H is about 0.2 μsec, fields can be measured that have rates of change as high as 10^8 gauss/sec.[2] Homogeneity requirements are somewhat relaxed, but are still severe.

c. Flip Coil - Integrating Method[6]

If a coil is rotated in a dc magnetic field, a voltage is induced in it as given by

$$e_{coil} = NA\omega B_o \sin \theta$$

where

- N is the number of turns
- A is the area
- ω is the angular frequency
- B_o is the magnetic field
- θ is the angle made by the coil axis with B_o

If the coil is rotated through exactly 180°, from $\theta_1 = 0°$ to $\theta_2 = 180°$, and the output of the coil is integrated, the output voltage of the integrator will be independent of ω:

$$e_{int} = \frac{2NAB_o}{RC} \text{ where RC is the integrator constant}$$

Thus, if the constant NA/RC is determined, a measurement of B_o can be made. Accuracy of the measurement is determined by the accuracy of the integrator, the accuracy of initial positioning of the coil with the field, and the accuracy of the 180° angle through which it turns. It can be shown that the accuracy factors are about

$$\frac{de_{out}}{d\theta_1} \cong .0002 \text{ (degree)}^{-1}$$

for $|\theta| < 5°$

$$\frac{de_{out}}{d(\theta_2 - \theta_1)} \cong .0002 \text{ (degree)}^{-1}$$

Thus the conditions on θ_1 and θ_2 are not severe; if

$$\Delta(\theta_2 - \theta_1) \leq 0.1^\circ, \text{ and } \Delta\theta_1 \leq 0.1^\circ$$

the accuracy is primarily determined by the integrator. Integrator and readout combinations can be made with accuracies of about .02%, and thus field measurements can be made to about this accuracy.

Three types of integrators are being contemplated. The first type is a standard Miller integrator, as shown in Fig. 1.

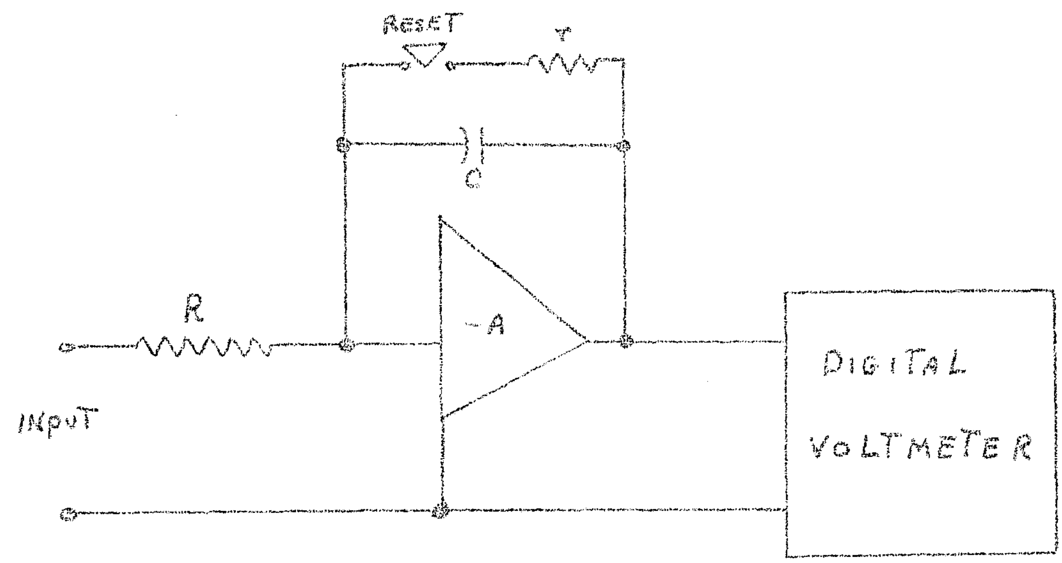


FIG. 1--Miller Integrator.

Such an integrator has the advantage of being insensitive to coil bounce and vibration, since such effects produce spurious voltages whose integral is zero. The integrator can be reset just prior to the measurement, eliminating inter-measurement drift. After the coil has turned, however, there is a further delay which is required for the DVM to balance. During the measurement and during this balance delay, integrator drift occurs which results in measurement error. The leakage resistance across the capacitor varies between 10,000 and 300,000 megohms, depending upon temperature and humidity. For a capacitance value of 0.1 μfd (integrator gain of 10) and a leakage resistance of 10 k meg, the time constant of the leakage decay is 10,000 sec, corresponding to a decay of .01%/sec. This decay, coupled with integration errors and DVM accuracy, sets an upper limit of about 0.02 to 0.05% in the accuracy of measurement.

Another type of integrator which is being considered is the voltage to frequency converter type, coupled with a digital scaler. Such a system is shown in Fig. 2. Circuit operation is as follows: A positive voltage step at the input of the integrator causes the output of the integrator to drop linearly at a rate E_o/RC. When the integrator output reaches a present level (about 0.2 volts) a negative level detector sends out a pulse. This pulse triggers a blocking oscillator whose output appears at A, and also triggers an impulse generator. This consists of a saturating core transformer coupled to a flip-flop circuit. The output of this generator is a pulse of well-defined volt-second area, and is chosen to just reset the integrator to zero output. If the input voltage is still present, the output of the integrator again falls to the preset level, and is again reset to zero, with a second pulse appearing at A. This process continues until the voltage is removed from the input or changes polarity. If the input is negative, a similar set of stages detects the positive output of the integrator and resets it to zero, with a pulse train appearing at B.

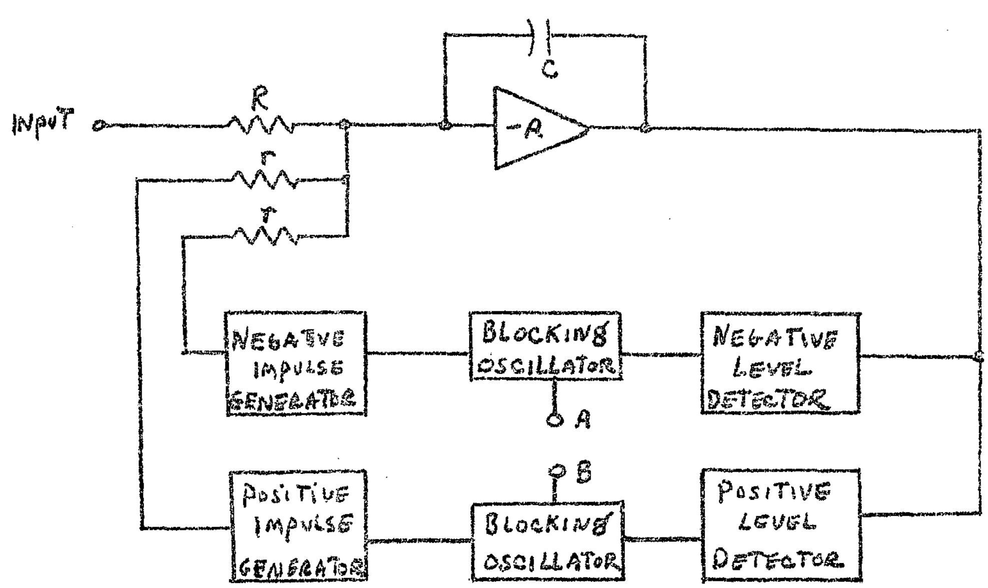


FIG. 2--Voltage To Frequency Convertor.

The waveforms for a single cycle of a square wave of amplitude E_o are shown in Fig. 3.

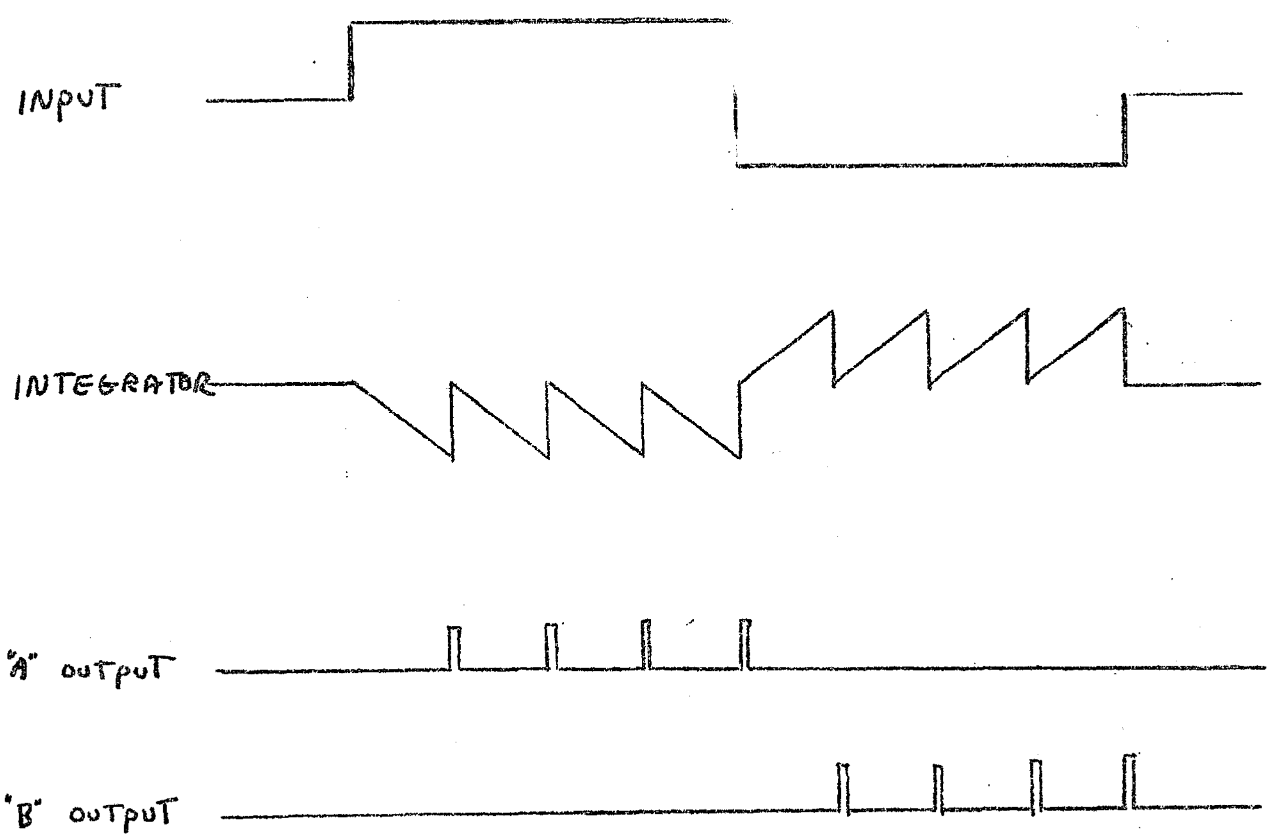


Fig. 3-- Voltage to Frequency Waveforms.

Since the time between pulses is given by

$$t_p = \frac{e_t}{E_o} RC,$$ where e_t is the trigger level,

it is clear that the rate of the pulses is proportional to E_o, and the total number of pulses at A is the positive portion of the integral of E_o, within a proportionality constant. Similarily, the numbers of pulses at B represent the negative portion. If the pulse trains appearing at A and B are fed to the positive and negative inputs of a reversible (up-down) counter, respectively, the total count will be proportional to the integral of the input waveform. An analogous argument can be made if the input varies during the interpulse interval.

Voltage to frequency converters of the type described above are available commercially with accuracies of .02%, linearity of .002%, and sensitivities of 1000 cps/mv. At reduced accuracy (.1%), sensitivities of 20,000 cps/mv are obtainable.

Since the integrator range of operation is always less than $2e_t$, which is typically less than 500 mv, the requirements on the integrating amplifier are greatly relaxed. Higher gains can therefore be obtained in the integrator before linearity is lost; integrals as small as 100 μvolts-seconds can be measured with an accuracy and resolution of 10^{-7} volt-sec. Miller integrators with the same accuracy have typical sensitivities of 1/100 of this figure. Despite the apparent increased complexity of the v-f integrator over the Miller type, the reduced requirements on the analog amplifier and the absence of the digital voltmeter make the v-f converter scheme less expensive. Also, the counter (scaler) on the output follows the input with no lag, and therefore the counter can be gated off immediately after the measurement is taken, resulting in an infinite display, drift-free readout. Coil vibration and bounce have no effect on the measurement.

A third type of integrator also uses the v-f converter, but the outputs at "A" and "B" are fed to a summing network and counted alike. The total count then corresponds to the sum of the area under the input waveform, regardless of polarity. That is:

$$N = K \int_{0}^{t} \left| e_{in} \right| dt,$$

where

N is the total counts

K is a proportionality constant.

Such an integrator has the advantage that the coil which is being rotated in the field need not be aligned exactly with the field; (i.e., $dN/d\theta_1 = 0$) provided $\theta_2 - \theta_1 = 180^\circ$. Also, since a simple scaler can be used instead of the reversible type, cost is reduced by about 30% for the whole system. This integrator suffers from the disadvantage, however, that coil bounce and vibration are not averaged out as in the other types, and thus additional error is introduced if these effects are present.

d. Gated Integrator - Pulsed Magnet Interlock System

This system has been described in a previous technical note[7] and will be briefly described here for completeness. The system block diagram is shown in Fig. 4. Since the field in the pulsed magnet is varying with time, voltage is induced in a stationary coil according to the relation

$$e_{coil} = NA \frac{\partial B}{\partial t}$$

If the output voltage of this coil is integrated, the voltage at the integrator output will be proportional to the instantaneous magnetic field. The output of the integrator and the coil output are fed to level detectors, and when these signals reach preset levels at the same time, an interlock signal is formed by a coincidence circuit. Also, the output of the integrator is fed to a gate circuit driven by a variable delay, and this gate forms a pulse of 2 μsec width whose amplitude is proportional to the magnetic field when the gate is opened.

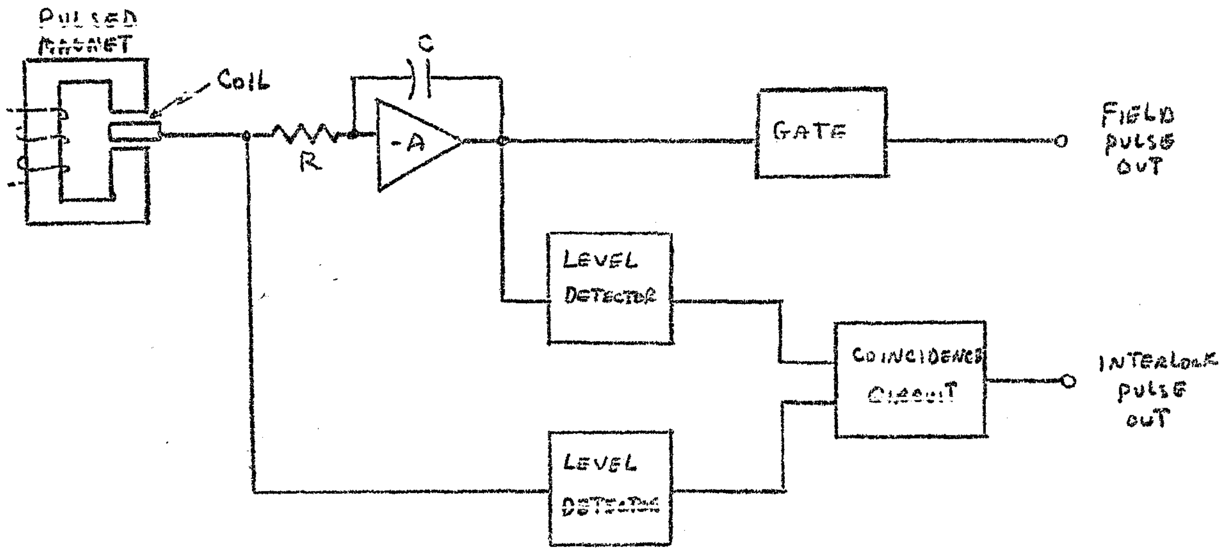


FIG. 4--Gated Integrator.

For a full discussion of the interlock system, reference to Technical Note TN-63-73 should be made.

e. Hall Devices

Magnetic measurement devices utilizing the Hall Effect cannot be used due to radiation sensitivity of the material used in the probe.[9] Field measurement in magnets outside the radiation area could utilize these devices.

III. PROBES

a. NMR

The NMR probe consists of a vial containing the sample in aqueous solution (usually also containing a paramagnetic salt solution to decrease the relaxation time), surrounded by two or more coils connected to the electronic equipment. Usually about 1 cc or more of sample solution is required to achieve reasonable signal strengths. One of the coils is connected to a 60 cycle source of alternating current, and is placed so that its field is parallel to the magnetic field to be measured. This coil provides a magnetic field sweep of about 0.5 - 1.0 gauss so that the resonance condition is continually swept and ac coupling can be used in the detection equipment. The second coil is connected to the source of rf power, and is placed so that its field is perpendicular to the magnetic field to be measured.

If no third coil is used, the oscillator is made so that its oscillations are marginal, i.e., the source is just barely oscillating. When resonance occurs, the amplitude of oscillations is damped, and the resonance indication is observed. In some systems a third coil is used, placed at right angles to both of the other coils. A receiver is connected to its terminals; when resonance occurs, the amplitude and phase of the receiver output changes and a resonance indication is obtained. Construction details of a typical 3-coil probe are shown in Fig. 5.

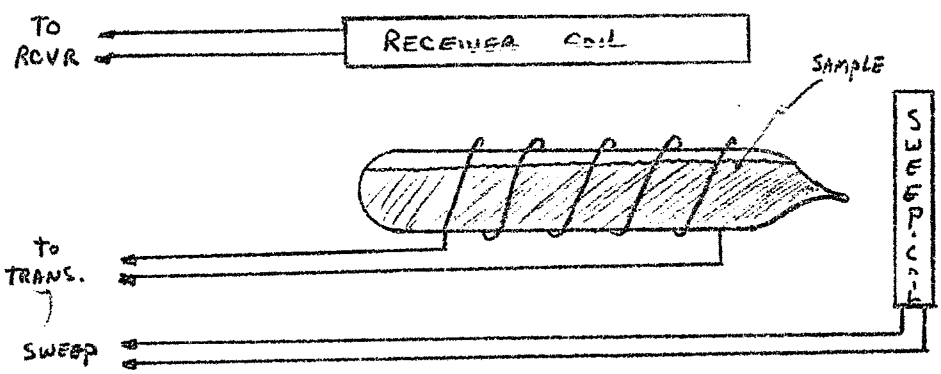


FIG. 5--NMR Probe Details.

b. <u>EMR</u>

The EMR probe consists of a helix, 1.55 mm in diameter, 20 cm long, with a 1.5 mm glass tube containing the sample of D P P H inserted within the helix. See Fig. 6 for constructional details. Coupling to this main helix is accomplished with another helix, 3.2 mm in diameter and 1.8 mm long. This coupling helix is directly connected to coaxial cable, and is terminated at the other end in a 50 ohm resistor.

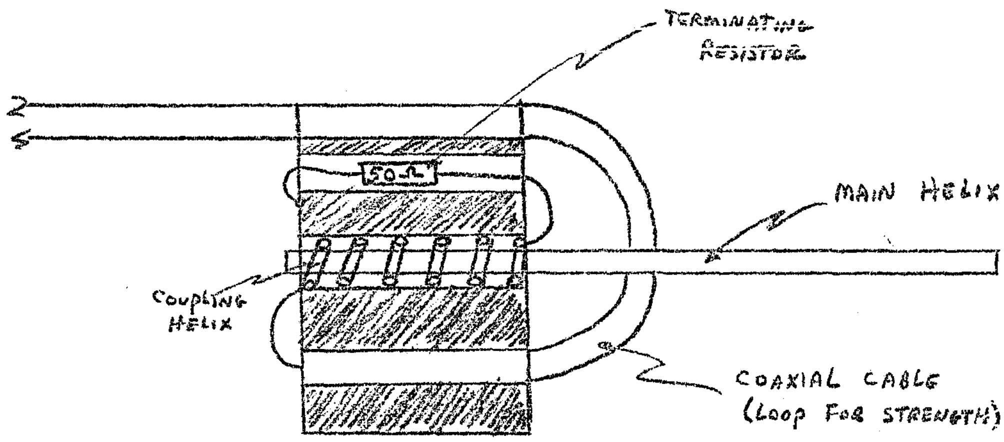


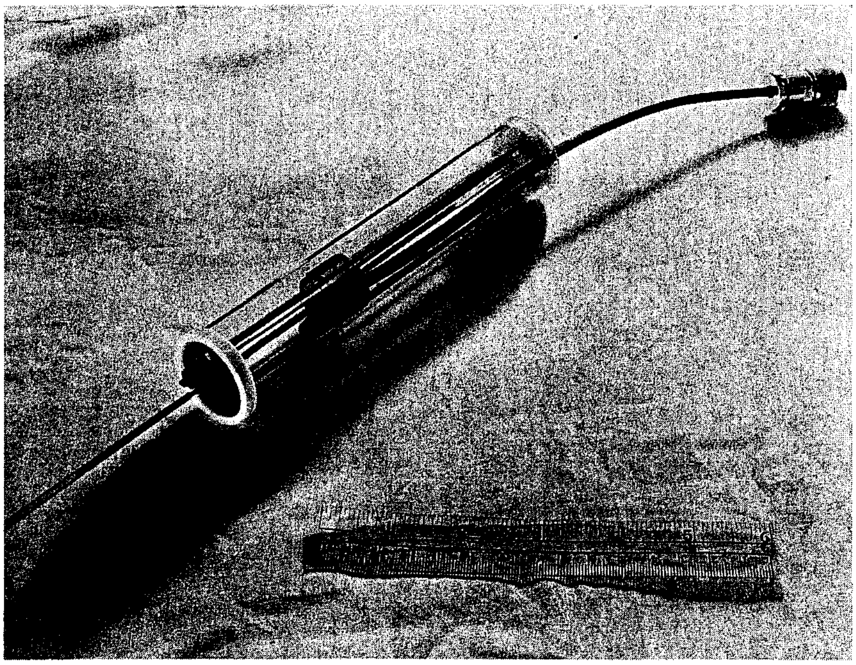
FIG. 6--Cutaway View of Helix Coupler.

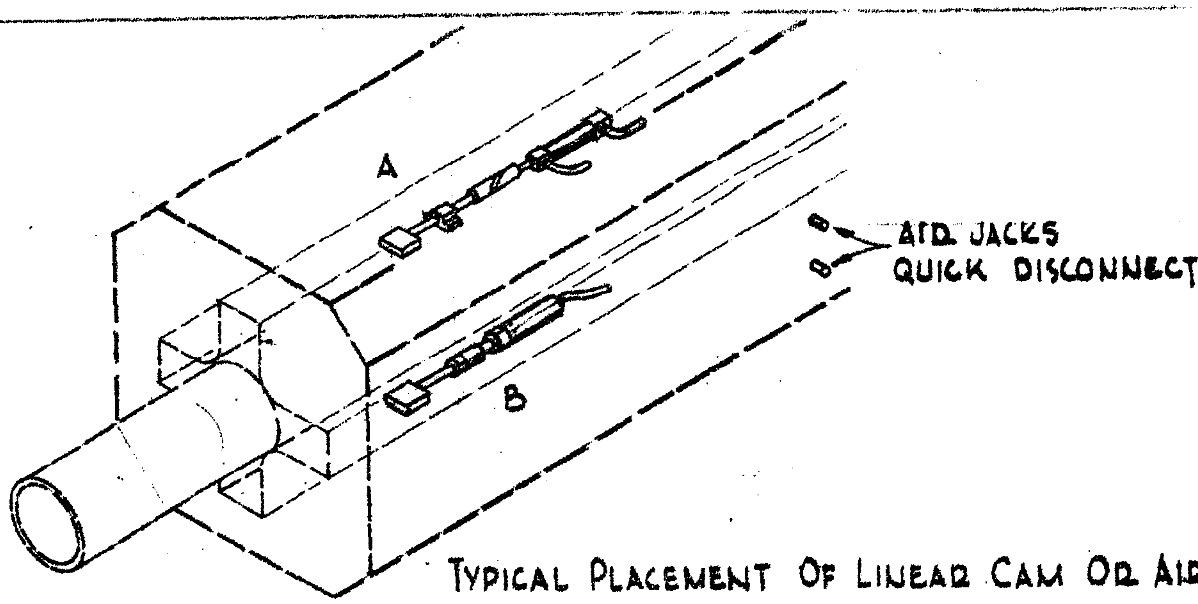
The probe assembly is mounted in a plastic tube for protection and helix alignment. See Fig. 7.

c. Flip Coil

The flip coil consists of a rectangular coil of wire with a turns-area product large enough to provide sufficient signal for the integrator at the smallest field to be measured. Since the sensitivity of the integrator unit is not yet established, this turns-area product is still undetermined. The actuator for the flip coil is designed as follows:

Fig. 8 shows two types of actuators permanently placed in a quadrupole magnet. The type shown in Fig. A is a linear cam driven by a double acting air cylinder. Construction of all parts are of non-magnetic materials. In operation the air cylinder piston moves forward driving the cam block with it. The cam block has cut into it a cam groove which engages a pin protruding from the flip coil shaft. As the cam moves forward (or back) the pin is rotated 180° by the action of the cam groove on the flip coil shaft pin. The number of degrees of rotation of the coil is controlled by the contour of the cam groove and cannot be adjusted after having been cut. Thrust force on the pin is taken up by the thrust collars on the flip coil shaft which bear





TYPICAL PLACEMENT OF LINEAR CAM OR AIR MOTOR DRIVEN ACTUATOR IN QUADRUPOLE

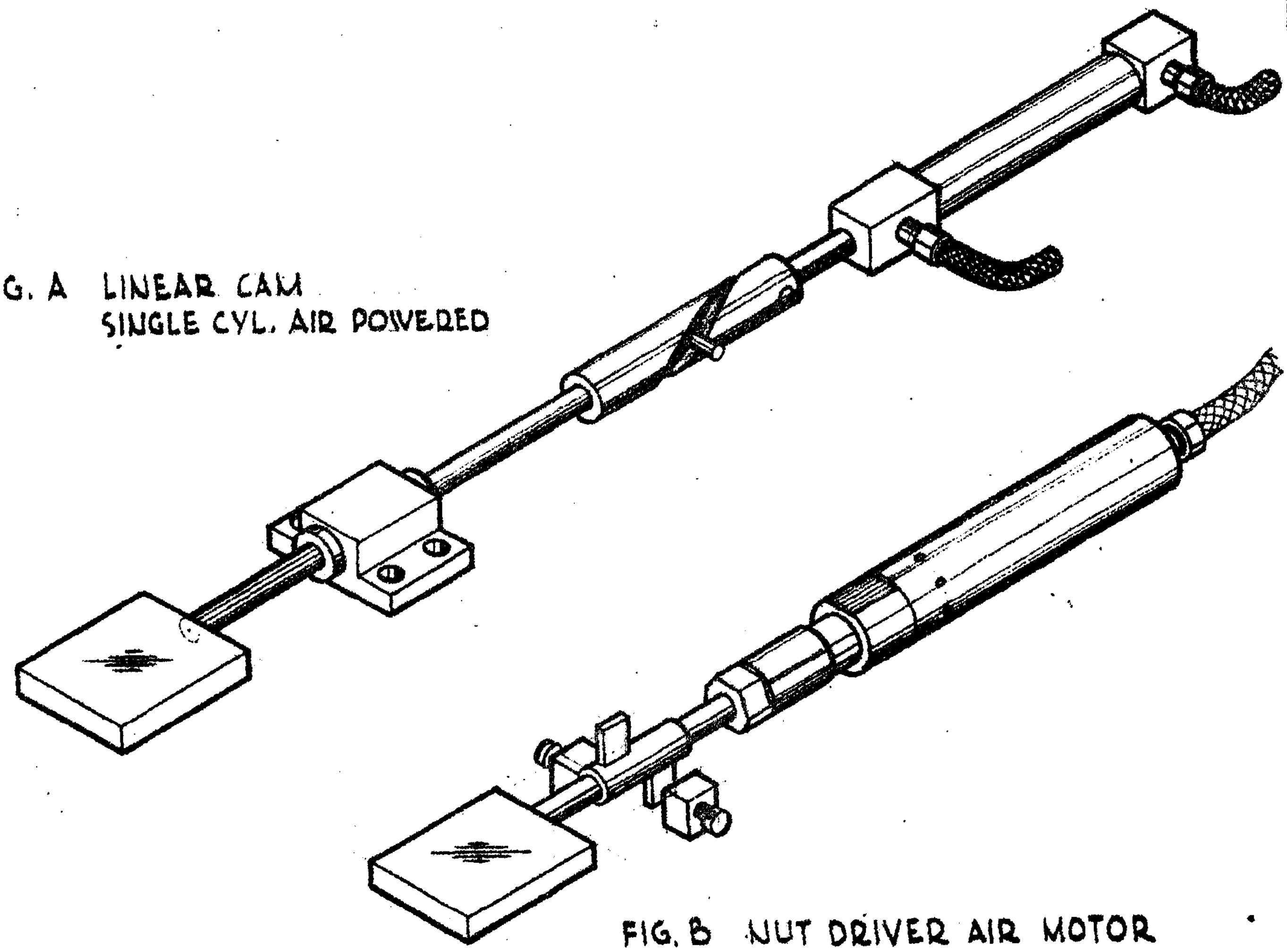


FIG. A LINEAR CAM
SINGLE CYL. AIR POWERED

FIG. B NUT DRIVER AIR MOTOR

ILLUSTRATION 8

DWN BY J.BARDEN

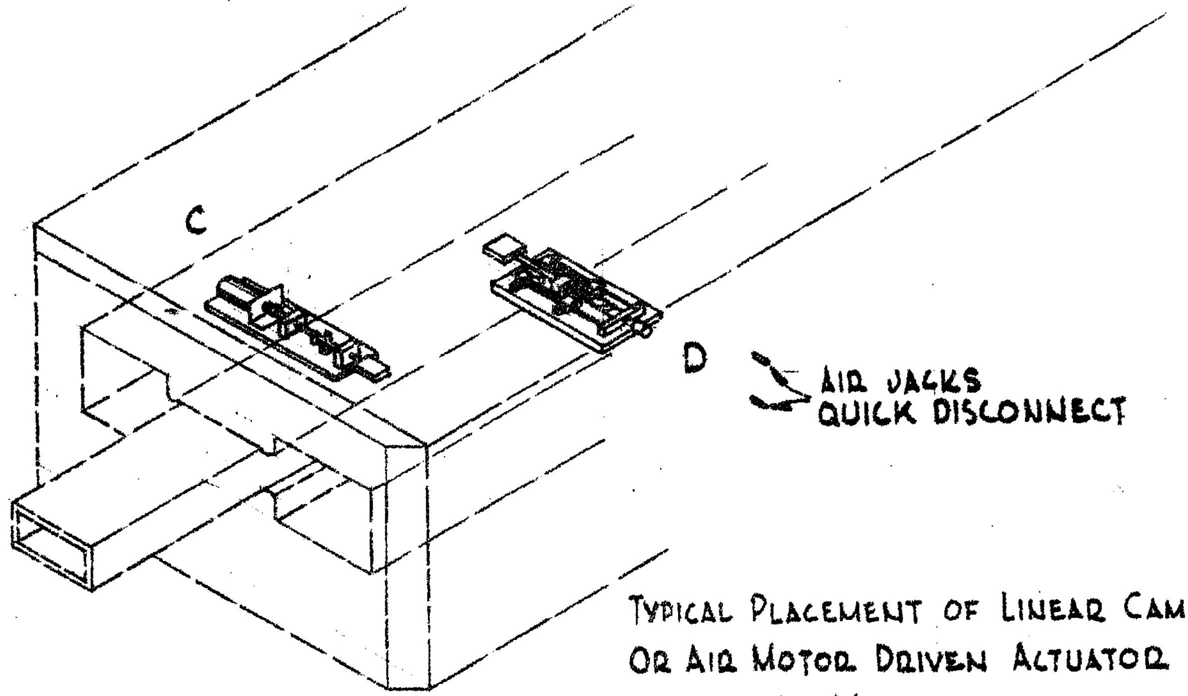
against the bearing clock. Envelope dimensions for the mechanism are approximately 1 inch square by 12 inches long. The air cylinder is an off-the-shelf item costing approximately $15. An advantage of the cam type type construction is that acceleration and deceleration, velocity and dwell at the end of stroke may be varied to best advantage by various designs of cam profiles. Also there are no stops or fittings which may get out of adjustment during operation.

The air motor type shown in Fig. E uses a reversible air motor commonly used to drive screws and nuts. It is specially constructed of non-magnetic materials. As the air motor would continue to rotate as long as air is supplied, it is necessary to use stops on the output shaft. The stops are capable of screw driver adjustment, thus allowing the degrees of rotation to be varied. Its envelope dimensions are approximately 3/4 inch diameter by 10 inches long. Available output torques are limited to rather low values, so that the mass to be rotated is a consideration in the design unless output gearing is used. While acceleration is capable of control by regulating the input air, deceleration is caused by the stop lug striking the stop and is relatively uncontrolled. Cushion or dash pot stops could be used to decelerate more slowly if sudden deceleration should prove to be a problem. Time to rotate 180° is probably less with the nut driver type air motor than with the air cylinder cam type.

The twin cylinder linear cam type shown in Fig. 9-D is essentially the the same as that previously described except that it is "folded over" to shorten the total length. Two cylinders are used to equalize bending forces which would be imposed on the cam if one cylinder offset to one side were used. Its envelope dimensions are 1 inch thick × 4 inches wide × 8 inches long.

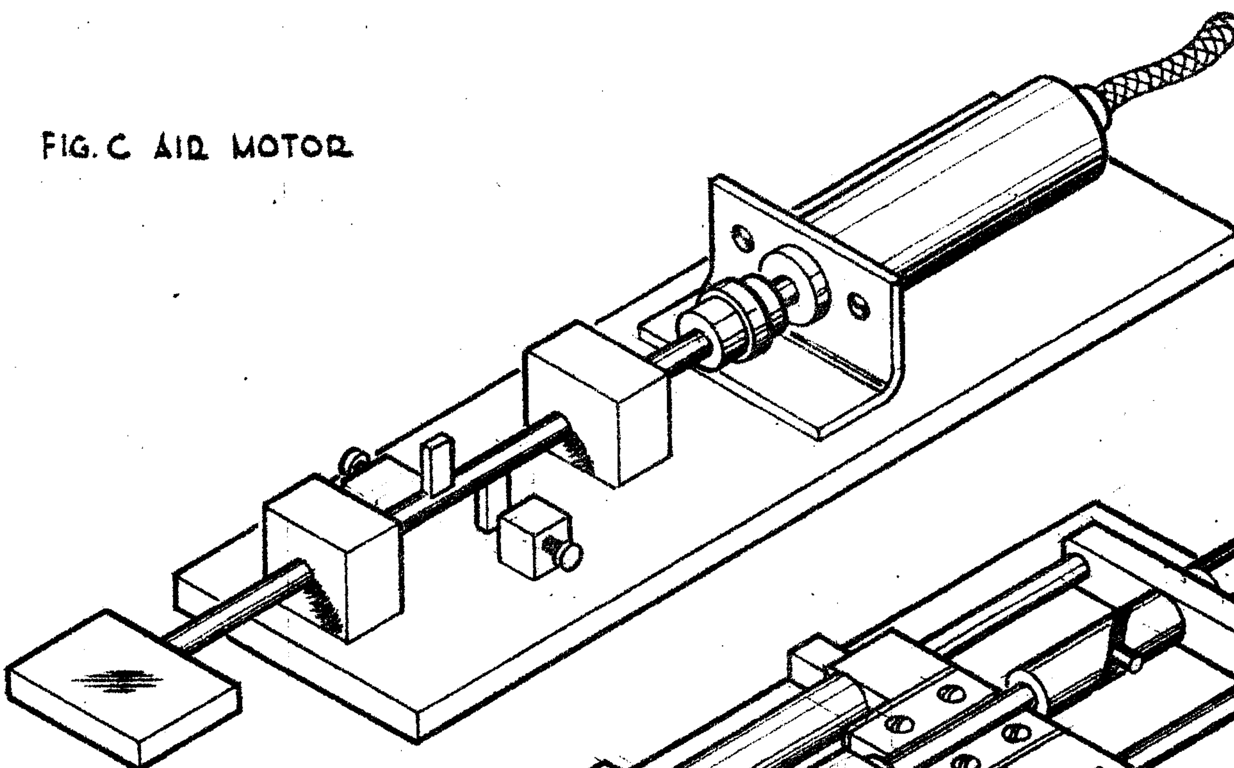
The air motor type shown in Fig. 9-C is essentially the same as that described previously except that the air motor is larger in diameter and shorter in length and has more output torque. Its envelope dimensions are 1-1/2 inches dia. × 8 inches long.

All of the actuators described will have their pneumatic controls remotely located and will have quick disconnects in the air lines. Organic materials of low radiation resistance will be avoided in the design.



TYPICAL PLACEMENT OF LINEAR CAM
OR AIR MOTOR DRIVEN ACTUATOR
IN MAGNET

FIG. C AIR MOTOR



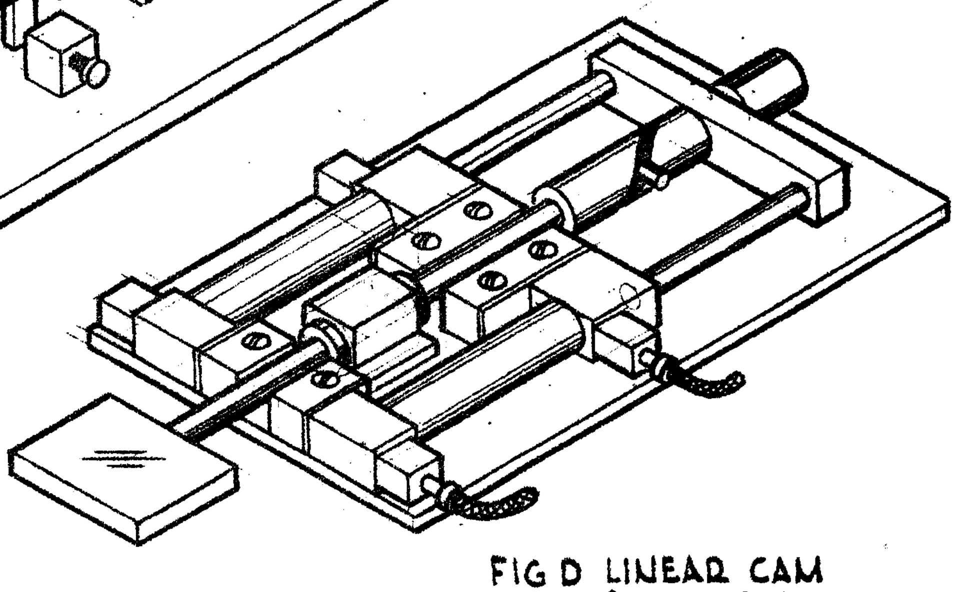


FIG D LINEAR CAM
2 CYL AIR POWERED

ILLUSTRATION ~~2~~ 9

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d. Gated Integrator

The probe for the gated integrator consists of a stationary coil, with a turns-area product of 0.1 m^2. The signal from this coil will be transmitted to the electronics via coaxial cable.

IV. CABLES

Radiation sensitivity of coaxial cable filled with various dielectrics has been carefully studied.[8] Of the cables studied, only those with Magnesium Oxide (MgO) dielectric are suitable. The attenuation properties of RG-81/U at the highest frequency of interest (4 - 6 KMC) have been measured and are plotted in Fig. 10. The curve for MgO cable is not smooth due to a standing wave set up in the measurement equipment by the connectors at the ends of the cable. It can be seen that the MgO cable compares favorably with RG-8/U cable, with an attenuation of 20-40 db/100 ft. This cable will be used wherever coaxial cable is needed, from the EMR Helix to the waveguide system, from the flip coils to the integrators, and as cable for the gated integrator and NMR.

Because 20 db/100 ft at 4.0 KMC is excessive attenuation, waveguide will be used to transfer power from the EMR electronics to the probes, about 55 feet below ground. At the switching magnets, a transition to coax will be made and an air-actuated, coaxial 5-pole switch will select which of the 5 magnets in which a measurement is to be made. (See Fig. 11.)

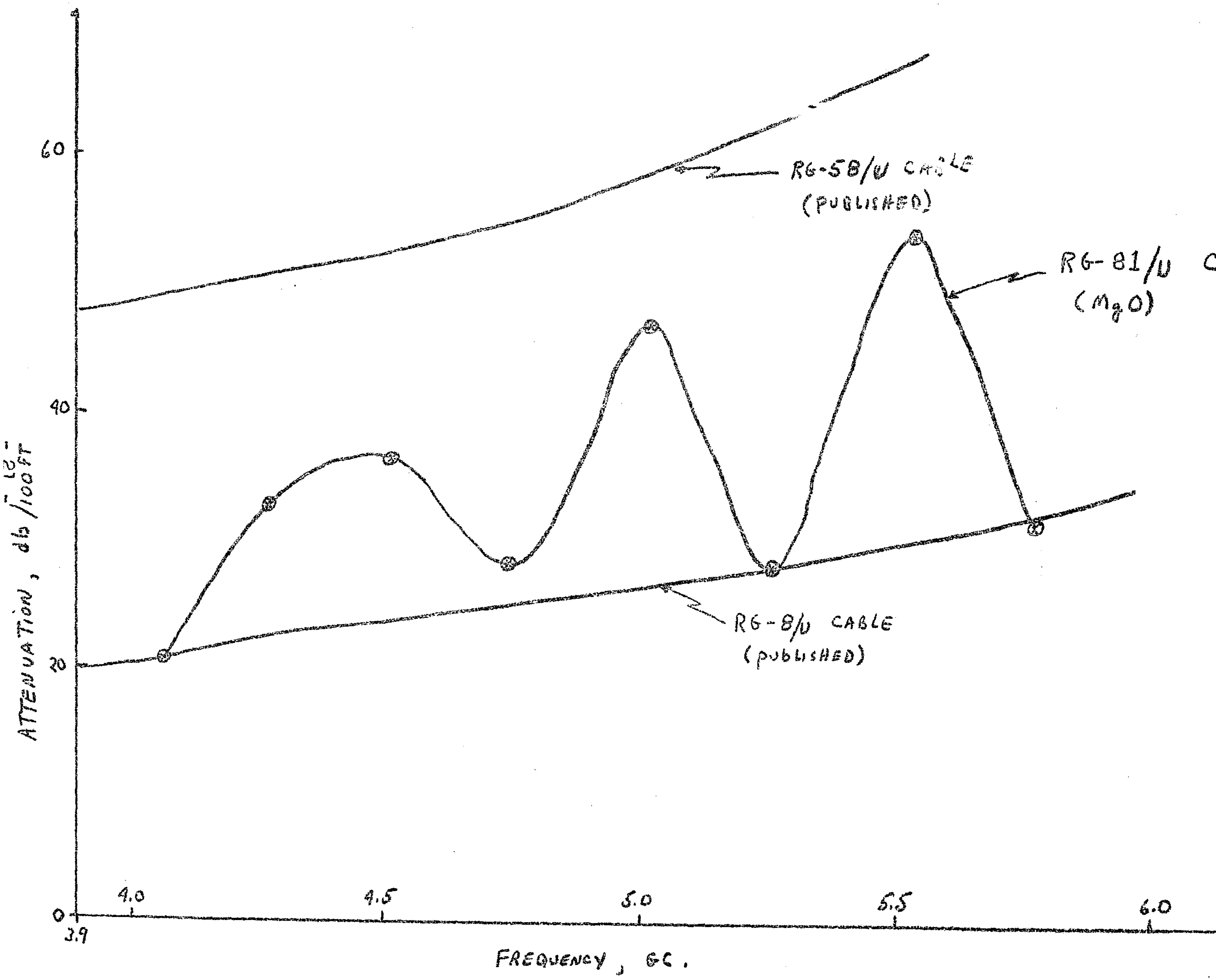


FIG. 10--Attenuation of MgO cable

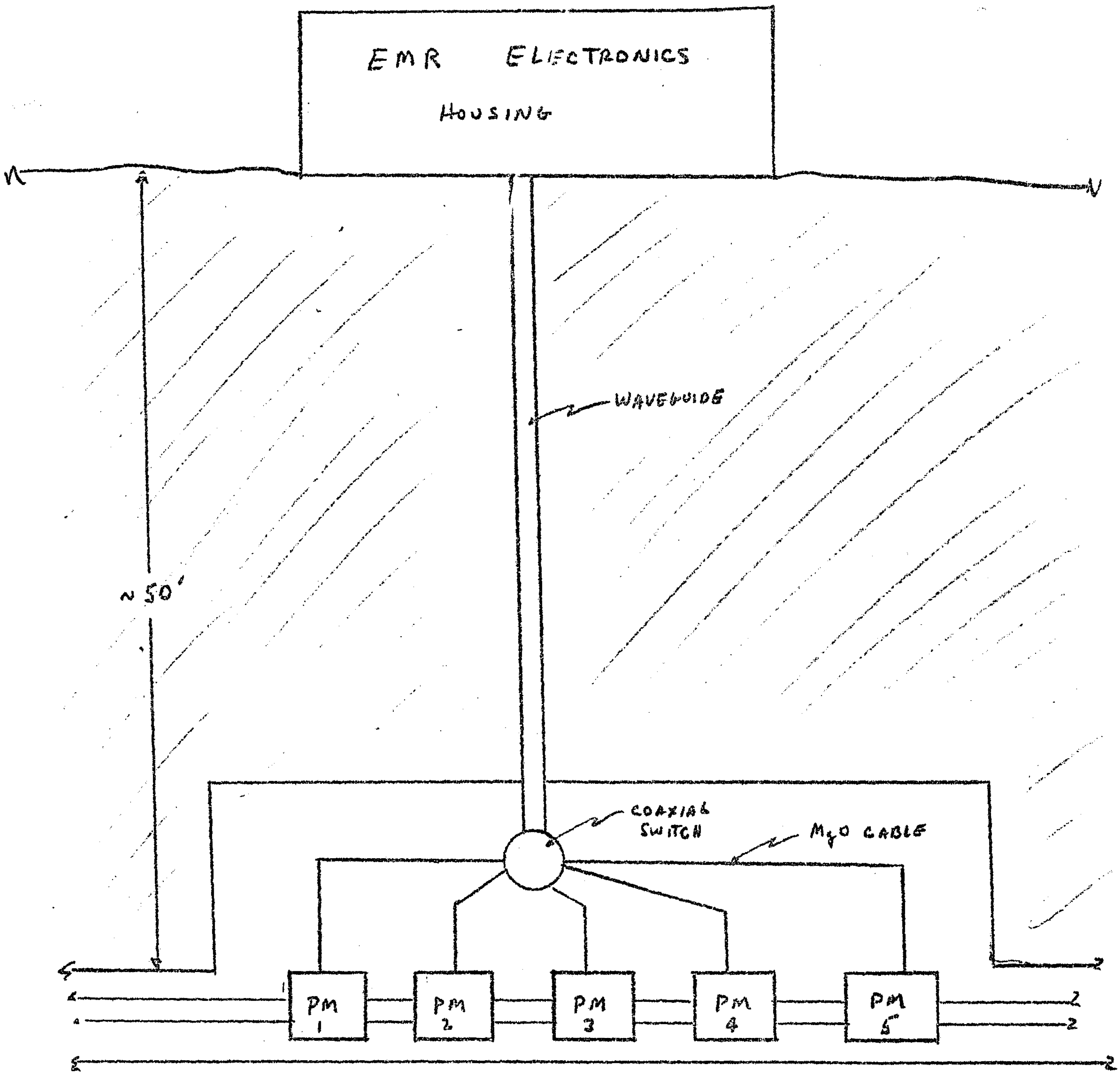


FIG. 11--EMR Transmission system

V. PROPOSED SYSTEM

a. Bending Magnets

Since these units are dc magnets, NMR could be used. However, long runs of cable (up to 500 feet) are necessary between the oscillator-inditator unit and the probe. For this reason, NMR cannot be used in all magnets unless a set of buildings are provided to house the NMR electronics. (See Fig. 12.) Flip coils and integrators will also be used with the bending magnets. Here, long runs of cable are permissible since the coil is a low-impedance, high-voltage signal generator. For economy, a single integrator and readout will be used for each set of bending magnets (four in all), and a selector switch used to select the magnet to be measured. To eliminate drift, a pre- and post-trigger will be provided from the coil flipping control to gate the DVM or counter. Placement of coil flipping mechanism can be seen in Fig. 9-C.

b. Quadrupoles

Because of the obvious inhomogeneity in the quadrupoles, NMR cannot be used. Flip coils, 2 per magnet, will be positioned as shown in Fig. 8. Except for the fact that 2 coils are needed, all remarks with respect to flip coils in the above paragraph apply here. The coils to be used may have different geometries, however.

c Pulsed Magnets

A stationary coil will be used to drive the gated integrator for pulsed magnet measurement. This equipment will be used to provide the interlock signal for the gun. In addition, EMR probes will be used for calibration purposes. Because excessive transmission loss cannot be tolerated, a separate building above the pulsed magnets must be provided for the EMR electronics. The gated integrator electronics will also be housed in this auxiliary building. (See Fig. 12.)

d. Magnet Power Supplies

The magnets are connected in four series circuits:

1. Bending Magnets, Beam A
2. Bending Magnets, Beam B
3. Quadrupole Magnets, Beam A
4. Quadrupole Magnets, Beam B

LAYOUT OF BEAM TRANSPORT SYSTEMS FOR END STATIONS A AND B
(ALL LENGTHS IN METERS)

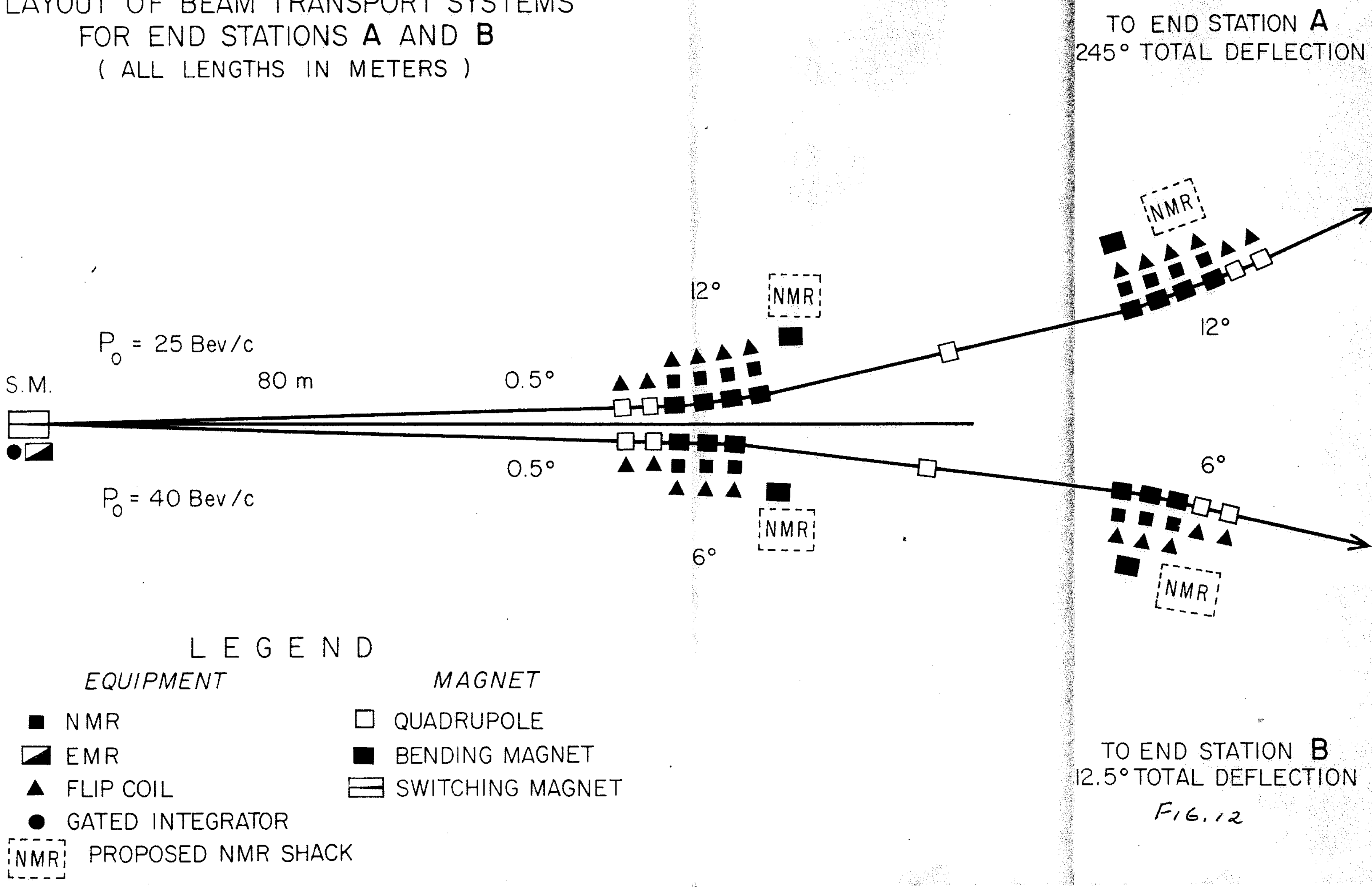
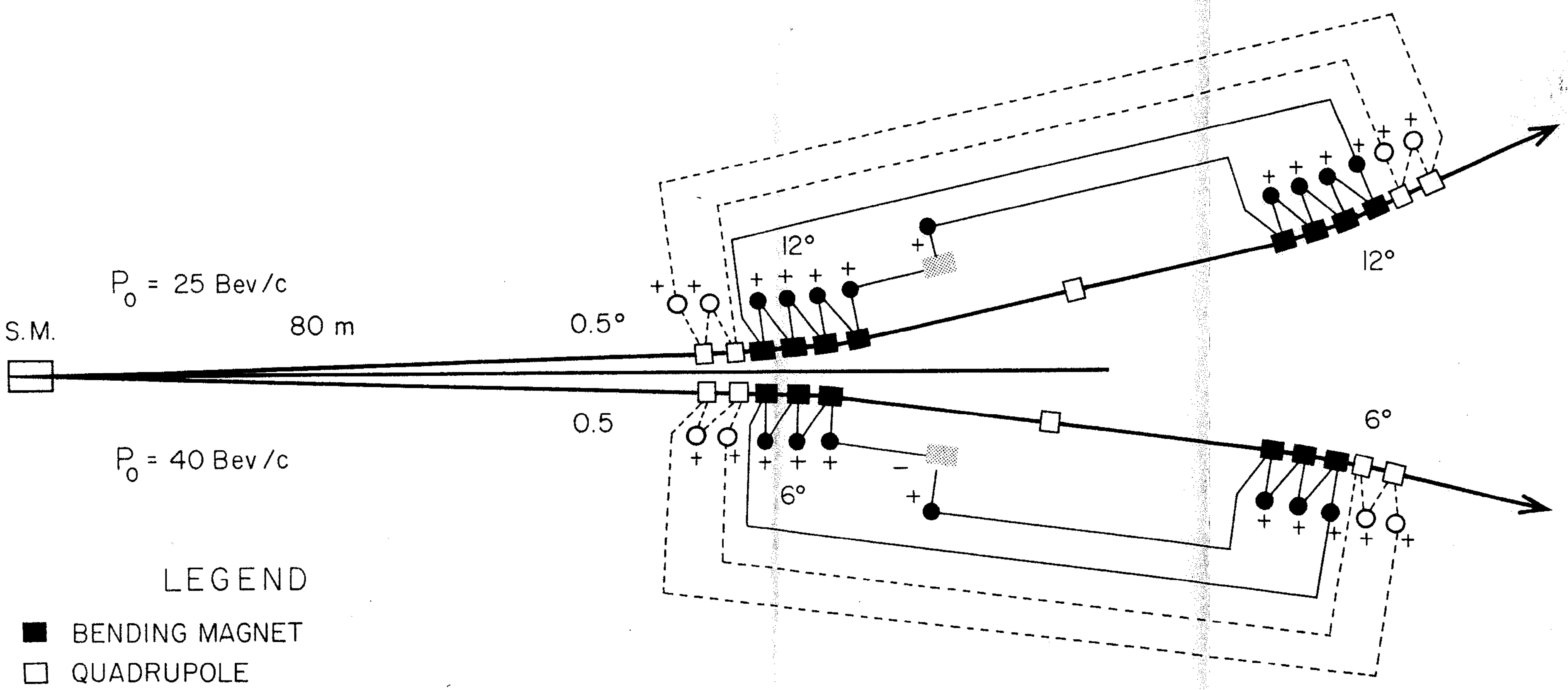


FIG. 12

The series circuits are connected as shown in Fig. 13. This arrangement assures that the current through each magnet in a given set is the same, while the voltage drop in steady state between any magnet terminal and ground is never far above the power supply voltage. Transients due to turn-on and fast current changes are limited to acceptable values by spark gaps.

LAYOUT OF BEAM TRANSPORT SYSTEMS
FOR END STATIONS A AND B
(ALL LENGTHS IN METERS)



LEGEND

- BENDING MAGNET
- QUADRUPOLE
- REF. BENDING MAGNET
- POWER SUPPLY, BENDING MAGNET
- POWER SUPPLY, QUADRUPOLE MAGNET

FIG. 13

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