ANL-5864
Particle Accelerators and
High Voltage Machines

ARGONNE NATIONAL LABORATORY
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PARTICLE ACCELERATOR DIVISION

Summary Report

October 1, 1957 through April 15, 1958

John J. Livingood, Division Director
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May 1958

Previous Summary Reports:

ANL-5803	April through September 1957
ANL-5713	October 1956 through March 1957
ANL-5630	April through September 1956

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DISCLAIMER

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PARTICLE ACCELERATOR DIVISION

Summary Report

I. PUBLICATIONS

Abstracts of ANLAD Reports

ANLAD-45 " 'GEORGE' Program for the Studies of Synchrotron Oscillation and Frequency Errors"
L. C. Teng (October 15, 1957)

The new computing machine "GEORGE" has been coded to study the synchrotron oscillation and frequency errors numerically. The accelerator is a simplified version of the ANL synchrotron consisting of eight identical sectors with symmetric magnets. The radio frequency is supplied by one cavity operating at a harmonic number h. No betatron oscillation is introduced. The radio frequency phase angle, the energy deviation (from the equilibrium value), and the increment in equivalent radius of the orbit are printed out for each revolution. From these values phase plots can then be made and compared with those obtained analytically under the smoothed adiabatic approximation.

ANLAD-47 "Study of the Equilibrium Orbits in the ANL Synchrotron With D.C. Magnets"
L. C. Teng (February 19, 1958)

The parameters of the equilibrium orbits in the ANL synchrotron were studied. Approximate formulas were derived for the shape of the equilibrium orbit as it moves across the vacuum chamber radially and during acceleration. A parameter characterizing the degree of inscalability of the equilibrium orbits was introduced. It was shown that, as bigger and bigger field gradients are introduced in the D.C. magnets to correct bigger and bigger error field gradients in the guide magnets, the degree of inscalability gets larger and larger. As far as the scalability of the equilibrium orbits is concerned, an average error gradient in the guide magnets on the inside (radially) of the chamber does not matter at all, but that on the outside of the chamber it should not be less algebraically than -1.3 gauss/ft.

A new set of machine parameters for D.C. magnets, with a gradient index of 4 and negative edge angle (extensions of the edges intersect at a point radially outward of the center of curvature) to give more available short sector length, were derived. The degree of inscalability for this set of parameters was less. The corrective ability of these D.C. magnets was investigated and found to be essentially the same as that for the zero gradient D.C. magnets.

Internal Memos

Those which may be of interest to others are listed below and will be mailed upon application.

L. C. Teng

LCT-3	The Delft Synchrotron, (October 8, 1957)
LCT-4	Gas Scattering in the ANL Synchrotron, (November 7, 1957)
LCT-5	Shielding the Floor and the Ceiling of a Plastic Vacuum Chamber from Radiation Damage, (November 7, 1957)

Harry Fechter

HF-1	Field Perturbations in a Magnetic Inflector, (October 30, 1957)
HF-2	Pulsed Current Resonant Wire Method for Determining Quadrupole Centers, (November 6, 1957)
HF-3	Space Charge-Induced Expansion of Proton Beams (November 14, 1957)
HF-5	Regulation of Voltage Applied to an Accelerating Column, (January 8, 1958)
HF-6	Report on Ion Sources and High Voltage Supplies, (January 25, 1958)

Harry Fechter and Rolland Perry

HF-RP-1	Proton Beam Deflection and Injection, (October 1, 1957)

Cyril H. M. Turner

CHMT-1	Some Notes on the Control of the Orbit of a Bunch of Particles in a Synchrotron, Part I (March 5, 1958)
CHMT-2	Ditto, Part II, (March 10, 1958)

Matthew Simon

MS-1	Hexagonal Shielding Blocks, (November 19, 1957)

Henry A. Kampf

HAK-5	Dynamic Tests of Analog to Digital Converter (January 23, 1958)

William A. Siljander

WAS-4	Method of Assembling Ring Magnet Coil by Pre-Stressing (June 5, 1958)

David F. Cosgrove

DFC-2	Report on 8" Magnet Test Section, (March 11, 1958)

G. O. Calabrese

Magnetic Forces on Various Parts of the Synchrotron, (November 22, 1957)

A. V. Crewe; R. H. Hildebrand; U. E. Kruse; S. D. Warshaw, S. C. Wright, C. M. York

CHKWY-3 Layout of the Experimental Areas of the 12.5-Bev Accelerator, (January 1958)

CHKWY-4 Power Required for Beam Handling and Experiments (December 1957)

CHKWY-5 Beam Characteristics of the 12.5-Bev Accelerator (February 1958)

External Publications

L. C. Teng, "Resonant Excitation and Damping of Betatron Oscillation" Bull. Amer. Phys. Soc., Vol. 3, No. 2 p. 102 (March 27, 1958)

Henry A. Kampf, "Transistors and Diodes in Strong Magnetic Fields" Electronic Industries, p. 71, (March 1958.)

II. THEORETICAL STUDIES

E. A. Crosbie, L. C. Teng

A. Study of the $2\nu_z - \nu_x = 1$ Resonance

The IBM-704 code for integrating the exact equations of the betatron oscillations has finally been completely debugged and tested to give results with satisfactory precision. Many test cases have been run and methods for understanding and analyzing the results developed. It has been rather difficult to excite this resonance rapidly enough to make the effect visible within, say, 8 revolutions. A systematic program sketched below will now be followed and the results analyzed by the methods developed.

Program

1. Linear - without error - with no coupling. This case will be employed to adjust the machine parameters to give precisely $\nu_x = 3/4$ and $\nu_z = 7/8$. These parameters will be used for the rest of the program.

2. Nonlinear - without error - with no coupling. This will show the effects of the nonlinear terms on each oscillation when the other one is put equal to zero.

3. Linear - with error - with no coupling. These results will show the effects of errors on the linear oscillations.

4. Nonlinear - without error - with coupling. We should see the effects of the coupling through nonlinear terms. These effects give the $p\nu_x + q\nu_z = 0$ resonances (where p and q are integers).

5. Nonlinear - with error - with no coupling. This will furnish a basis for comparison with the one below.

6. Nonlinear - with error - with coupling. This is the problem at hand. A comparison of programs (6), (5) and (4) should give us the desired information on the $2\nu_z - \nu_x = 1$ resonance.

B. "GEORGE" Study of Synchrotron Oscillations with Frequency Errors

The computing machine "GEORGE" was coded to study numerically the effects of frequency errors in the radio frequency (RF) on the synchrotron oscillation of the beam in the ANL synchrotron. The machine studied was a symmetric eight-sector synchrotron with no D. C. magnet. The parameters were adjusted to produce the same betatron and synchrotron oscillations as in the more elaborate ANL synchrotron. The assumed frequency error was a sum of a constant error and a sinusoidal error with approximately constant amplitude and phase. The mathematical analysis leading to the code has been presented in ANLAD-45.

The code is now being used to make a thorough survey of the entire effect. Preliminary results show that (1) the synchrotron oscillation amplitude, (2) the effect of harmonic number, (3) the effect of adiabatic damping, (4) the effect of a constant frequency error, and (5) the effect of the frequency of the sinusoidal error all quantitatively confirm the original calculations (based on the adiabatic approximation) upon which the present synchrotron parameters were chosen. The complete result of the survey will be presented in a forthcoming ANLAD report.

C. Study of RF Self-Tracking Mechanisms

It is planned to control the amplitude and/or the frequency of the accelerating RF by monitoring the average radial position of the beam in the vacuum chamber and/or the average phase of the particles relative to the RF. Since the average phase is coupled to the average radial position, two or three coupled differential equations are obtained, depending on the manner in which the monitoring and control are related. Approximate solutions of possible schemes show that stable damped solutions can be obtained. In one scheme proposed by Cyril Turner, a programmed frequency is used. Any error in the programmed frequency relative to the particle revolution frequency will cause a displacement of the average radial position. This displacement and its rate of change can be amplified properly and used to control the oscillator frequency so that the error is reduced. Further study of the approximate equations indicates that, if both the average phase and the average radial position of the group of particles are used to monitor the amplitude and the frequency of the accelerating RF, complete self-tracking can be obtained.

At the present time a code for the computing machine "GEORGE," which will give more accurate and more reliable solutions of the problem, has been almost completed. The code follows the behavior of a large number of particles with random initial conditions of phase and energy around the machine, evaluating suitable averages of their phases and energies, and uses this information to control the amplitude and/or the frequency of the applied RF. The results should demonstrate the validity of the approximate treatment mentioned above, whether or not self-tracking, and also will permit exploration of alternate and possibly better self-tracking procedures.

D. Study of the Equilibrium Orbits in the ANL Synchrotron

Because of the edge angles and the D. C. magnets in the ANL synchrotron, the orbits are non-scaling. In a synchrotron this means that the radial beam width is not uniform all around the machine. When field gradients are introduced into the D.C. magnets to compensate for error field gradients in the main guide magnets, this non-scalability of the orbits becomes more pronounced. This, therefore, imposes an upper limit to the ability of the D. C. magnets in correcting the error gradients in the guide magnets. In this study, first a set of approximate formulas giving the non-scaling properties of the equilibrium orbits under all conditions has been derived. Secondly, with these formulas available the limitations on the corrective ability of the D. C. magnets can be studied. As an independent development, a new set of parameters for D. C. magnets with a negative edge angle (to give more usable length of short straight sectors) and, hence, a positive field gradient index, was derived. The corrective ability of these new D. C. magnets has been investigated similarly and found to be essentially identical to that of the old ones. This work has been written up in ANLAD-47.

E. Chamber Height Studies

First, a few minor errors in the computation of the loss of beam intensity due to scattering by residual gas atoms in the chamber, presented in ANLAD-44, have been corrected. An experimental fudge factor of 3 in the gauge-measured pressure value was introduced to make the theoretical results agree with measurements on the Bevatron. The formulas thus modified can be considered as semi-empirical and of greatly improved validity. These formulas have been employed to calculate the percentage survival of the particles in the beam for pressures of 3×10^{-6} and 6×10^{-6} mm Hg and qualities of injected beam of ± 0.4 and ± 0.8 inch milliradian, as functions of useful vertical gap (inside vertical chamber height minus vertical height of beam caused by construction errors).

This study indicates that the design height of $h = 5.25$ inches inside the vacuum chamber is adequate, even under very pessimistic assumptions. The assumed errors of magnet construction can be described by stating that the irregularities and tilts of the lower (for example) pole faces of the eight magnets form a surface which will lie between two ideal flat planes separated by 0.020 inch; it is further assumed that all the errors have the same sign or else have one sign in one half of the machine and the opposite sign in the other half (although such regularity of error is extremely unlikely). These errors produce an additional height of the beam given by E ≡ 1.25 inches. The quantity $F = 1/2\ (h - E)$, used as the absissa in the accompanying Figures 1 and 2, then has the value 2. With the double vacuum chamber contemplated, a pressure of 3×10^{-6} mm appears reasonable. The real unknown is the beam quality at injection. Since a quadrupole-focussed 50-Mev linac has never yet been constructed anywhere, one must depend on calculated quality figures. These range from 0.4 to 0.8 inch m radian. At the former figure, a survival of 93% is indicated, while with 0.8 inch milliradian the survival drops to 80%.

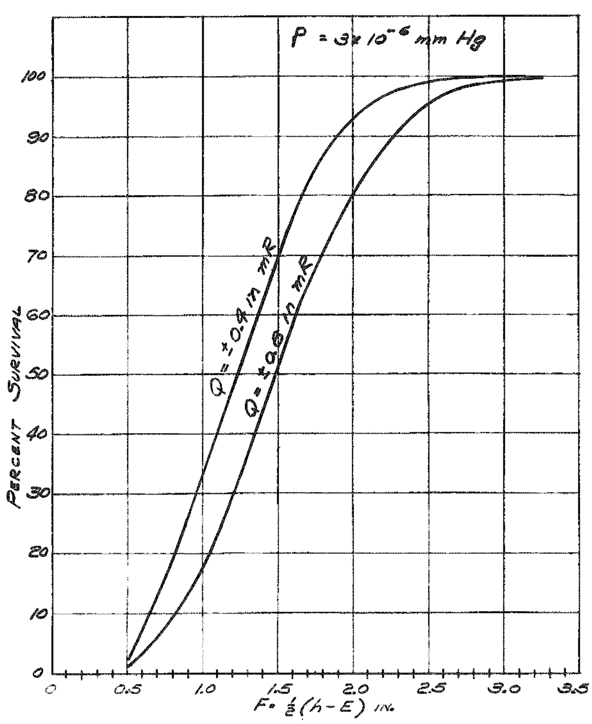

Fig. 1

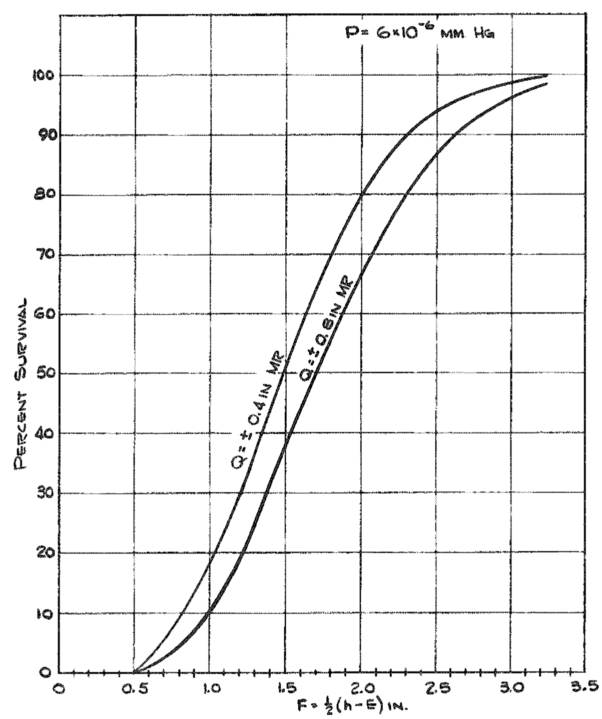

Fig. 2

On the other hand, the magnet alignment assumed above is extremely crude, attainable with the very simplest surveying instruments. With the use of a precision Wild level, the errors can be halved, giving F the value 2.3; the survival values are then 98% and 91% for the two assumed values of Q.

Since alignment errors will surely not be regular, as assumed above, the value of F can be expected actually to be somewhat larger, leading to closer approach to 100% survival. All in all, it appears that the point of diminishing return has been attained -- there is little to be gained and much expense to be incurred by increasing the chamber height to a figure greater than 5.25 inches.

Details of these calculations are given in the memo EAC-LCT-1.

F. Designs of Achromatic Bending Magnet Systems

The 50-Mev beam from the linac either will have to be bent or displaced before being injected into the synchrotron. Because of the energy spread in the beam, achromatic beam bending or shifting magnet systems are necessary. It is shown that for bending through any angle a minimum of 3 magnetic elements is required and that for parallel shifting a minimum of 4 elements is needed. Designs where all elements have uniform magnetic fields are shown to be possible. Detailed designs for (1) a system which bends the beam 110° and (2) a system which parallel-shifts the beam to just clear a 2-ft step have been derived. The focusing properties of these achromatic systems were studied in detail also. This study leads to the conclusion that it is preferable to locate the linac so as to point approximately at a right angle to the synchrotron beam (to clear the second external proton experimental area) and to bend the beam with an achromatic magnetic system.

This work is presented in ANLAD-48.

G. Shielding of Plastic Vacuum Chamber at Injection

The necessary thicknesses of the stainless steel linings on the top and the bottom of the vacuum chamber to shield the plastic chamber from radiation damage by scattered protons has been studied. It was found that 5 mils is an ample thickness for this lining (LCT-5).

H. Permissible Variations of Betatron Frequencies at Injection

The allowable deviations of ν_x and ν_z from the designed values of 3/4 and 7/8, respectively, to still provide an 8-turn dodge of the inflector lip are being investigated.

I. "IBM-704" Code for the Study of Betatron Oscillations in a General Sectorial Cyclotron

A code has been written for the IBM-704 computing machine to study exactly the behavior of the linear betatron oscillations in a general sectorial cyclotron. The mathematical analysis follows closely that given in the paper "Linear Theory of Betatron Oscillations in Sectorial Cyclotrons," L. C. Teng, Rev. Sci. Instr. 27, 1051 (1956). The magnetic field is defined by giving the momentum compaction α and the Fourier components of the curvature parameter μ of the equilibrium orbits in the accelerator. The computing machine, then, computes the radial and vertical force functions g_x and g_y by numerical integration. With these force functions the computer proceeds to integrate the Hill equations and gets the radial and vertical betatron oscillation frequencies ν_x and ν_y. Another part of the code starts from α and μ and computes back to derive the required magnetic field shape to accomplish the desired equilibrium orbits.

The program now is to find first the appropriate α and μ for a constant frequency cyclotron and then the appropriate magnetic field. The purpose of this investigation is fourfold: (1) to show that a flutter gradient effect on the betatron oscillation does exist; (2) to show that it is possible to produce constant-frequency sectorial cyclotrons to energies above one rest mass energy of the particle without crossing the $\nu_x = 2$ resonance; (3) to design a practical constant-frequency sectorial cyclotron for about 1-Bev energy for injection into a ring-type sectorial accelerator; and (4) to design a constant-frequency sectorial ring accelerator which will accelerate particles from 1 Bev to, say, 10 Bev.

III. ONE-SEVENTH SCALE MODEL MAGNET STUDIES

M. Foss, H. B. Phillips

General

The magnet work carried out so far has been with direct current models with no curvature; it has been demonstrated that an adequately uniform field can be obtained with properly sized and positioned shimming holes.

It has long been realized that with a curved magnet some changes in hole size and position may be necessary with respect to holes near the inner and outer conductor bundles. The construction of a series of curved models for a variety of hole patterns would be extremely expensive and time consuming; to avoid this, a detailed study has been made on the straight one-seventh scale D.C. model, where changes in hole size and position can be made with relative ease. As indicated in Fig. 3, the effect of holes at four different positions with respect to a coil bundle has been examined, with a variety of hole sizes at each position. A large amount of information, too voluminous to be

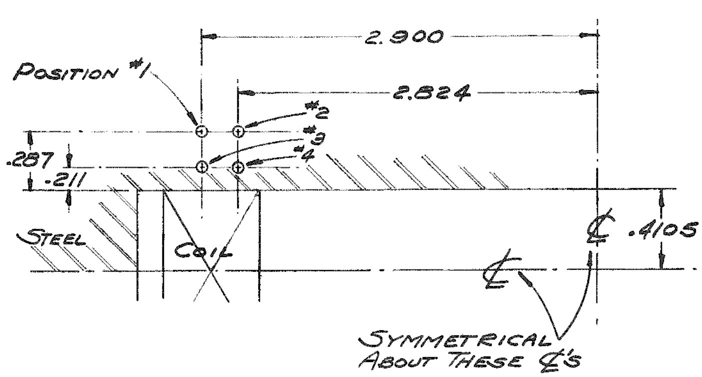

Fig. 3.

reproduced here, has been accumulated, which not only will permit machining tolerances to be set on final hole size and position, but will permit appropriate asymmetrical hole patterns to be produced in the curved model with the minimum expense. That is to say, it is now possible to pre-locate shimming holes, deliberately under size; measurement of the resulting field pattern, coupled with accumulated knowledge of the effect of changes in hole size and position, will permit these holes to be simultaneously enlarged and moved, in a few steps, into the correct position in a single curved model.

Flatness of Field

Figure 4 shows the full scale radial error fields (as excess over the value at the chamber center) for a variety of central values, with 3/8-inch diameter holes drilled in the 1/7-scale model at hole position number 2, as shown in Fig. 3. (Without the holes, the error for, say 21.7 kg, is 325 gauss at the chamber edge.)

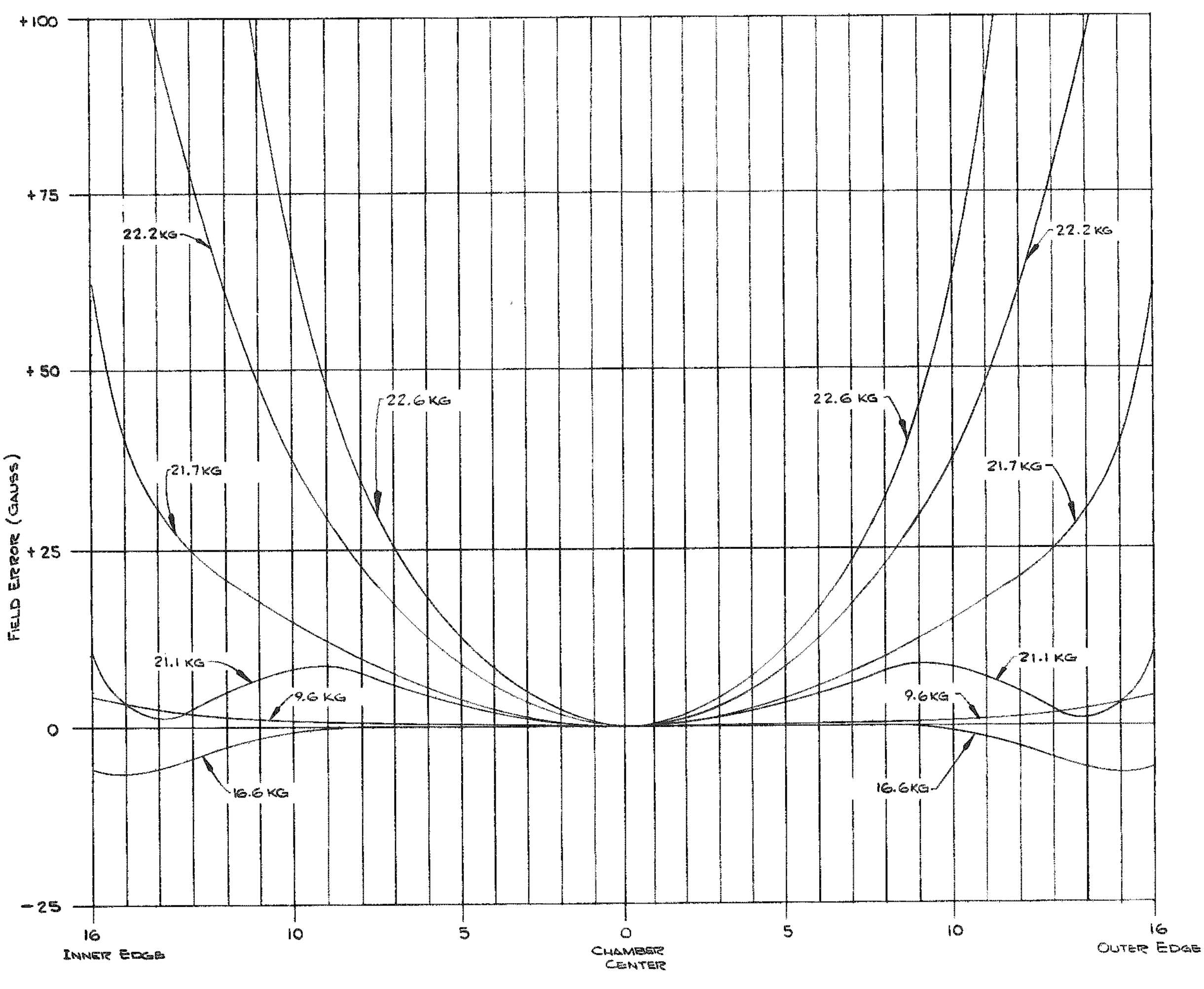

Fig. 4.

It will be recalled that high energy orbits do not travel parallel to the center of the magnet gap; their path lies within a 22-inch wide envelope which is sloped across the 32-inch wide physical gap. Consequently, the stability of the high energy orbits is determined by the average value of the field index taken along orbits which lie within and are parallel to the sides of this 22-inch envelope. A typical example of the variations of $\bar{n}$ across this region is exhibited in Fig. 5. It may be observed that $\bar{n}$ lies within the stability limits up to 21.7 kilogauss; this is particularly important for the

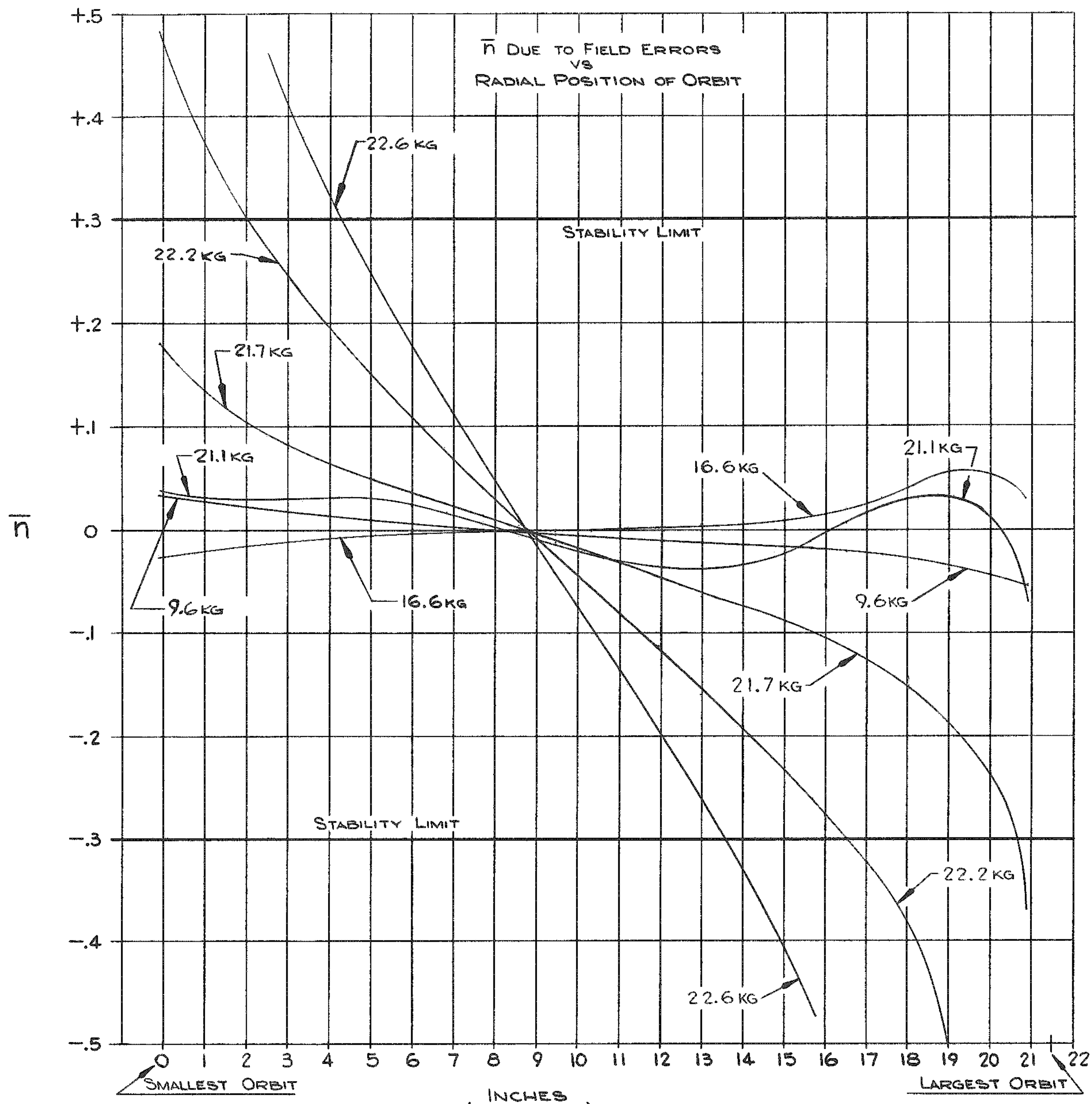

Fig. 5.

smallest orbits (towards the inside edge of the chamber) since the protons must enjoy good optics in passing through the Piccioni magnet. (The small excursion past the stability limit for the largest orbit towards the outside edge of the chamber is not serious, since the protons will have been deflected already towards the outside and will, moreover, traverse this region but once.) It is also noteworthy that for non-deflected beams, appropriate for internal targets, the flatness of field is adequate for energies above the design figure of 12.5 Bev.

Magnetic End Measurements

It is important that the effective length of a magnet octant does not vary too greatly during a magnet pulse, for the reasons given in the previous Summary Report ANL-5803, p. 20. Such variations of length have been reduced to an entirely negligible extent through the use of appropriately shaped ramps cut into the steel at the magnet ends.

Besides providing for a good field termination at the magnet ends, the ramps also allow the coil conductors to flare gradually near the ends, and give large radii of curvature to the conductors where the coil bends into the jumpers across the magnet faces.

In order to choose a ramp which is compatible with good coil design, as well as providing the desired magnetic behavior, a series of experimental ramps were cut into the one-seventh-scale magnet and the corresponding magnetic field shapes were studied. In these experiments the same coil was used for all ramps, the measurements being made in the center of the air gap, where the effects of the improperly flared coil would be minimized.

Figure 6 shows a summary of those experiments, where the behavior of six different ramp shapes is illustrated. (Ramp No. 5, whose characteristics lie between those of Nos. 3 and 6, is not shown.)

Ramp No. 0, which represents the unaltered magnet face, causes the effective magnet end to move from an initial position 3/8-inch outside the magnet to 0.050 inch outside as the field is increased to 23 kilogauss. This variation in length is altered by removing steel, and the final ramp shape, No. 6, exhibits almost no variation in magnetic length over the range 0-23 kilogauss; the variation of length for this case is about 0.005 inch, which is only about 1/32-inch full-scale.

A new coil, flared to approximate the shape of the magnetic equipotentials of ramp No. 6, is under construction and will be used for studying the radial variation of the magnetic end. It is believed that, by thus properly locating the coil conductors, the radial position of the magnetic end will vary negligibly over the full operating range of field intensities.

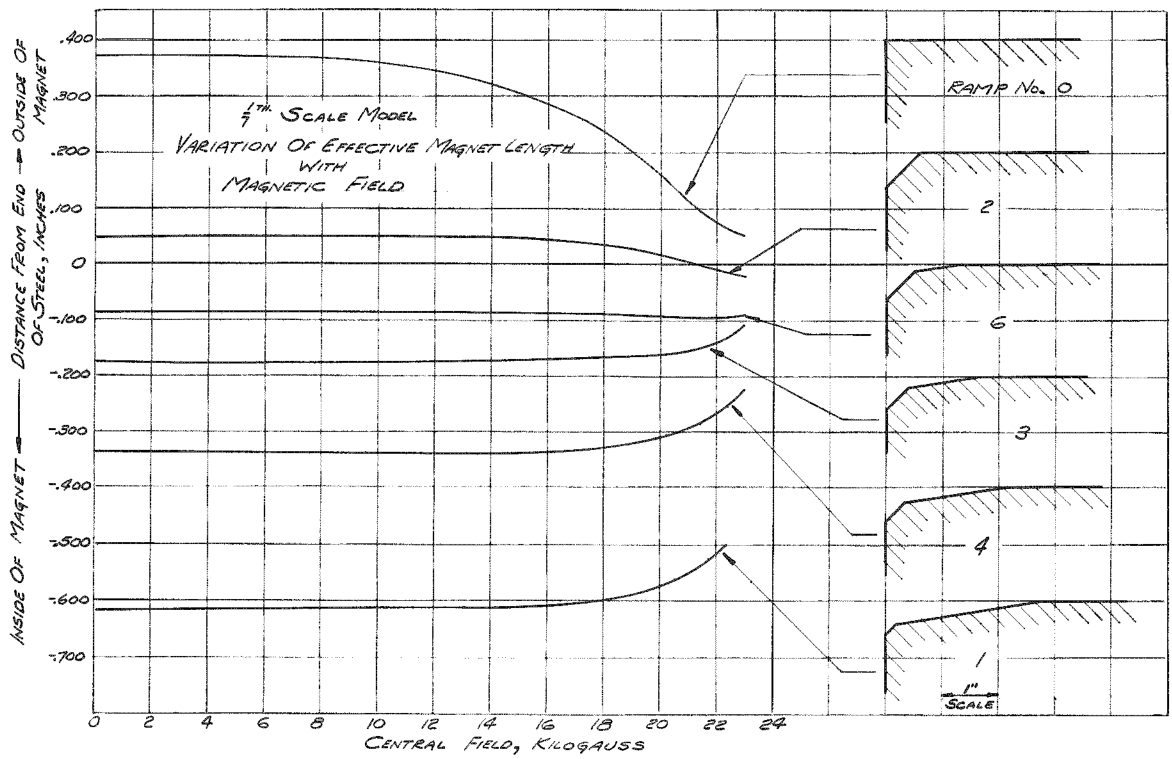

Fig. 6.

IV. MODEL MAGNET CONSTRUCTION

R. Lykken, W. Siljander, D. Cosgrove, R. Krizek

As described elsewhere in this report, the vertical flaring of the end of the one-seventh-scale D.C. model magnet has been adjusted to an optimum value, excitation being supplied with a coil designed for a magnet with no flare. A new coil, built to follow the contour of the best flare, has been fabricated and shipped to the National Coil Company for potting.

Another one-seventh-scale D.C. model magnet is under construction. This will simulate the final model, with scaled curvature, appropriate angles of the end faces, and with both radial and vertical flaring. It is expected to be finished by the middle of June.

The first pulsed model (one-fourth-scale) magnet is nearing completion; it will provide a laminated, curved model of the central portion of an octant, 8 feet in length, full scale.

Additional one-fourth-scale models are in the planning stage.

V. INSTRUMENTATION FOR DYNAMIC MAGNET STUDIES

D. E. McMillan

The fast multichannel analog-to-digital converter system, commonly called the "Rea machine," arrived at the end of January. Since then it has been assembled and checked out with the control systems for the pulse model magnet and for R.F. measurements, as well as with the 523 IBM card punch and a Commercial Controls Corp. paper-tape punch and typewriter system. Figure 7 is a photograph showing from left to right the following:

(a) Pulse model magnet control system.
(b) The Rea machine power supply rack.
(c) The Rea machine console which contains the multiplexer, converter and programmer.
(d) The Rea machine magnetic tape to IBM card or punched paper tape translator.
(e) The Commercial Controls paper tape punch, flexowriter, etc.
(f) The IBM 523 card punch.

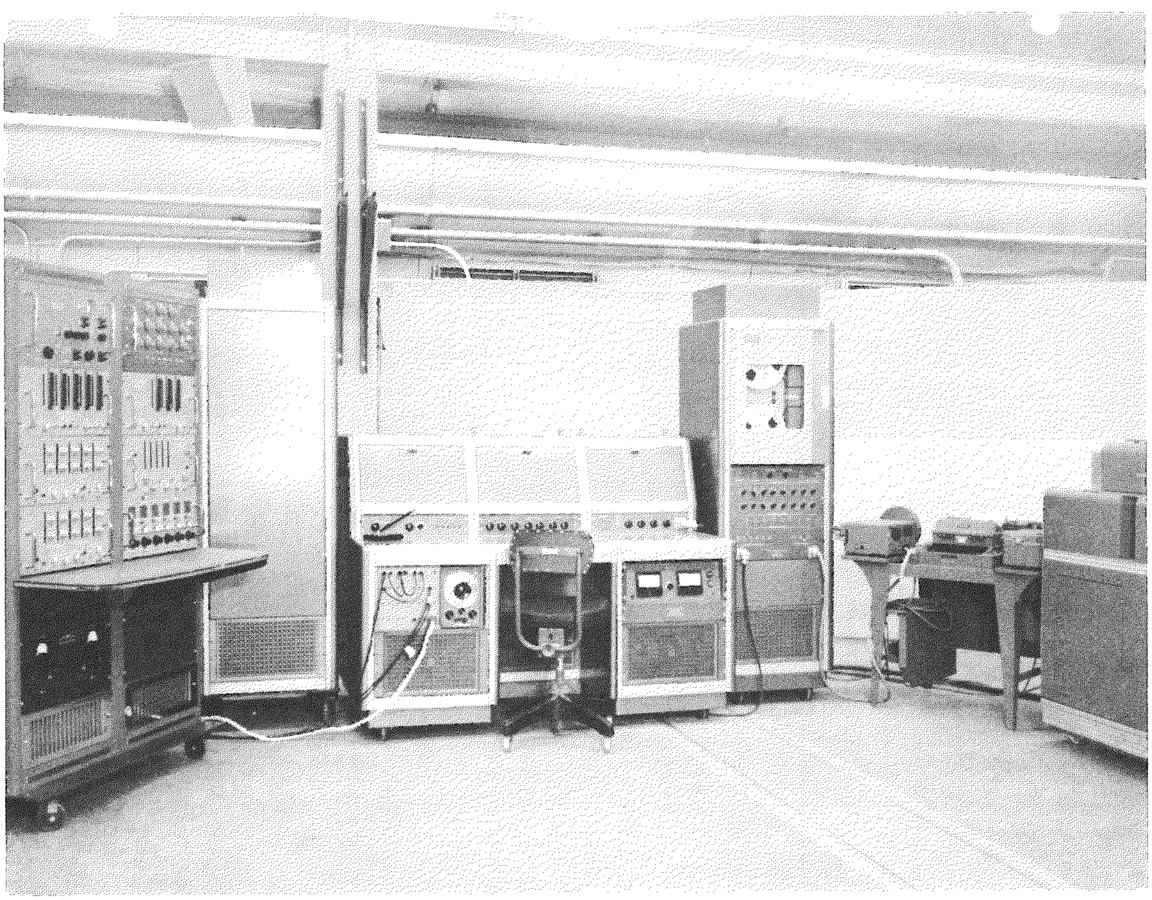

Fig. 7.
Pulse Model Magnet Control and
Rea Analog-to-Digital Converter

After considerable work, the over-all system has started to look satisfactory except for some relatively infrequent malfunctions of the magnetic tape translator. These errors are so erratic that, although they were thought to have been eliminated on several occasions, sooner or later they have shown up again. One of the Rea Company's engineers is due here in the near future to try and help resolve the problem once and for all.

Several tests have been made to check the operation of the converter including some actual experiments with the R.F. function generator. One set of tests was a D.C. calibration of the machine made on successive days for about two weeks. An IBM 650 computer program was written to determine the frequency distribution for each analog channel. This data was taken at the maximum sampling rate of 1000 samples/sec/channel in the simultaneous sampling mode over an interval of 240 milliseconds. Though very little time has been available for analyzing the results, Table I shows the kind of results we may expect, although only 3 of the 13 test voltages are shown. There is evidently some drift in the gain of the various amplifiers and a spread in the data due to amplifier noise of the order of 1/2 to $1\frac{1}{2}$ counts (standard deviation). This is considered to be quite good, although improvements can probably be made. If the rash assumption that the data follow a normal frequency distribution curve is made, the above chart indicates that a probable error of $\pm$ 1/2 to $\pm$ 1 count might be expected, which at half scale of 500 counts is a relative probable error of from $\pm$ 0.1% to $\pm$ 0.2%. Therefore, it may very well be worthwhile to write the computer programs such that corrections may be made for drifts in amplifier gain, etc., such that the noise will then be the limiting factor in the accuracy of the measurements.

TABLE I

Calibration Run on 3/11/58

Channel Number	Constant = 000 (Run No. 16)		Constant = +500 (Run No. 6)		Constant = -500 (Run No. 7)	
	Arithmetic mean	Standard deviation	Arithmetic mean	Standard deviation	Arithmetic mean	Standard deviation
1	-0.43	0.496	+498.9	0.752	-500.2	0.716
2	-0.09	0.303	+499.0	0.580	-501.0	0.725
3	+0.25	0.572	+499.5	0.717	-498.4	0.556
4	-0.15	0.494	+499.0	0.468	-500.5	0.805
All channels	-0.11	0.534	+499.1	0.672	-500.0	1.22
P. E. all channels	-	0.360	-	0.454	-	0.824
% P. E. all channels	-	-	-	0.091%	-	0.165%

Calibration Run on 3/12/58

Channel Number	Constant = 000 (Run No. 29)		Constant = +500 (Run No. 19)		Constant = -500 (Run No. 20)	
	Arithmetic mean	Standard deviation	Arithmetic mean	Standard deviation	Arithmetic mean	Standard deviation
1	+0.07	0.947	498.5	0.975	-499.0	0.558
2	-0.85	0.604	497.7	0.669	-500.9	0.404
3	-0.20	0.437	497.6	0.624	-499.5	0.597
4	+0.01	0.734	497.4	0.795	-500.6	0.834
All channels	-0.23	0.759	497.9	0.889	-500.0	0.974
P. E. all channels	-	0.512	-	0.600	-	0.657
% P. E. all channels	-	-	-	0.120%	-	0.131%

Calibration Run on 3/13/58

Channel Number	Constant = 000 (Run No. 44)		Constant = +500 (Run No. 34)		Constant = -500 (Run No. 35)	
	Arithmetic mean	Standard deviation	Arithmetic mean	Standard deviation	Arithmetic mean	Standard deviation
1	-0.07	0.810	500.2	0.609	-499.0	0.793
2	-0.40	0.523	501.4	0.946	-500.2	0.795
3	-0.21	0.429	498.4	0.909	-499.2	0.718
4	+0.20	0.716	501.0	1.37	-499.2	1.01
All channels	-0.12	0.667	500.3	1.52	-499.4	0.965
P. E. all channels	-	0.450	-	1.03	-	0.651
% P. E. all channels	-	-	-	0.206%	-	0.130%

VI. GENERATOR REGULATOR

J. F. Mech

The Particle Accelerator Division has long had a generator regulator* on the four G.E. generators in Building 805. This regulator has been changed from time to time, sometimes simply being altered by choice of components and sometimes by building a new electronic circuit. There have been five distinct forms, each representing some improvement on the preceding regulator. The present model, Model 5, represents a system which is applicable in theory to any generator with slight modification and which has sufficiently good regulation to meet any static loading requirement. It is no more difficult to build and operate than previous models with less regulation, and in addition, certain devices have been added to improve operation. The system in Building 805 is now a 2-generator cascaded system where the four G.E. generators may be considered a single generator, excited by an amplidyne.

The problem of generator regulation may be broken down into two parts: (1) establishment of a stable feedback system,** and (2) elimination of the effects of generator ripple on the regulator without introducing undesirable characteristics. A stable system may be constructed by altering the effect of the time constants of the generator and the exciter by the addition of phase-shifting networks*** and by the use of additional enclosed feedback loops. Ripple is usually eliminated by adding one or more time constants in the form of a filter which may have an unstabilizing effect. Two feedback loops were established about the amplidyne and had the desirable functions of improving the response (decreasing the effective time constant), controlling the gain in such a way that the effect of poorly defined circuit constants were minimized or eliminated, and of controlling the amplidyne to an equal or better degree than the main generators. This last function is a vital one in accomplishing good regulation.

The control of the main generators is then accomplished by a feedback loop which includes the circuit of the amplidyne. The principal feature of this control is the method by which phase shift and ripple are limited. An ideal amplifier used for this purpose would have a flat frequency response with no phase shift except for the frequencies of the generator ripple where the gain would be zero. If this were easily done, the only problem would be the magnitude of the phase shift caused by the time constant of the main generator and of the amplidyne feedback loop. An alternate plan, which is

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*ANL-5803, Particle Accelerator Division Summary Report, (April 1957) p. 29.

**"Servomechanisms and Regulating System Design," Vol. 1, H. Chestnut and R. W. Mayer, 5th Printing, J. Wiley, New York, p. 124.

***<u>ibid</u>, p. 245.

the system in use, is to modify the response of the amplifier so as to provide the necessary rejection for the unwanted ripple simultaneously using this modification to produce a phase shift sufficient to produce stable operation. The circuit actually used is a feedback amplifier where the input impedance is a resistance and the feedback impedance is a resistance and a capacitance in series. The feedback resistor is varied to adjust the gain for ripple and the capacitance may be varied to alter the damping with the input resistance fixed. This circuit is effectively a lag circuit where one time constant is fixed and the other is determined by the gain of the amplifier; hence, the circuit is not sensitive to changes in gain.

Use of this regulator in the laboratory has shown it capable of current control sufficient to "freeze" the indicating pip on the Nuclear Magnetics Corp. precision gaussmeter at magnetic fields greater than 20,000 gauss.

VII. PULSING CIRCUIT FOR QUARTER-SCALE MODEL MAGNET

K. Burba, J. Mech

The future location, in Building 805, of the pulsed quarter-scale model magnet and of the pulsing circuit* (employing the existing G.E. generators), has been determined so that all arrangements and testing may be completed before the actual installation of the magnet. The magnet table has been mounted and construction of the necessary bus work is underway. It is intended that a bus with minimum spacing will be used to minimize stray magnetic fields and to minimize the inductance of the magnetic external circuit. The portion of the bus nearest to the magnet, which is about 15 feet in length, will be watercooled in order to decrease space requirements and to simplify installation. All other bus work will be air-cooled.

VIII. ADDITIONAL LABORATORY POWER SUPPLIES

J. F. Mech

Two Lincoln welders have been installed as an additional laboratory power supply. These are as well regulated as the large generators. They will supply continuous currents as high as 600 amperes at approximately 20 volts. Future generator modifications will provide voltages as great as 70 volts, if required. These generators are very fast and may be used to supply voltages and currents capable of large voltage and current changes in less than 0.1 second by choosing appropriate driving signals.

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*ANL-5803, Particle Accelerator Division Summary Report (April 1957) p. 31.

IX. 1200-kw MOTOR GENERATOR

K. Burba, J. Mech

Bids have been obtained and an order has been placed for the construction of new motor generator sets to be used for larger D.C. and pulsed model magnet testing than is possible with our existing power supplies. These generators, four in number, are each rated at 300 kilowatts D.C. and are each capable of producing 2400 amperes at 125 volts. They will be powered in pairs, each pair driven by a single centrally located 900-horsepower induction motor. The generators may be used either singly, in parallel to produce some multiple of 2400 amperes up to 9600 amperes at 125 volts, or in series to supply 2400 amperes at 500 volts.

Plans are being made for the mounting and installation of these machines. A simple building will be constructed to house the motor generators, together with the necessary controls and auxiliary equipment, immediately south of and adjoining Building 805. Adjacent to this structure, an electrical substation of sufficient capacity will be installed and powered from the existing 13,200-volt transmission line. Installation is expected by mid-summer.

X. RING MAGNET POWER SUPPLY

G. O. Calabrese, E. F. Frisby

Comparative analyses of a number of schemes of power supply are in progress. These schemes have also been submitted to the Westinghouse Co., the General Electric Co., and the Allis-Chalmers Co. prior to meeting with representatives of these companies for discussions of the problem. Preliminary discussions have already been held with engineers of the Westinghouse Co. and of the General Electric Co. A date has been set for meeting representatives of the Allis-Chalmers Co.

The schemes submitted to the manufacturers and the modifications or new schemes suggested by the two manufacturers, with whom we have already met, fall into two general lines of approach, namely:

(1) A scheme involving induction driving motors, flywheels and cascade D.C. generators with field-reversing control.

(2) Various schemes making use of mercury-arc rectifiers and involving induction driving motors, flywheel and A.C. generators.

The schemes using mercury-arc rectifiers are to be preferred. Source of the reasons for this conclusion are: economy and reliability; efficiency and ability to operate with relative ease over a wide range of voltages and currents during both the rectifying and the inverting conditions.

The schemes making use of mercury-arc rectifiers may be subdivided into two subgroups:

2A Those using one or more motor flywheels with one or two 12-phase generators supplying directly the mercury-arc rectifiers, and

2B Those using one motor flywheel with one or two three-phase generators connected to a three-phase bus, which supplies appropriate transformer banks so connected as to provide the 12-phase power to the mercury-arc rectifiers connected for single-way or double-way rectification.

The following table gives a brief comparison of the two schemes at present preferred by the two manufacturers with whom the problem has been discussed:

	Company A	Company B
Motor	One wound rotor induction motor, 900 rpm	One wound rotor induction motor, 720 rpm
Flywheel	One	Two
Generator	One - three-phase, 13.8-kv, 900 rpm	Two - 12-phase generators, 720 rpm
Rectifier transformer units	Four	None
Number of ignitrons	96 connected for single-way rectification	96 connected for double-way rectification

The matter is still in a state of flux. As already stated, the Allis-Chalmers Co. has not yet been visited. The Westinghouse and General Electric companies have asked for more time to consider the problem and we ourselves are in the process of analyzing the various schemes submitted to the manufacturers, the changes they have or will suggest, as well as any new scheme that they have proposed or will propose. With this understanding, Figs. 8 and 9 show schematically the two schemes preferred respectively by Company A and Company B.

The manufacturer preferring the scheme of Fig. 8 gives the following reasons for the preference: better utilization of the ignitrons, more positive protection of equipment, only one alternator exciter is involved, and all ignitrons and transformers are supplied from the same bus. Even though the plan requires rectifier transformers, the proponents believe

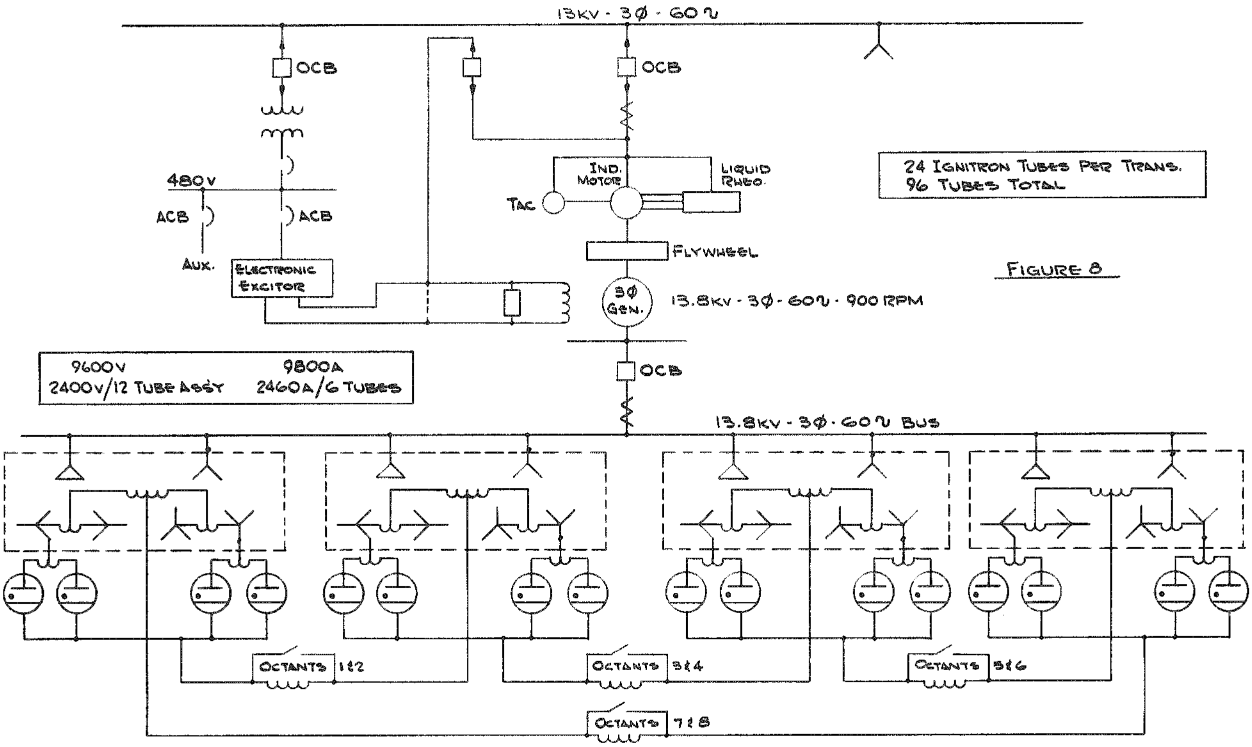
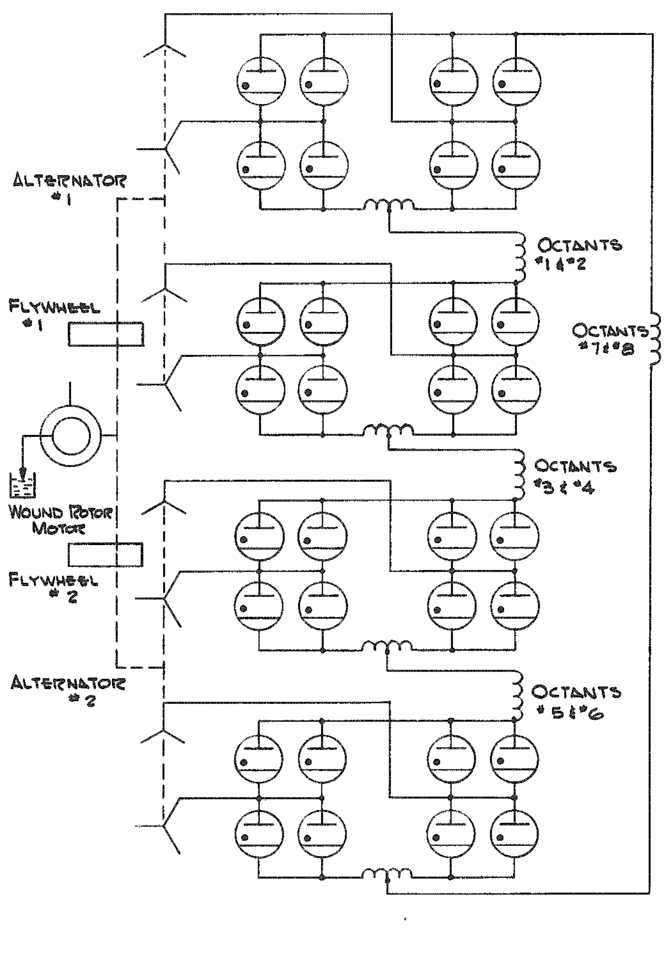


FIGURE 8

FIGURE 9



that it will be more economical than the equivalent scheme with 12-phase generator or generators. The primary reason behind their opinion is the elimination of the long D.C. power conductors due to the fact that the transformers and rectifiers can be located near the ring magnet.

The manufacturer preferring the scheme of Fig. 9 is of the opinion that it will be cheaper from the manufacturing and installation standpoint to split the generator into two units. Lighter weight was mentioned as one of the reasons for this. Using two flywheels instead of one was also based on this type of reasoning. Double-way rectification was proposed because it was thought that general performance would be enhanced. It was pointed out that in the event of an arc-back, there would be no D.C. short circuit through the faulty ignitron. Another point in favor of double-way rectification was that smaller interphase transformers could be used if 12-phase rectification were required. With 6-phase rectification, no interphase transformers would be needed for this plan. Engineers from this company were definitely in favor of sealed-type ignitrons. They thought that the sealed type would be more reliable and less expensive to maintain than the pumped-type rectifier.

In connection with the power supply, we are also studying the effect on the various components of holding the beam in orbit at the end of the rising period (1.0 sec) for a length of time up to 0.5 sec.

XI. FORCES ON MAGNET AND COILS

G. O. Calabrese

Calculations have been made of the forces expected on the various components of the magnet of the proton synchrotron as follows:

(a) Forces of attraction between the top pole and the bottom pole of each octant: 6043 tons/octant.

(b) Azimuthal force tending to separate from one another the plates of the magnet: 31 tons.

(c) Forces on the current-carrying conductors forming the two sides of the coil of each sector: 12.1 tons/ft.

(d) Forces on the coil jumpers at the ends of each sector: 13.8 tons on each bundle of jumpers, directed away from the median plane.

(e) Forces of attraction between each end plate and the corresponding guard: 25.1 tons.

(f) Forces due to the misalignment of the slabs: negligible.

This information, given in detail in Memo GOC-8, is being used in the mechanical design of the magnet and coils.

XII. RING MAGNET DESIGN

David Cosgrove, R. H. Lykken

The proposed ring magnet studies aimed at obtaining design and fabrication experience, as outlined in the previous report (ANL-5803), have produced much information, generated several new ideas, and resulted in redirection of magnet test section studies.

Twenty full-sized 1/2-inch plates were successfully ground to a taper on the Carborundum Corp. of America's 84-inch belt grinder at Niagara Falls, New York, with the hope of being able to produce an "ideal" ring magnet made of all tapered plates. Although actual grinding costs turned out not to be excessive, the necessary extra handling and shipping charges make this method uneconomical.

Two ring magnet test sections made of flat plate were fabricated, one at Rock Island arsenal and one at Bethlehem Steel Co. (see DFC-2). Although the vacuum testing and disassembly of the blocks to determine extent of impregnation are not complete at this time, much has been learned about materials and fabricating techniques.

Bethlehem Steel Co. was able and interested in producing 1/2-inch plate on their Sparrow Point 60-inch mill to within the 0.500 (+0.015/-0.000)-inch flatness tolerance as required by our stack-up problem, in contrast to the commercial tolerance of 0.500 (+0.020/-0.010)-inch.

Bethlehem was able to produce plate within our maximum allowable crown tolerance of 0.003-inch, required to reduce magnet errors, by means of special "fish belly" rolls which deflect to a straight line under the load of rolling. Commercial tolerance is 0.007-inch.

Stack annealing of plates under load at 1150°F prior to machining brought the plates to within our required flatness tolerance of 1/64-inch without formation of excessive scale.

Lay-up and assembly of the blocks served to emphasize:

(a) The desirability of a clean shop. Conducting particles floating in the atmosphere apparently settled on the cleaned and degreased plate surfaces penetrating the interlaminar insulation and causing shorts as the load required to compress the block was applied.

(b) The necessity of being able to disassemble the stack readily during lay-up to eliminate shorts without the difficulty of handling tacky "B" stage-type interlaminar insulation or tacky epoxy sprayed plates.

(c) The advantage of unbleached muslin (approximately 0.008-inch thick) over glass cloth as interlaminar insulation:

1. Greater "body" makes for easier handling and cutting during lay-up.

2. Greater resistance to penetration of conducting particles.

(d) With a nominal amount of care and vertical lay-up of plates in the jig, the greatest difference in height of plate edges at the pole face can be held to 0.005 inch or even 0.002 inch.

The experience outlined above combined with the results of discussions between the magnet and mechanical groups has resulted in the following revisions and additions to the ring magnet studies:

1. In an effort to use a dry lay-up method, it was decided to vacuum impregnate the ring magnet block weldment. This would allow the use of the magnet as a vacuum chamber and prevent the accumulation of magnetic particles between laminations during operation of the machine. To this end, the two test blocks were vacuum impregnated with polyester resins. The results of this are now being evaluated. In addition, 40 plates from plate-tapering experiments have been laid aside for future work if necessary.

2. Conferences between the physicists have resulted in a decision to go to a four-piece magnet cross-sectional design because of the advantages of symmetry. The revised magnet cross section is shown in Fig. 10, which also shows revisions to magnet girder and lift lug design to facilitate handling in the tunnel.

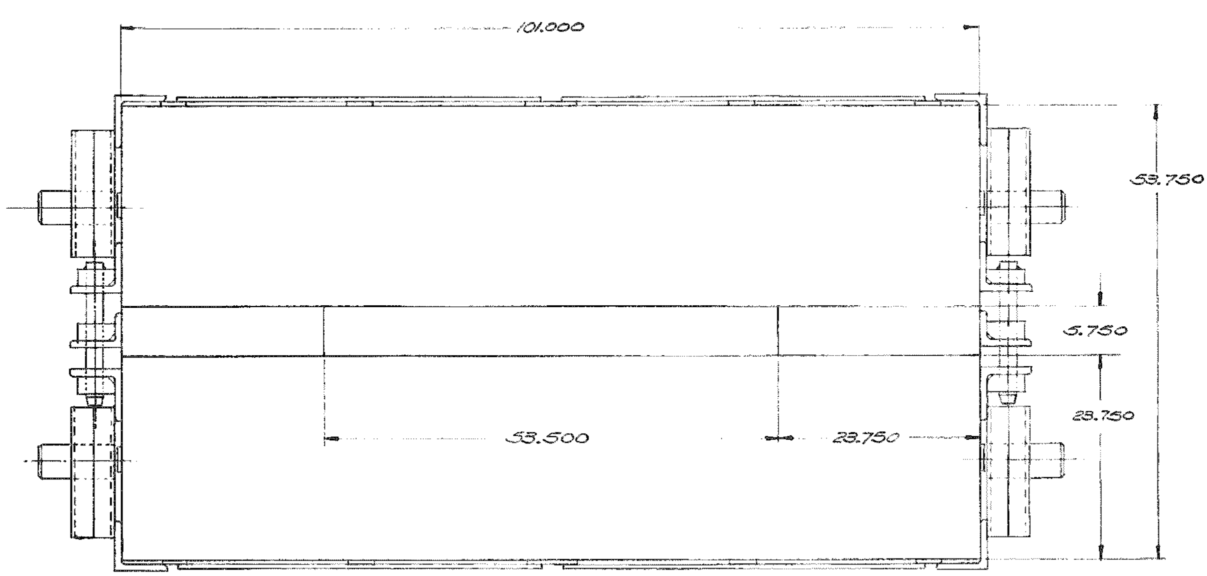


Fig. 10.

3. Due to the kindness of Reynolds Aluminum Co., McCook, Ill. in offering to try to roll tapered plate for our magnet, effort is again being expended toward building the "ideal" magnet made of all tapered plate. Reynolds has a 6000-hp rolling mill, possibly the only one in the world, which, because of its electronically controlled screw-downs, can produce a uniform taper on a sheet of steel as it passes through the rolls. These taper plates have been rolled cold from oversize hot-rolled, pickled and oiled plate. Maximum deviation on twenty sample plates from the desired taper was ±0.005 inch. In addition to the taper, the fine rolls used in aluminum work provide a desirable finish on the plate, free of bumps, peaks, and metal whiskers which might cause shorts. Preliminary cost estimates between an "ideal" magnet produced this way and an alternate design consisting of repeated packs of twelve 1/2 inch plates followed by a 13th machined tapered plate appear about equal. One hundred plates have been ordered taper rolled by Reynolds for the construction of a full-size top pole block by a local fabricator. This project will be closely followed for valuable cost and fabricating experience.

4. Plans are being made for a full-size complete magnet block and supporting girder mock-up. This would consist of a concrete pad and simulated foundation built adjacent to one of the shop buildings as a source of heat and power. It would allow dry runs to be made with full-size blocks on such problems as block handling, alignment, jacking, vacuum sealing between blocks, welding of girder, and girder deflection.

XIII. RING MAGNET COIL DESIGN

W. A. Siljander

The electrical, thermal, and physical forces that will be imposed upon the coil assembly have been determined. Likewise, the physical dimensions and allowable tolerances that will satisfy the stringent magnetic and electrical requirements have been prescribed. The plan view is shown in Fig. 11, the cross section in Fig. 12, and the end jumper configuration in Fig. 13.

A decision has been made that the only feasible means of meeting the requirements for coil configuration and strength is to fabricate the coil into a monolithic section of copper conductors and plastic insulation by means of a suitable, accurate mold fixture. The spacing between conductors should be held by pressure-molded shims that will not compress appreciably during stacking and molding. They should also be of a material content that will be compatible to the plastic adhesive resin used. This compatibility

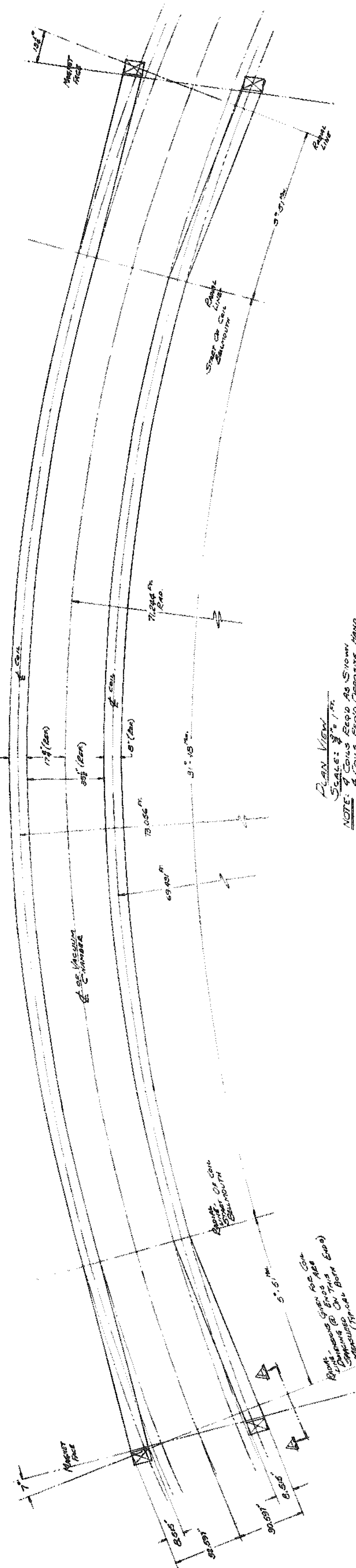
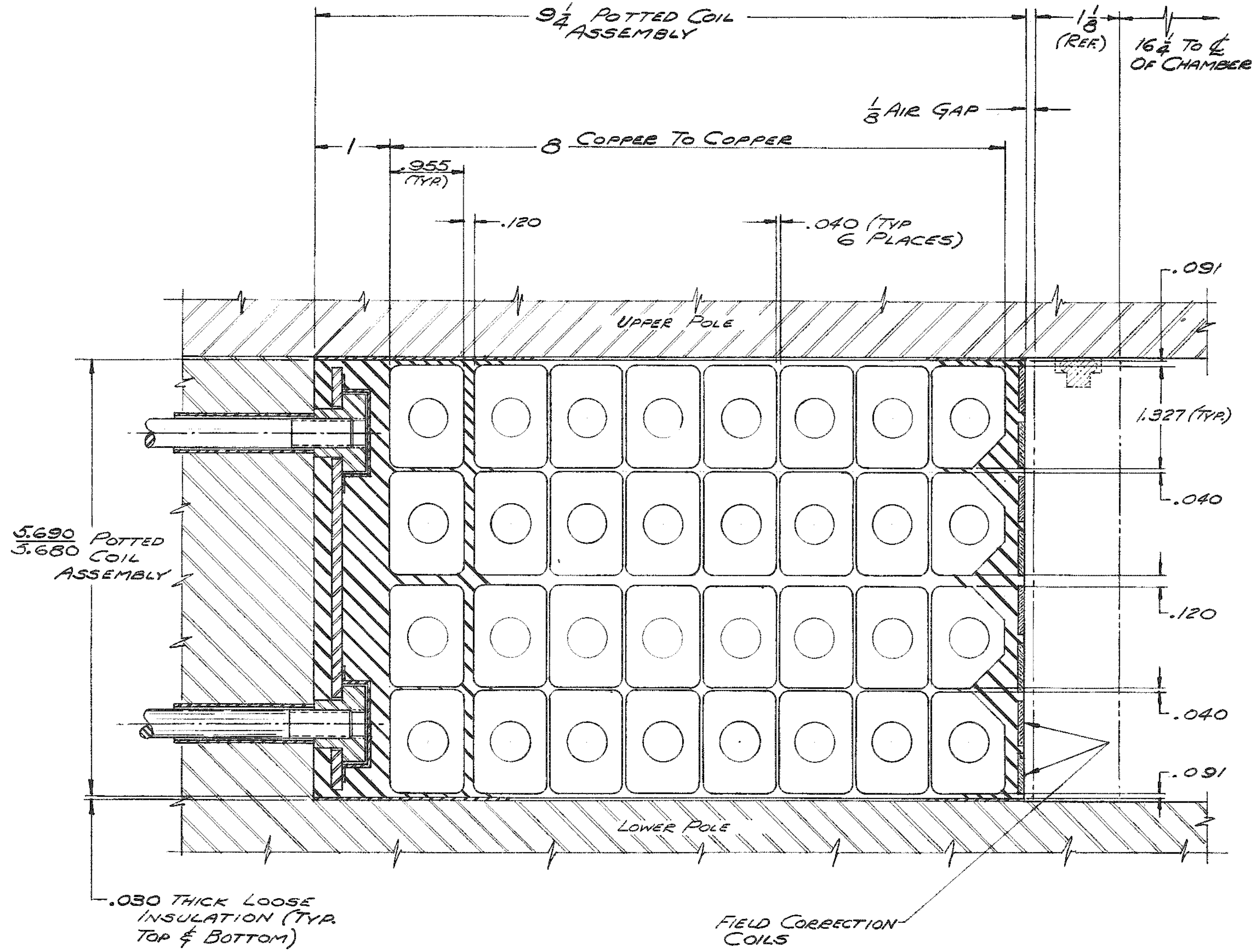

PLAN VIEW
SCALE: 3/8" = 1 FT.
NOTE: 4 COILS REQ'D AS SHOWN
4 COILS REQ'D OPPOSITE HAND
ALL DIMENSIONS ARE COPPER TO COPPER.
INSULATION NOT SHOWN.

Figure 11



TYPICAL CROSS-SECTION OF POTTED COIL

Figure 12

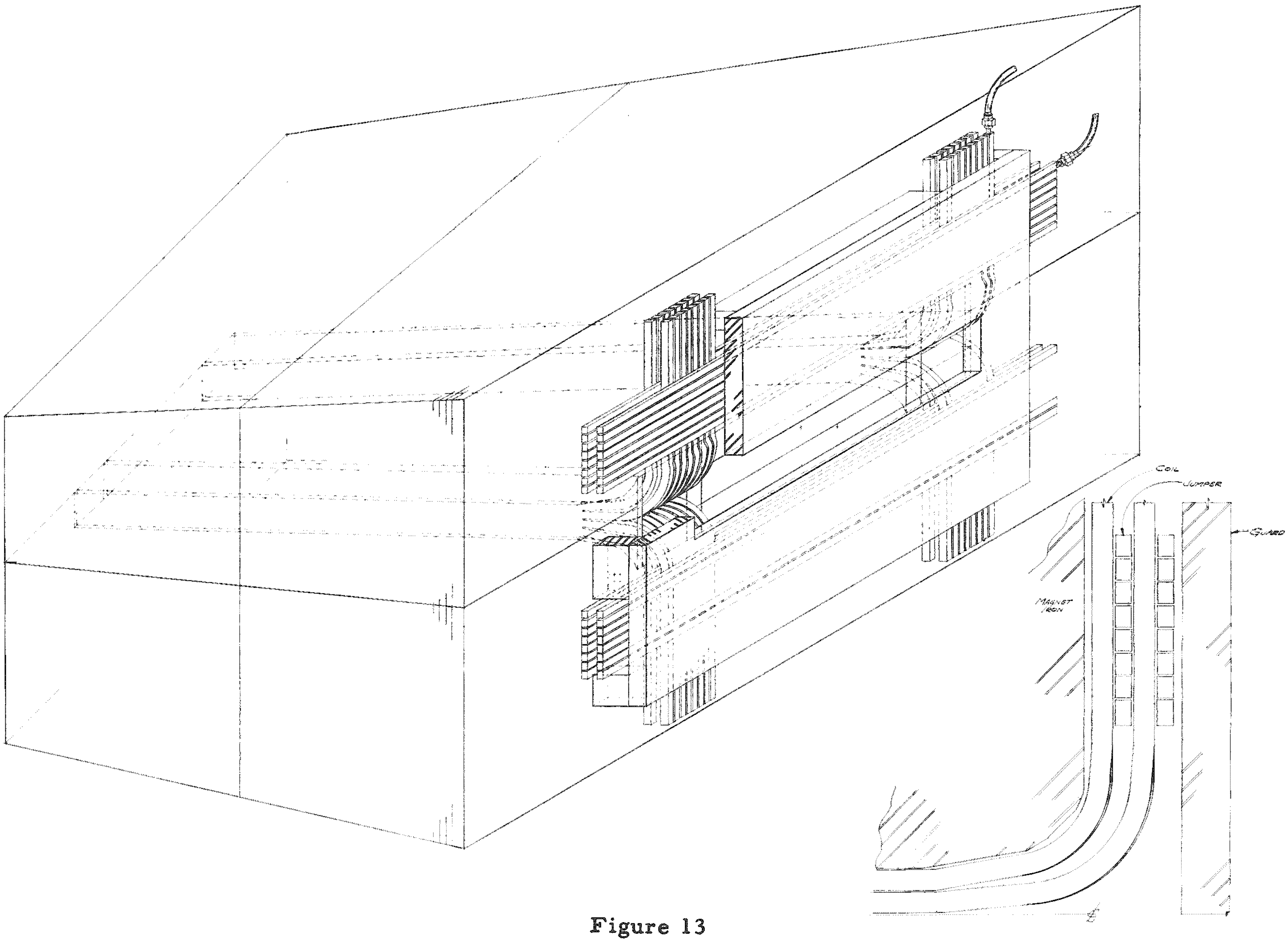


Figure 13

can be achieved remarkably well by using an epoxy resin (Epon 828) with hardener "Z," or BF 3-400 as the adhesive and a pressure-molded shim shim plastic of 40% by weight of Epon 828 plus hardener and 60% glass cloth, or an acrylic resin and glass cloth as used on the Brookhaven AGS coils.

Physically, the epoxy combinations have the best properties. Tests conducted by Particle Accelerator Division's Plastic Laboratory and The National Electric Coil Company, and results given by the Shell Chemical Company in their technical bulletin SC:55-15R lead to the following physical characteristics of Epon 828 plus hardener and 60-75% glass:

Ultimate Flexural Stress	82,700 psi
Ultimate Tensile Stress	47,900 psi
Ultimate Compressive Stress	52,400 psi
Modulus of Elasticity	$3 - 3.6 \times 10^6$ psi
Adhesive Strength	1000 - 1530 psi

The magnitudes of the physical properties as stated above indicate the combination to be a potent tool for the fabrication of the ring magnet coil.

Several methods of construction can be utilized. In one method, the conductors are spaced by horizontal and vertical plastic shims, which are staggered in such a way that the residual gaps between conductors form an interconnected honeycomb. Glass cloth or glass matting is introduced into these cells, as assembly proceeds, as a filler for the resin and hardener, which is drawn by vacuum suction on the accurately shaped steel mold in which the assembly is built up. Curing is effected by passing hot water through the holes in the conductors.

The second method is to separate the layers of conductors by continuous sheets of plastic, the conductors in any layer being separated by additional continuous plastic sheets. This assembly is built up in a mold, with the conductors pre-coated with adhesive resin in the "B" stage. Curing heat is applied through the holes in the conductors, while pressure is applied to the movable top and one side wall of the mold.

A third method would repeat the second, but with spatial allowance for a final wrapping of the coil assembly along its entire length with glass tape, to be followed by an impregnation procedure in a mold built to the final outside dimensions of the coil. This is similar to a method used by the National Electric Coil Company for the Brookhaven AGS coil.

Full-scale section models are now being constructed by the National Electric Coil Company for complete physical, electrical and thermal strength tests. It is hoped that within the next two months the best combination of fabricating materials, methods of construction and expected strengths will be established.

A method of mounting the coils in the magnet by pre-stressing has been proposed. Briefly, the plan is as follows: The two coils for one octant are pre-potted along their azimuthal length, as described earlier. After being placed in the magnet, the cross connections are secured. The entire coil is then brought to a higher temperature than that planned for operation, and the cross connections are then cast in resin between the end face of the magnet and the iron guard plate. As the system cools, the coils are put under tension; any subsequent temperature changes bring about only a change in the stress.

It is obvious that the outer coil must be restrained from assuming the shape of a chord; this is accomplished by radial tie rods which pass through slots in the yoke to adjusting nuts. The other ends of the rods terminate in stainless steel plates embedded in the outer wall of the coil assembly, these plates being further attached to the coil by glass cloth belts which also form part of the potted structure.

Although not required for the same reason, similar tie rods are contemplated for the inner coil, to hold it firmly in position when the magnetic forces are periodically relaxed.

This method of coil mounting, along with expected stresses in the coil assembly, has been written up in detail in the Memo WAS-4.

Further studies are proceeding on the feasibility of resistance silver brazing the coil and jumpers on the side coil assemblies. Experts consulted in this field consider this method entirely feasible. Experimental tests are to be undertaken shortly to determine the practicability, along with the joint physical and electrical strengths, as well as the necessary equipment to do the job along production lines.

XIV. RF ACCELERATING VOLTAGE

J. Martin, H. Kampf, L. Wadhwa, C.H.M. Turner, R. Daniels

A. Master Oscillator R.F. Control System

The plan for the master oscillator bias system was described in the previous summary report, ANL-5803, pp. 45-50. Such a system has been constructed using input signals which simulate those which would come from the synchrotron's pulsed guide magnet. The stability and repeatability of the generated function has been tested dynamically by oscilloscope traces to an accuracy of $\pm$ 2%. Tests have been started, using the Rea data converter. It is apparent that the accuracy is better than $\pm$0.25%, which is the limit of the Rea unit. Preliminary tests using the Rea machine to read out the radio frequency of the master oscillator have been made satisfactorily. Next, the shape of the frequency program generated will be fitted to that required by using a multipoint diode switching network for making the final small correction for a fit.

Delay in delivery of the Rea converter and the need for higher precision prompted the development of a semidynamic testing system for the bias program. It is indicated in Fig. 14. It was first used to test the linearity and repeatability of an integrator for measuring B from $\dot{B}$. The value of the integral was found to be repeatable within $\pm 0.05\%$ or within ± 0.2 millivolt, whichever was greater. These limits were set partly by the Fluke electronic potentiometer in the test circuit and partly by contact potentials in the switches on the integrator. This indicates that the full value of the integral should be at least 100 volts, so that a dynamic range of a factor of 50 has a repeatability of $\pm 0.01\%$, using somewhat improved switches. The linearity of the integrator has not been checked with high precision and such precision is not required.

This good performance of the integrator indicates that B probably will be determined directly by integrating $\dot{B}$, and it will not be necessary to employ the more complicated system described in ANL-5803. The generation of the required bias function, by taking the sum of 4 components, is still contemplated.

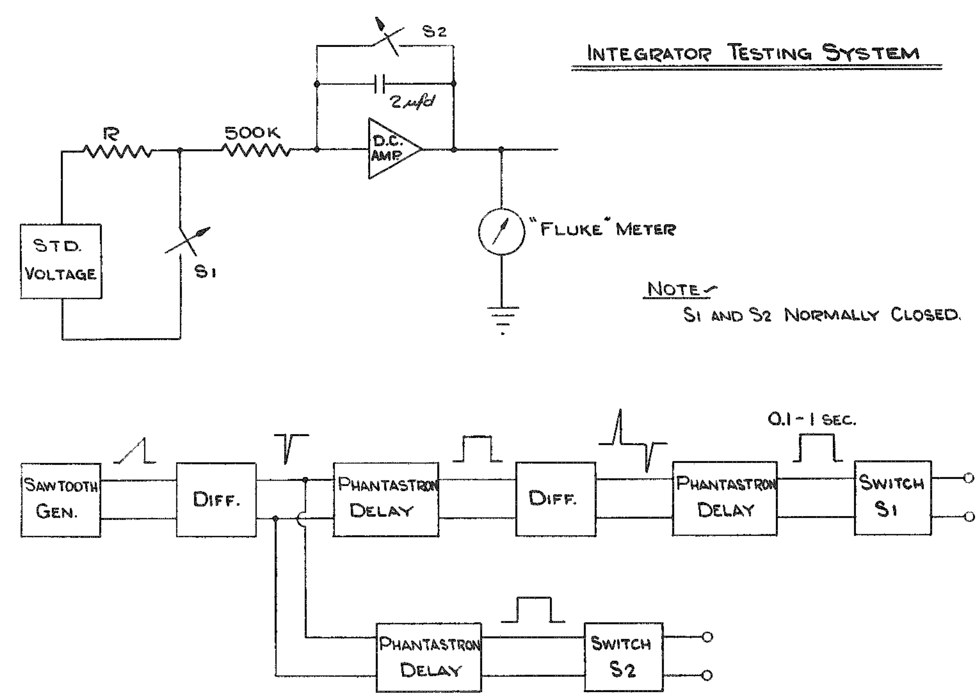


Fig. 14.

B. Noise Measurement in the R.F. Signal

Based upon a suggestion made by Kenneth Green of Brookhaven National Laboratory, a system for measuring the frequency modulation noise in the radio frequency signals has been partly developed. It is being used to examine the noise in the signal from the master oscillator or from any stage of amplification. It is shown in the block diagram of Fig. 15. The signal under study is swept in frequency at a relatively constant rate. This signal, after a 10-microsecond delay, is mixed with the undelayed signal. A relatively constant difference frequency should result if the sweeping is smooth. This difference frequency is suppressed by a high pass filter. The R.F. which leaks through the modulator is suppressed by the low pass filter. Amplitudes of frequency deviation as small as 500 to 5000 cycles per second are observable, depending upon the rate at which the frequency is swept. Repetition rates for the noise frequency deviation in the range of a few kilocycles are observable. Revisions are under way to extend this repetition rate up to the several hundred kilocycles per second range. A variable narrow band pass filter, to be placed ahead of the oscilloscope in order to decrease the lower limit on amplitude of frequency deviation, is under development.

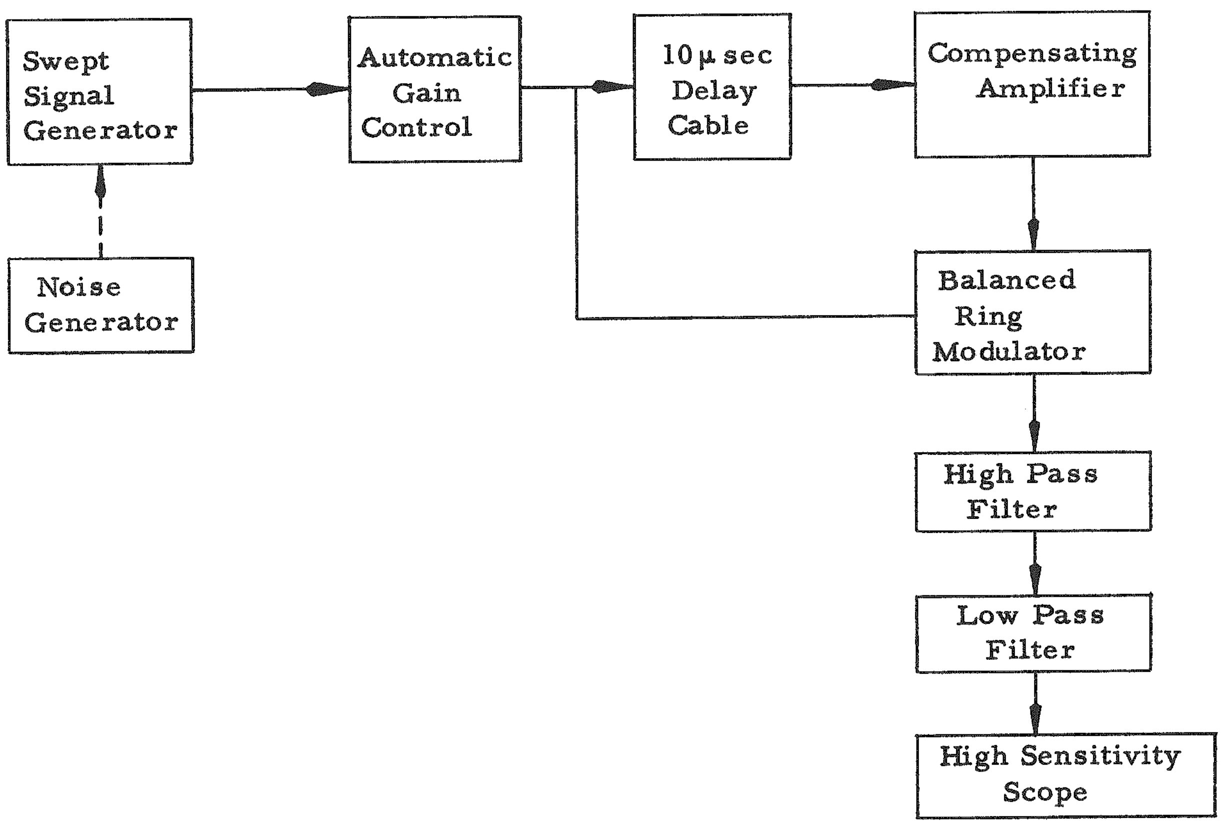


Fig. 15.
FM Noise Measuring System

The master oscillator, when examined with this system, reveals no noise within the sensitivity of the equipment. The expectation is to improve the noise-measuring system and the R.F. system if necessary to prove that the frequency modulation noise is less than one part in 10^5 in a fairly narrow frequency band. The Rea data converter has indicated a 60-cycle F.M. noise with an amplitude of about two parts in 10^3 at the lower end of the R.F. frequency program. This will have to be considerably reduced.

C. Proton Beam Self-Tracking

A study has been completed of certain features of the beam self-tracking loops for controlling the frequency and magnitude of the potential across the particle accelerating cavity, by information obtained from the beam induction electrodes. The results of this study are described in memos CHMT-1 and CHMT-2.

The interdependence of machine parameters may be indicated by the introduction of step frequency or step cavity voltage errors. If there is a sudden small reduction in the frequency, the particles make a transient slip in phase so as to gain less than the normal average energy per turn. With this, they spiral inward and proceed to oscillate about a smaller than normal radius. In the case of many particles the whole bunch will move inward and then return to the normal phase. If there is a sudden small reduction in the peak voltage across the accelerating cavity, the bunch will make a transient shift to a smaller than normal radius. With this the bunch advances in phase so that it can make the normal energy gain per turn. It then returns to the normal radius but with an advanced phase.

This indicates that the frequency control should be obtained from information about the radial displacement of the beam. Cavity voltage control may be obtained from information about the relative phase of the particle bunches and of the R.F. cavity voltage. In the two reports mentioned above it is shown how servo loops can be closed to obtain this control, particularly for the frequency.

The motion of a bunch of particles in the accelerating system without feedback may be described by the equation

$$x'' + \Omega^2 x = K(N),$$

where x is the radial displacement of the bunch of particles, x'' is its second derivative with respect to turns about the machine, Ω is the synchrotron oscillation frequency in radians per sec referred to the orbit frequency, and K(N) is a very slowly changing parameter. In the two papers there is described a servo loop which will change the description of the motion of the bunch of particles to that given by the equation

$$x'' + 2b\,\Omega\,x' + (1 + a)\,\Omega^2 x = K(N).$$

The b-term will damp out transient-induced oscillations and other coherent disturbances introduced into the motion of the bunch of particles. The asymptotic limit of the radial displacement due to a frequency error will be reduced by a factor of $1/(1 + a)$. The choice of a and b will depend upon the errors in the pre-programmed master oscillator. For the machine under design this error will be $1/(1 + a) \cdot 1/232$ inch per turn about the machine per second. The width of the beam in the chamber and the radial extent of an adequately good guide field will set an upper limit on the error which can be tolerated.

D. The R.F. Power Amplifier

The power amplifier for driving the model cavity has been completed except for the last stage, and the power supply for the latter has not yet been received from the manufacturer. The driver for this stage is capable of delivering 5 kilowatts of power into a tuned load over the frequency range of 2 to 7 megacycles per second. It has not yet been tested on a reactive untuned load like that which will be presented by the input to the last stage. The completed assembly is expected to be capable of delivering more than 50 kilowatts into the ferrite-filled model cavity. All stages up to the cavity are operated untuned.

A ferrite-cored transformer with a compensating network has been designed and built for coupling the driver to the last stage of the amplifier. It is designed to provide about 5 db of gain compensation at the high-frequency end of the band.

A partial study has been made of the consequences of operating the accelerating cavity at the 8th harmonic (4 to 14 Mc) of the orbit frequency instead of the 4th harmonic for which the power amplifier is now designed. It will have to be completely re-designed. It is estimated that the cost will be increased by about three times and the power requirement will be increased about two times.

E. Prototype R.F. Cavity

There has been an unfortunate delay of six months in the delivery of the first batch of the ferrite blocks with which to load and tune the prototype cavity; the manufacturer appears to have had great difficulty in producing mechanically stable slabs of the specified dimensions (28 x 10 x 4 cm), which are to be bonded into a picture frame structure. Twenty-four slabs are required to make a test in the cavity, but only twenty-two have been delivered. Hence, it has been necessary to test the slabs in an improvised setup, using a 5-kw driver.

The slabs have been found to be greatly inferior to the test rings on the basis of which the cavity was designed and the order placed;

the Q value is far too low for satisfactory use. This is possibly caused by inadequate curing of the interior of the blocks, as became evident when a slab was broken open. The manufacturer has requested permission to reduce the thickness (and to increase the number of blocks); it is hoped that this procedure will resolve the difficulty. If not, another firm will be approached.

F. Coaxial Shunt and Mutual Inductance

According to the considerations described in ANL-5803, page 48, a coaxial shunt has been built and tested. It was designed for use on the one-quarter scale pulsed model magnet. A 6-inch long section of the outside conductor of a shorted coaxial line is made up of a 5-inch diameter manganin shunt strip cylinder. The readout leads are attached about 4.5 inches apart on the outside of this cylinder, which has a 0.025-inch wall thickness. These leads are arranged so as to have a very small exposed loop area to minimize magnetic flux linkage.

The readout resistance of the shunt is $0.199576 \times 10^{-3} \pm 0.000024 \times 10^{-3}$ ohm. It is intended for either constant currents up to 2500 amperes or a pulsed current which rises from 0 to 2500 amperes in one-sixteenth of a second. It is water cooled for a temperature rise not to exceed 5°C, which means a temperature-dependent resistance change of less than 0.01%. The dynamic range required for the one-quarter scale model is approximately 50 to 2500 amperes. The propagational error for a constant rate of rise of current is worst at the lowest current. At 50 amperes it is less than 0.035%, determined by calculations. The measured error due to magnetic flux linkage in the loop formed by the readout leads is about 0.01%. This requires reasonable care in the placement of the bus bars near the shunt.

The design of a mutual inductance suitable for reading out the rate of change of the current in the magnetizing pulse of the quarter-scale model magnet has been completed. It consists of a coaxial line assembly with an enlarged section near the shorted end. In this enlarged region is placed a 600-turn torroidal winding linking the magnetic flux which passes between the inner and outer cylindrical conductors of the coaxial line. The winding is placed on a rigid form which is about 1 ft in diameter and 1 ft long and having an axial hole about $1\frac{1}{4}$ in. in diameter. This arrangement produces a mutual inductance of about 90 microhenries. Because of its high order of symmetry it should be very insensitive to stray magnetic fields. Due to the favorable distribution of the leakage inductance and capacity in the secondary winding, it should have a very flat frequency response to some hundreds of kilocycles.

XV. LINEAR ACCELERATOR

P. Livdahl, R. Perry

A. General

It has been decided to adopt the design of the BNL 50-Mev linear accelerator, and we have received permission to make use of the BNL design drawings. Such details as have been received are being carefully studied and we expect to incorporate into our final design any improvements which may be suggested by future experience at Brookhaven.

Because of the different requirements of beam pulse length (250 μsec compared with 60 μsec at BNL), our machine will require minor changes from the BNL design, but it is not expected that these will affect the RF cavity nor the drift tube contours. Modification of the quadrupole focussing magnets for D.C. operation with water-cooled coils is under way (see below), together with changes of the interior of the drift tubes and stems to accommodate the magnets and power leads.

B. R.F. Power

At the design gradient of 1.89×10^6 volts/meter, the peak R.F. power required to drive the linac cavity will be about 2.5 megawatts. During the initial testing and conditioning period it is expected that appreciably more peak power will be required, so it is planned to provide an R.F. driving system which will give about 5 megawatts peak in order to have adequate reserve power.

Studies of all the suitable R.F. power systems are continuing. These include the following types: (1) a single 200-megacycle/sec Klystron driver, (2) a single high-power triode driver, and (3) two or more triodes paralleled. The Eitel-McCullough Co. has for some time been working on the development of a 200-megacycle/sec Klystron to give peak pulsed power of 5 megawatts. Should this development prove to be successful, the Klystron would be very attractive for our use from the point of view of high power gain and relative simplicity of the over-all system. However, it is not yet certain that this will be realized by the time we must freeze on a driver system.

Two RCA triodes, No. 2342 and No. 2346, are available, with possibly adequate power capacity to drive the linac cavity. Circuitry with resistive-type loads exists for both tubes, but neither has been used to drive a high Q load, and their performance under such conditions is yet to be determined.

On the basis of initial cost, it appears that paralleled multiple triodes have definite advantages. However, this advantage may be more apparent than real when the problems associated with parallel operation are taken into account.

At this stage it is not clear that there is a "best" system for driving the linac, and it is evident that the final system must be a compromise between the ideal and the available modified by economic factors.

C. Beam Dynamics

Work is in progress to extend the calculations made by Smith* on the beam dynamics of the BNL linac. This will include the effect of non-linear terms in the R.F. fields in the gaps and will attempt to determine a schedule for the quadrupole field gradients which will result in optimum beam quality and beam intensity.

XVI. LINAC QUADRUPOLE FOCUSSING MAGNETS

D. Cohen

Initial design studies have been completed for the 124 quadrupole magnets, each of which will be situated in and enclosed by a linac drift tube. Due to the long injection time, the exciting coils will be continuously driven and must be water-cooled, which necessitates a change in magnet structure from the Brookhaven design. The objects of the experimental work on various prototypes were:

1. to measure and analyze the non-quadrupole error fields;
2. to investigate saturation properties;
3. to measure the effects of eddy currents, due to exciting current ripple, on the magnetic field;
4. to measure end effects; and
5. to develop a rugged design for the exciting coils.

This work is described in some detail in the Memo DC-1, and the following discussion will be a summary of the memo.

A long quadrupole search coil, shown in Fig. 16, was designed by Martyn Foss and precision wound by Arthur Neubauer. The outer coil (windings 1 and 2) is able to link flux with all the lower field harmonics, while the inner coil (windings 2, 4, 5 and 6) responds only to the pure quadrupole field. When these two coils are externally connected in series-bucking and rotated as a rigid body about the cylinder axis, the large pure quadrupole component is nearly eliminated from the output signal, and the error field components may be detected with high sensitivity.

The coil, placed coaxially inside the quadrupole gap, was rotated in 5° steps by an accurate manipulating device, and the flux linkage every 5° was measured with the servo fluxmeter. The data was punched onto IBM

*Lloyd Smith, BNL Internal Report LS-3

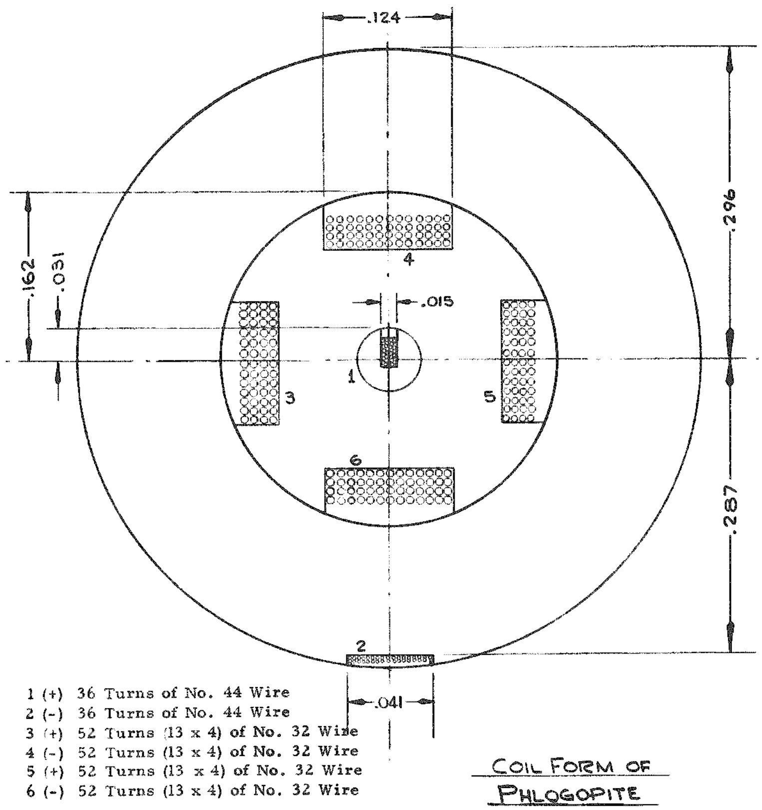


Fig. 16.

Cross-section of the $3\frac{1}{2}$ inch long search coil for analyzing some field properties in quadrupole magnets. The complicated crossovers, which are not shown, pull the wires toward the slot walls instead of between lower neighboring wires.

cards with the summary punch and Fourier analyzed with the IBM-650 digital computer. In this way it was possible to evaluate the error flux densities at 1/4 inch from the magnet center, which is the outer proton beam radius for the entrance drift tubes. The criterion adopted was to reject magnets which had more than $1\frac{1}{2}\%$ error at 1/4 inch. Saturation properties were determined through ordinary B vs. I curves, and eddy current effects were evaluated by exciting the magnet with A.C. and determining with a search coil in the gap the fraction of flux which is countered by the steel currents. End effects were measured both with a small "spool" coil and by rotating the coil of Fig. 16 at the magnet ends.

Three different prototypes for the first eight quadrupoles at the linac entrance end were tested; these are shown in outline in Fig. 17.

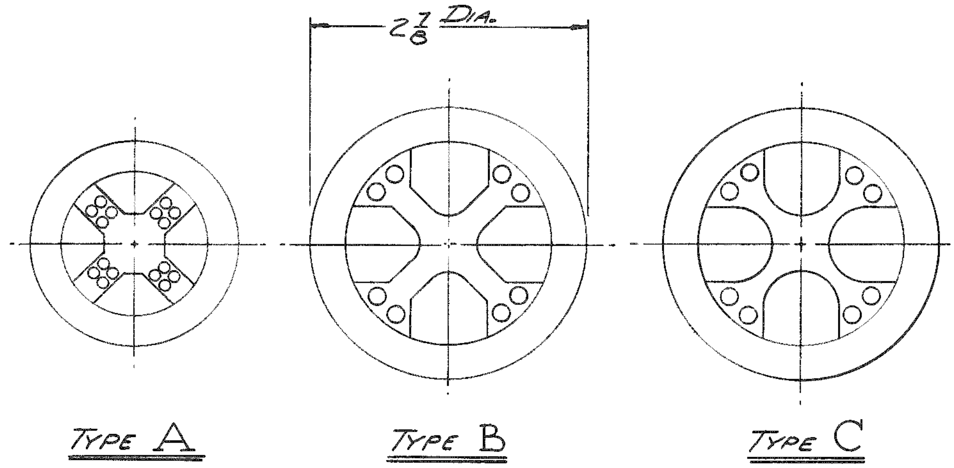


Fig. 17.

The three types of quadrupoles vary in length between $1\frac{1}{16}$ and $1\frac{3}{16}$ inches. The copper tubing coils, with the O.D. shown in cross section.are of 1/32 inch wall thickness.

The first prototype to be built and tested was type A; although the 4% error field was decreased by successive cutting on the pole tips, it was felt that type A should be abandoned because of winding difficulties and lack of adequate coil space. It was also decided to avoid 1/16-inch I.D. (1/8-inch O.D.) water tubing because of the long-range hazard of blockage. Type B was then designed and tested; the pole tip shape was made to conform with the machining techniques of type A and was found to introduce some 4% of error field at 1/4 inch. By examining error fields as a function of the placement of steel shims on the pole tips, it was found that a circular shape was warranted. This shape of pole (which had been investigated at Princeton some years ago) was machined and is shown as type C. The error fields at 1/4 inch were less than 1%; hence this pole shape was acceptable and has been adopted. Successive groups of magnets toward the exit end of the linac, with dimensions of smaller O.D. and larger gaps, will have pole shapes scaled from type C, with a modified yoke.

Eddy current tests on type A have shown that the steel along with the copper boundary tube (not shown) have no significant effect in shielding the beam from current ripple at frequencies below 1000 cps. End-effect measurements confirm the theory as discussed in DC-1; more studies must be made on the Z-component (beam direction) of the field to minimize disturbing effects.

It has been decided to overdesign the power and saturation situation to allow for operation in the + - + - mode of magnet rotation inside successive drift tubes, after beam properties have been experimentally studied with the operating linac in the + + - - mode. The former mode, while accepting a larger beam phase-space area for acceleration, demands some 7/4 of the fields necessary for the + + - - mode. Saturation and power tests to date show that, while the thicknesses of yoke and pole bases in type C do not saturate and may probably be cut down, more copper is needed to avoid heating problems with the 2000 amp necessary for + - + - operation. If necessary, the yoke diameter will be increased to allow more room for copper.

XVII. ION SOURCES AND THE ACCELERATION OF PROTON BEAMS

H. R. Fechter

The injection system for the Argonne synchrotron will consist of an ion source, a 750-kv preaccelerator, and a 50-Mev linear accelerator.

We have been studying the problem of accelerating a proton beam of 10-50 mamp to a voltage of 750 kv for injection into the linear accelerator. The production of a large current of ions presents two problems:

1. the development of the ion source, and

2. the development of means to hold the beam together against large space charge repulsion forces during its extraction and acceleration to 750 kv.

A. Ion Sources

An intensive study of existing ion sources has been made. Much valuable information has been made available to us by the University of California Radiation Laboratory (B. Cork, L. Smith, J. Hiskes, E. Zajec, W. Lamb, J. Fasola), the Brookhaven National Laboratory (C. M. Turner, J. Bittner, A. Vansteenbergen), and the Massachusetts Institute of Technology (Sanborn Brown and Russel Meyerand). We have benefited much from the writings of the groups at Harwell (L. C. W. Hobbis, E. R. Harrison), and CERN (F. Scheider). To all of these, our appreciative thanks.

A number of ion sources appear to be capable of developing the desired current. Our final choice of ion source will be determined by some experimental work with several types. At present, we have under construction a "Hot Cathode - P.I.G." We have made some calculations of the beam quality to be achieved at the input to the linear accelerator. Essentially we measure the skew angle of the beam at a point of minimum diameter using Poincaré's Invariant. The beam quality and the dependability of the source are of major importance.

B. Acceleration of the Beam

Holding the beam to reasonable proportions during its early acceleration is difficult. (A 50-mamp beam with energy of 1 kev has a potential at its edge due to space charge of 1.25 kv). One approach to the problem of controlling this large current has been to allow the beam to expand until it is fairly large at the entrance to the accelerating column; the space charge forces are now weaker. The ions are then given an inward radial impulse by a lens at the tube entrance to compensate for the spreading of the beam during transit through the tube. The result aimed for is to obtain a relatively small parallel beam at the tube exit.

We will make a series of calculations for a number of initial conditions and parameters. The first of these has been completed.

Initial Beam Radius	3.7 cm (as beam enters the column)
Entrance Half Angle	4° (converging beam)
Initial Energy	20 kv
Beam Current	20 mamp
Final Energy	750 kv
Column Length	2 meters
Final Radius	1 cm

A second approach is to "take hold of the beam" at the source with a series of very strong lenses and accelerating electrodes and to bring it to 750 kv before it has had a chance to spread more than a few cms or less. (At the exit of this short structure, lenses will bring the beam into a buncher and then into the linear accelerator.) We are working on a re-entrant structure to achieve this rapid acceleration and will make tests initially to 300-400 kv. (There is the additional problem now of controlling the high voltage in the structure and in the air.) It is hoped that by accelerating the beam to 300-400 kv and by understanding its behavior at this voltage, we will be able to make reliable predictions of how a 750-kv accelerating system will perform.

A preliminary calculation has been carried out, using an iteration method. The results below are for an initially parallel beam which enters the system at 50 kv and is accelerated to 750 kv in 1/2 meter. Only an axial field component has been used.

Initial Beam Radius	0.1 cm
Entrance Angle	0° (parallel beam)
Initial Energy	50 kv
Beam Current	50 mamp
Final Energy	750 kv
Column Length	1/2 meter
Beam Radius (Final)	1.6 cm (diverging beam)

C. Electrolytic Tank

An electrolytic tank for mapping electric fields has been completed. By tilting the tank, it is possible to study three-dimensional systems which have cylindrical symmetry. The tank depth has been chosen to allow field plotting in two-dimensional geometry also. As the sensing probe in the electrolyte crosses an equipotential, a recording pointer, fastened to the probe by an arm, burns an indicating dot on electrosensitive paper; thus field plots can be obtained quickly.

This tank will be used to determine the radial and axial fields for a number of electrode geometries. A series of calculations will be carried out in an attempt to understand the dynamics of the beam, its possible space charge neutralization, and its spreading or loss because of interaction with gas molecules.

D. General Purpose High Voltage-High Current Pulser

The design has been completed and parts ordered. These pulses will be used for ion source development and test, and for R.F. pulsing.

Parameters are: $V = 10{,}000$ volts, $I = 100$ amperes,
$t = 500\,\mu$sec,
Pulse Repetition Frequency = 10 cycles per sec.

XVIII. MAGNETIC INFLECTOR

H. R. Fechter

After leaving the debuncher, the 50-Mev protons will experience a large angle deflection by an achromatic magnet system, and then will be launched into the synchrotron at a straight section by an inflector of about two degrees bending angle. This inflector, which will be located a little above the median plane, must have minimum thickness in its bottom member and in its member which lies closest to the synchrotron center, in order to intercept as few as possible of ions already in orbit. To this end, a model magnetic inflector of "window frame" structure has been built of full-scale cross section, but of reduced length.

The iron yoke is thick on the top and on one side; it is thin on the bottom and missing on the other side. Current sheets exist on both vertical sides. Preliminary measurements have been made with a null-reading flip-coil field-measuring device with encouraging results. (This device has three degrees of freedom; it is small, portable, and will reproducibly record changes in field of 0.1 gauss.) Careful study will be made of the field inside, at the ends, and along the outer area close to which the beam must pass after inflection.

XIX. PLASTICS

D. Hafemeister and F. Markley

A. Vacuum Properties of Epoxy Plastics

Apparatus for measuring the vapor pressures and degassing times of plastics has been constructed and tested. A schematic diagram of the apparatus is given in Fig. 18. Three evacuated chambers are provided. One is the test chamber, the second is a storage chamber for the sample during calibration runs, and the third is a vacuum entrance port.

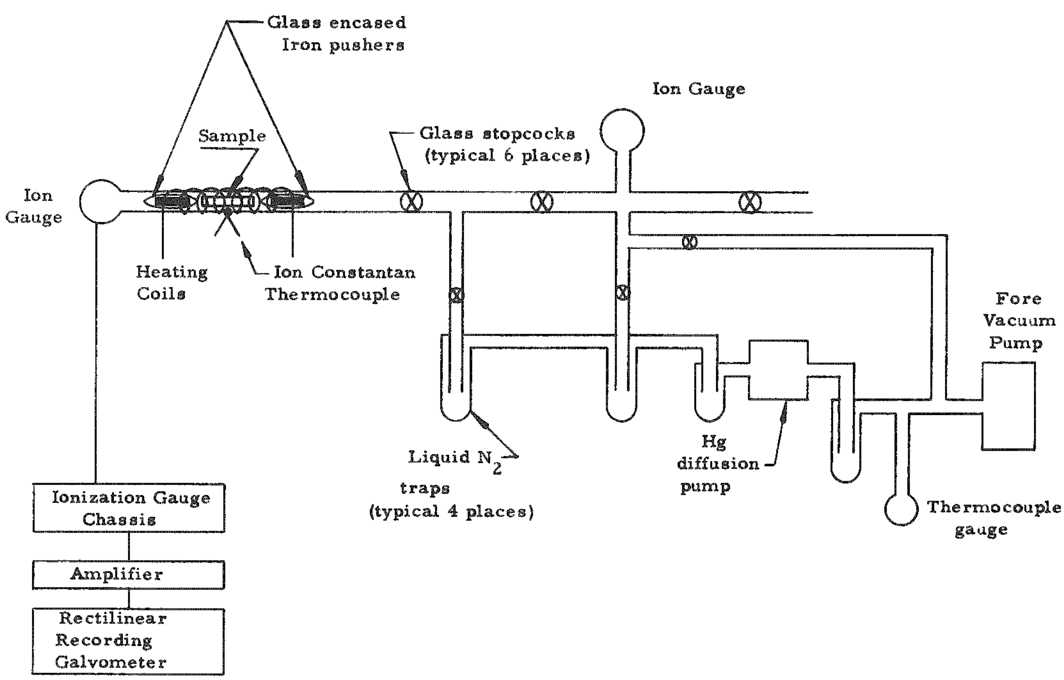


Fig. 18.

The sample (1/2 inch diameter by 4 inches long) is manipulated inside the system by means of two glass-encased steel pushers and a strong Alnico magnet. Measurements are taken by isolating the sample from the vacuum pump and recording the rate of pressure rise (dp/dt) in the chamber. Since the pressures involved are all less than 10^{-4} mm Hg, the perfect gas law applies, and we may multiply dp/dt by the chamber volume to get the rate at which gas is being evolved from the sample.

On all measurements to date, the value of dp/dt for the empty chamber has been from 1 to 3 orders of magnitude less than the value of dp/dt found with the sample in the chamber. Thus, the principal source of error at present comes from the ionization gauge. This gauge, when operated at the usual 10-mamp emission current, has a rather large pumping speed for the gases evolved from the epoxy plastic (about 0.002 μ-liters/sec). Therefore, we are now in the process of measuring the pumping speed of the gauge for epoxy plastic gases as a function of emission current. The effects of temperature, pressure, and past history on this pumping speed are also being investigated. An additional error due to the ionization gauge arises from our lack of a calibration curve of ion gauge plate current vs. absolute pressure for the gases evolved from epoxies. This will be obtained from a second system which will be built with both ionization and Knudsen type gauges as the measuring units. Such a system will also enable us to double check our measurements of ion gauge pumping speeds, and double our present rate of data production.

The data obtained will be processed to give us curves of gas evolution rate vs. temperature and time under vacuum, degassing time vs. temperature, and vapor pressures of degassed samples vs. temperature. In addition we will check whether the gas evolution rate is a function of exposed plastic surface only, plastic volume only, or both. We will also take plastic samples for which gas evolution curves have been measured and which have been thoroughly degassed, expose them to atmospheric conditions and then remeasure them to check on the quantity of gas adsorbed. Finally, we will measure samples made from resin degassed under heat and vacuum to see if this decreases the gas evolution rate and degassing time of the plastic.

Preliminary data obtained with this apparatus, on a sample made of Epon 828 resin with 3 phr (parts per hundred parts resin) of BF_3-400 curing agent, show a vapor pressure of less than 10^{-6} mm Hg at 30°C and degassing times of 10 hours at 170°C, or 50 hours at 70°C, or 1000 hours at 30°C.

This apparatus may also be used to measure the vacuum properties of other materials, particularly materials for gaskets or "O" rings.

B. The Quarter-Scale Model Magnet

Procedures for vacuum-pressure impregnation of the quarter-scale, laminated, model magnet sections with epoxy resin have been worked out and tested; such impregnations are now being made routinely with satisfactory results. The magnet sections consist of tapered steel plates about 1/8 inch thick, separated by double thicknesses of thin paper insulation. They are placed in a steel tank, heated to 65°C and evacuated overnight. Preheated epoxy resin (Epon 828 with 3 phr of BF_3-400) is then introduced and evacuation continued for 30 minutes or more to degas the resin. Evacuation is then stopped and a pressure of 40 psig is applied to the resin for 30 to 45 minutes. The tank is then drained, the matching surfaces of top and bottom sections are wiped clean, and the sections are cured overnight at 150°C.

C. Ferrite Bonding

At the request of the R.F. group, experiments were undertaken to find an epoxy adhesive system and bonding procedure which could produce large rectangular frames of bonded ferrite bricks. These frames must be produced with accurately held dimensions, glue line thicknesses on the order of 0.001 inch, and bond strengths of 3000 psi. These experiments have now been successfully completed. The resin system selected is Epon 828 resin with 30 phr of 4, 4', diaminodiphenylsulfone, and the curing cycle is 40 hours at 190°C and 30 psi. Prior to receiving ferrite bricks, test frames of aluminum, steel and refractory brick were assembled on a granite surface plate with a special jig for aligning the bricks and applying the necessary pressure. The entire assembly is contained in an oven designed to produce carefully controlled and uniform temperature. The temperature is raised and lowered quite slowly to prevent thermal cracking.

Special tensile testing equipment was also built to check the tensile ultimate of the ferrite bricks we have received. Those tested thus far have been deplorably weak. Therefore, actual assembly of the ferrite frames awaits a decision on the mechanical and magnetic acceptability of the bricks.

D. Radiation Damage to Epoxies

Studies of the ability of epoxy resin systems to withstand radiation damage (mentioned in the last summary report, ANL-5803) have slowly continued. Samples of Epon 828 resin with Shell hardeners D, Z, and CL have been exposed to gamma radiation for total dosages up to 1.3×10^8 rads. The mechanical properties in compression of these samples have been tested, and, within experimental error, no change was found. The comparatively low dose rates available in the gamma-irradiation facility have necessitated use of the CP-5 reactor in order to obtain the large total dosage in which we are interested. Preliminary irradiations in the reactor have shown that the cooling systems available are not sufficient to keep the sample temperature below a point where confusing thermal damage may result. Therefore, further irradiations must be postponed until a satisfactory cooling system can be built.

Equipment is being designed and tested for the irradiation of some samples in the proton beam of the cyclotron. These samples will be used to make a comparison of proton and reactor dosages for equal sample damage. Such a comparison is deemed advisable since the damage to plastics in the synchrotron will be from protons, and since pile dosages in rads are rather nebulous.

E. General

In conjunction with W. A. Siljander we are helping with the research and development work on the problem of potting the ring magnet coil. We are continuing work on laminating the ring magnet and on procedures for manufacturing a satisfactory plastic vacuum chamber. We have also completed many small service jobs in coating, potting, and cementing for other groups in the division. It is expected that such service jobs will continue to grow in number with our rapidly expanding knowledge of the epoxy resins and their capabilities.

XX. EVAPOR-ION PUMP DEVELOPMENT

J. Moenich

As reported in the last summary report, ANL-5803, increase of the titanium feed rate in the Evapor-ion pump resulted in higher pumping speeds for the common gases, such as nitrogen and hydrogen, but no significant increase was noted for air. At certain pressures and with increased titanium feed rate, a glow discharge, considered to be ionization, could be maintained during part of each feed stroke. At the pressures where this occurred, a significant increase in pumping speed for nitrogen, hydrogen, and air was noted. Since we are primarily concerned with the ability of the Evapor-ion pump to pump air and because of the above result, it was decided to develop the ion pumping ability of the pump.

Since R. Herb has had some success with increased ion-pumping by the use of volume grids, this approach was attempted first. Because the commercial version of his pump was not designed to accommodate a true volume grid (vertical tungsten wires spaced 1/4 inch apart throughout the entire volume enclosed by the grid), two grids, one 3 inches in diameter and another $5\frac{1}{2}$ inches in diameter, were placed concentrically with the existing $7\frac{1}{2}$-inch diameter grid. Although some increase in pumping speeds was obtained, it was not significant for the increase in power required.

The most important result obtained in this series of tests was the doubling of the pumping speed by removing the 3-inch and $5\frac{1}{2}$-inch concentric grids and merely increasing the power to the remaining grid (the original one) by approximately 25%. Where formerly the grid was at 1200 volts and drew 140 milliamps, we now draw 280 milliamps with the grid at 800 volts. This increase can be seen by the difference between Curve I and Curve II of Fig. 19.

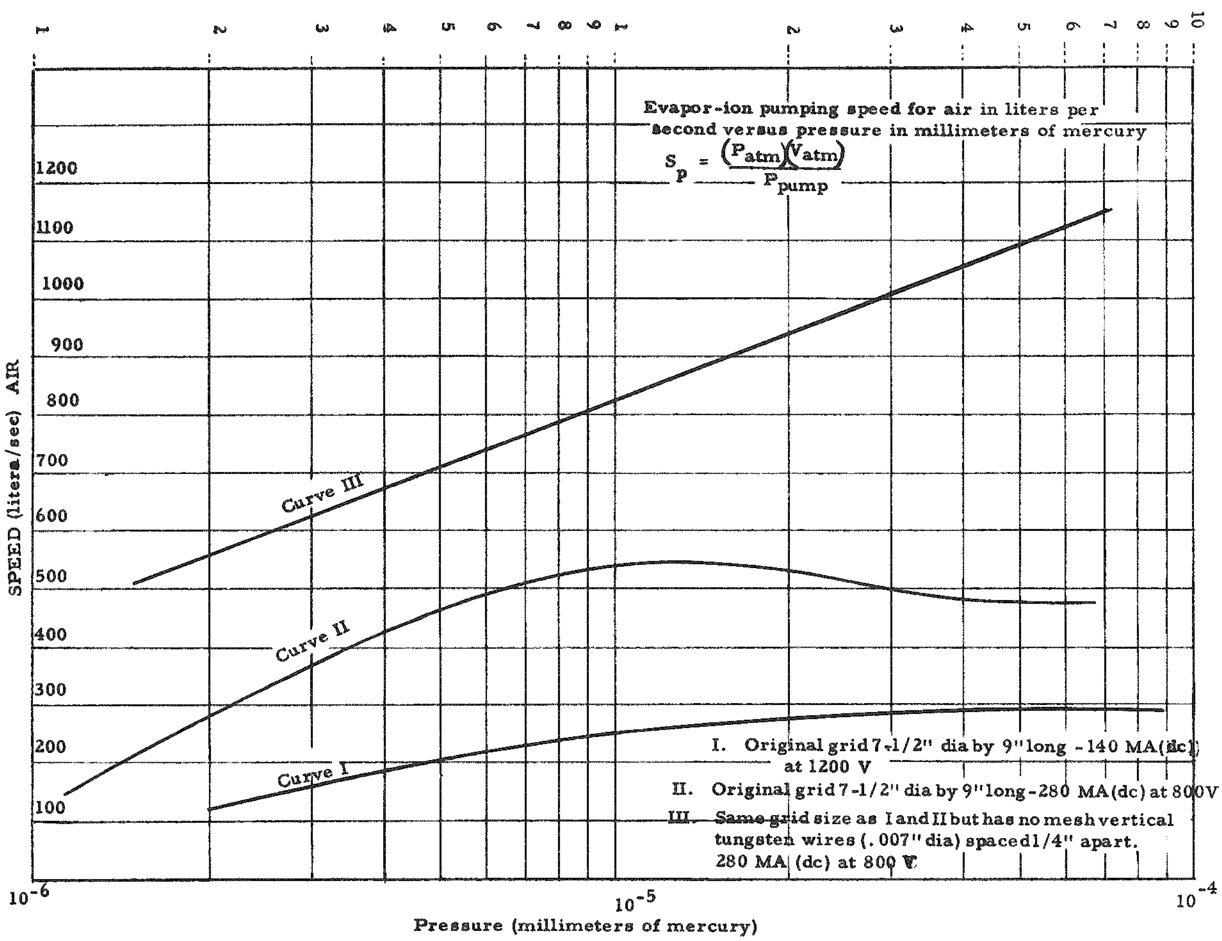


Fig. 19.

While experimenting with the grids, it was found that various grid structures affected the shape of the speed curves. Also, since the literature describing early experiments with this pump indicated some success with vertical tungsten wires on the grid structure, rather than a mesh, it was decided to run some experiments to determine the effect on the pumping speed from each.

The effect of the mesh having already been noted, it was removed; in its place 0.007-inch tungsten wires were placed vertically on a $7\frac{1}{2}$-inch diameter, spaced 1/2 inch apart. The resultant pumping speed curve was very gratifying. A second attempt using 1-inch spacing resulted in poorer pumping speed. The spacing was then reduced to 1/4 inch and this proved to be the best. Curve III, Fig. 19, shows the tremendous improvement in pumping speed that had been accomplished by this simple change.

Since it is felt that possibly only the lower portion of the grid closest to the filament is being utilized for ion pumping, an experiment is being set up to study this. In order to evaluate the distribution of electrons to the surface of the grid, three separate grids are being made up. Their diameters and combined lengths will be the same as for one full grid. The three grids will be electrically separated from each other, so that each will require its own power supply. The voltage on each grid initially will be the same in order that all these will appear as one unit to the electrons. With the regular filament at one end as normally used, any differences in grid current on the three separate grids can now be measured. If the distribution of current is not uniform, a voltage gradient on the grids will be established to create a uniform current condition. Subsequent speed tests will verify any improvement.

Should a voltage gradient be necessary to achieve uniformity and subsequently improve the pumping speed, the present feeder will be replaced by a different feeder to free the central position of the pump. This will then allow the insertion of a vertical filament down the axis of the pump. With such an arrangement, the entire grid surface will be equidistant from the filament and uniform distribution will be achieved, thus again requiring only one grid and one grid power supply.

XXI. TEST VACUUM CHAMBER

R. Lykken, J. Moenich

The accompanying photograph, Fig. 20, shows a 25-foot long, full-scale vacuum chamber which, although straight instead of curved, simulates the actual vacuum chamber half an octant in length.

This chamber is 95% completed and will provide information on the conductance of the final chamber, pumping speed curves of different pump assemblies, and outgassing rates of various surfaces. Also, transition sections and vacuum valves at the octant ends can be tested.

The chamber also simulates the magnet block assembly as it is formed of plates approximately one block in length, depending for its vacuum integrity on seals between the plates and along the side walls in a manner similar to that contemplated in the magnet assembly. It is planned to test various methods of sealing between the blocks, such as epoxy glue joints, stainless steel wallpaper, gaskets, etc.

This chamber will also be used, when sealed by one of the above methods, as a rough vacuum chamber for the testing of various thin-walled, inner, high-vacuum chambers. One such model (suggested by the MIT-Harvard group), now under construction, consists of 0.032-inch stainless steel sheet formed into a rectangular shape and slit at intervals, radially, to reduce eddy currents. This will be covered on the outside with a 3/32-inch layer of fiberglas and epoxy for vacuum tightness and strength.

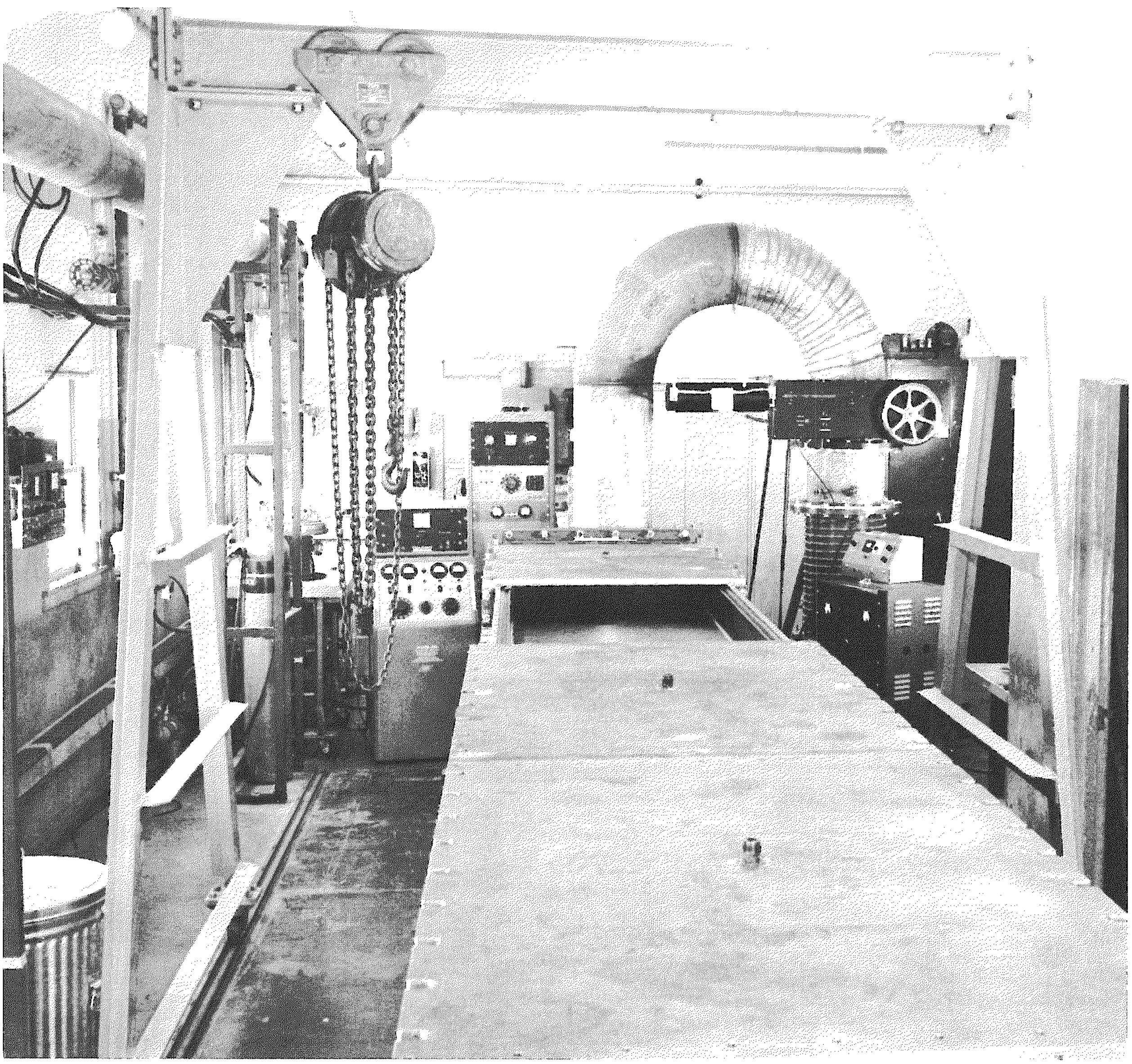


Fig. 20.
Test Vacuum Chamber

XXII. EXPERIMENTAL FACILITIES AT THE ACCELERATOR

A. V. Crewe, R. H. Hildebrand, U. E. Kruse, S. D. Warshaw,
S. C. Wright, and C. M. York

We present our recommendations for the layout of the experimental areas, the power requirements for these areas, and the characteristics of the various beams which we feel are desirable.

I. Layout of the Experimental Areas

A. Proton Areas

1. General description. The over-all plan of the machine with its experimental areas is shown in Fig. 21. The two external proton beams emerge from the machine at points 180° apart, as described in CHKW-2. The areas A1 and A2 are called the direct proton beam areas, and the areas B1 and B2 are called the deflected proton beam areas. The external beam can be switched from an A to an adjacent B area by means of the "switching" (s) and "bending" (b) magnets. These magnets are shown in more detail in Fig. 22.

If the beam is to enter an A area, the switching magnet bends the beam a few degrees to the right, after which it is handled by strong focus magnets. Alternatively, if the beam is to enter a B area, the switching magnet bends the beam to the left enough for it to enter the region governed by the bending magnet, where it receives the majority of its deflection into the B area strong focus system. This arrangement has "fail safe" features since positive action must be taken to provide a chosen area with the proton beam. For example, failure of either or both the switching and bending magnets will not send the beam into the currently unused area. Further safety devices will, of course, be necessary. Adjacent proton areas cannot be used simultaneously. However, two areas can be employed for experiments at all times while the remaining two are available for setting up and dismantling equipment.

For maximum flexibility, we suggest that area A1 have a concrete pad along its entire length, while area A2 have two concrete pads separated by about 100 ft. The gap in A2 can be excavated at will to accommodate experiments that require more than $4\frac{1}{2}$-ft beam height (e.g., up-down polarization experiments). We believe that these A areas should have first priority and be available when the machine is first operable. The B areas will be of similar dimensions and should be available soon after the machine first operates. To avoid a shutdown of the accelerator, the switching, bending, and first strong focus magnets should also be available when the machine first operates.

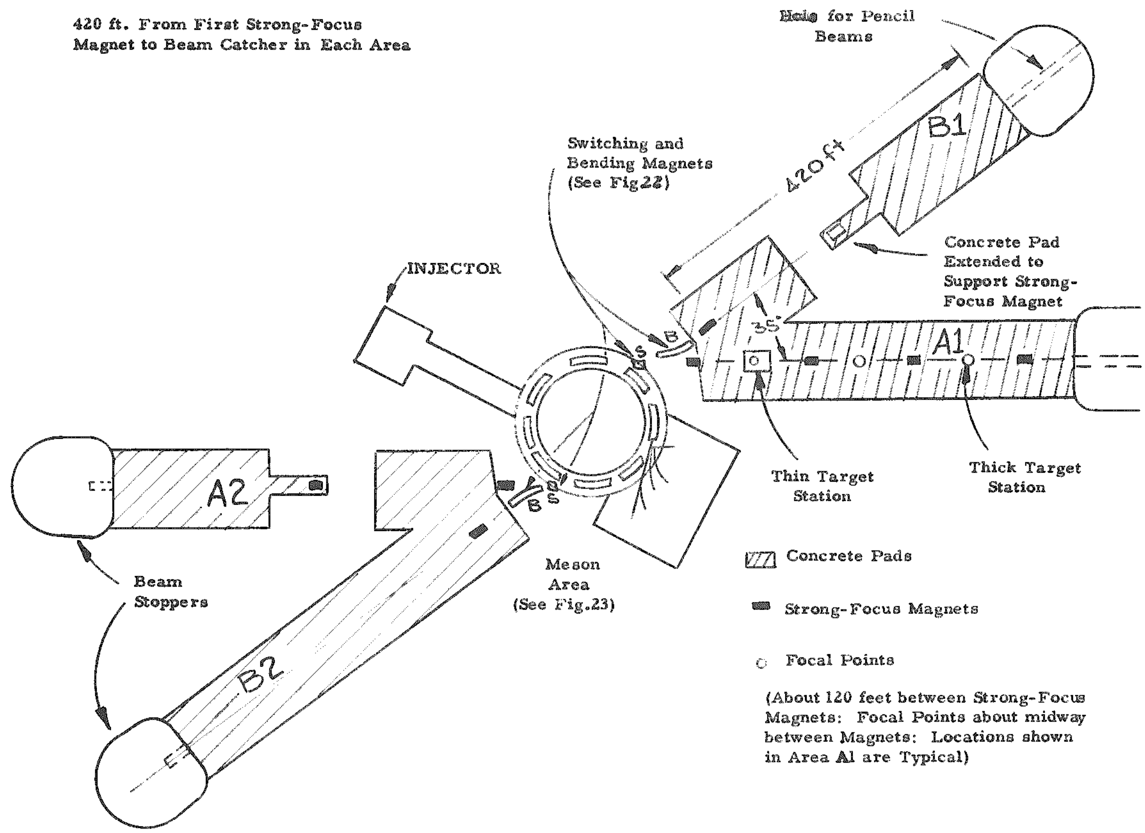


Fig. 21.
General Layout

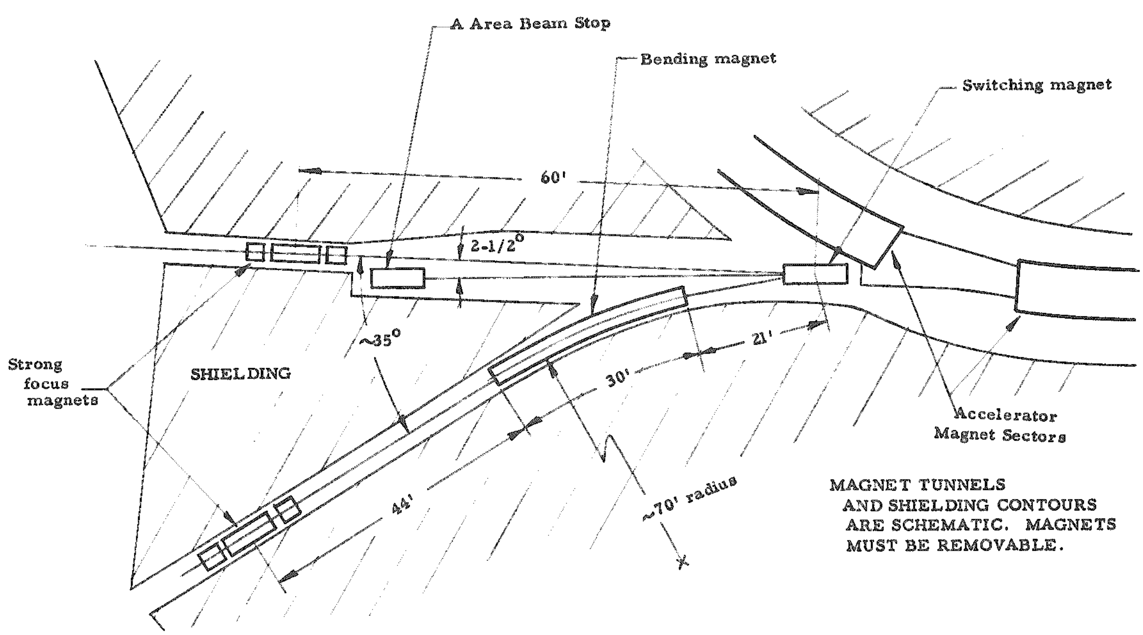


Fig. 22.
Switching and Bending Magnets

The proposed duplication of experimental areas A and B for each proton beam is strongly recommended. Experience with other high-energy accelerators has shown that a large fraction of the accelerator's potential operating time is spent in setting up and checking experimental apparatus. With the proposed arrangement the beam could be used continuously in two areas while equipment is being prepared in the other two areas.

Although we expect this to be the normal pattern of operation, there will doubtless be times when it is profitable to have equipment operating in adjacent A and B areas receiving alternate pulses. The switching magnet would be operated so as to put any predetermined number of beam pulses first in one area and then the other.

As the proton beam traverses an experimental area, it passes through several strong focus magnets and is finally absorbed in a large dirt and concrete beam stopper. Targets can be inserted at the focal points of the magnet system, indicated by circles in Fig. 21. Thick targets will normally be placed close to the beam stopper, while thin targets can be placed close to the accelerator. We consider a thin target to be one in which one percent or less of the proton beam will undergo a nuclear interaction. If it is necessary to provide a biological shield for such a target, it would be about 30 x 35 x 15 ft and would weigh about 1000 tons.

After passing through the thin-target station the proton beam is refocussed at other points, which can be either thin or thick-target areas. It is possible that the intervening strong focus magnets will be a source of background radiation and will have to be shielded. Our calculations on this point are not yet complete.

A thick-target station should be the last experimental station before the beam enters the beam stop and will, of course, be a strong source of radiation. It may not be feasible to provide a biological shield for such an area, but sufficient shielding must be provided to prevent interference with experiments in neighboring areas. For this purpose a shield similar to the one around the thin-target area will suffice.

The proton beam is finally stopped in a beam catcher consisting of a concrete plug with a blind hole, buried in a mound of earth about the size depicted in Fig. 21. Channels may be cut through the earth mound to allow for experiments requiring pencil beams, for example. Other concrete plugs with blind holes can be inserted to catch the beam if it has been deflected. Such deflection of the main beam may occur if a target is placed in a magnetic field or if secondary particles are deflected after going off in the forward direction.

Beyond the beam catchers in one A area and the adjacent B area, regions 200 feet long should be kept free of buildings to allow for experiments using special collimation or for high-intensity, neutral-beam experiments.

The beam must travel through a vacuum pipe from the point at which it leaves the machine until it reaches the beam stopper. Otherwise, the protons will produce an intense line source of secondaries by nuclear interactions with air molecules along the beam path.

B. Meson Area

This area is located at that long straight section which is not used for the external proton beams or the injector. It will provide space for using beams of secondary particles (mesons, antiprotons, etc.) emanating from targets placed in the circulating beam. These targets will be placed in the straight section or in the first five feet of the upstream magnet octant. The beams of secondary particles are focussed and deflected by a magnet complex which is shown in Fig. 23. We recommend three high-energy beams and one low-energy beam. These will be focussed in regions sufficiently separated so that neighboring experimental arrangements do not interfere with one another or with apparatus in the neutral beam indicated in the figure.

The relation of maximum energy and angle of production of secondary particles is depicted in Fig. 24. Most of the particle production will correspond to regions well below the curve of Fig. 24. The magnet complex is designed to bring outside the accelerator shield any type of negative secondary particle that can be produced at angles less than 30° and all positive secondaries produced at angles between 6.5° and 30°. The variation in emission angle of secondaries which enter the magnetic collecting system is accomplished by changing the azimuthal and radial position of the internal target. The secondary beams first enter strong focus magnets which form an image of the internal target in the experimental area. The bending magnets following each strong focus magnet remove neutral components from the beam, perform some momentum analysis, and serve to separate laterally the various beam foci formed by the strong focus magnets. Large angle beams of all energies are obtained from targets in the straight section. To do this a strong focus magnet in a rotating portion of the shield can be aimed at targets anywhere in the region shown in Fig. 23. This magnet covers an angular range from about 60° to 120°.

In accordance with the principle that beams be available on demand without shutting off the machine, the magnets should be permanently installed and embedded in the shield wall separating the meson area from the accelerator. The shielding should be removed only for magnet repairs. Internal target adjustment and insertion must be automatic.

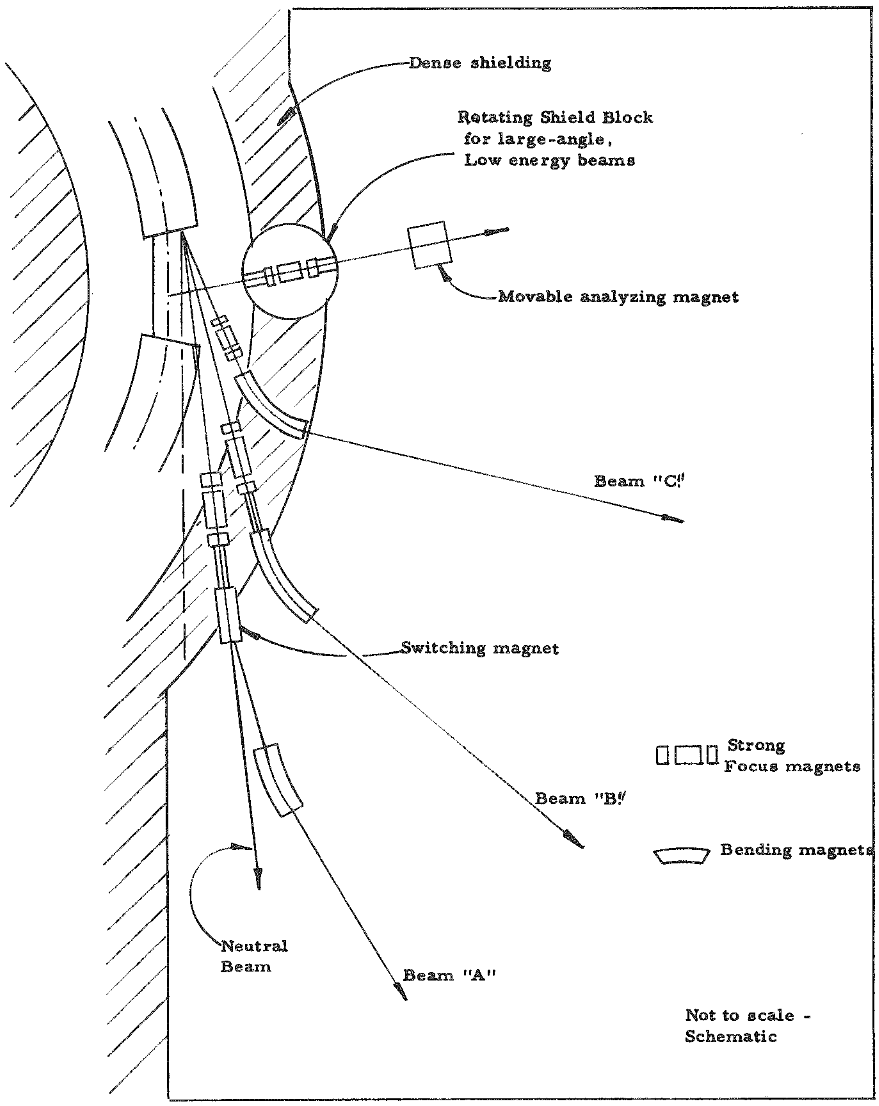
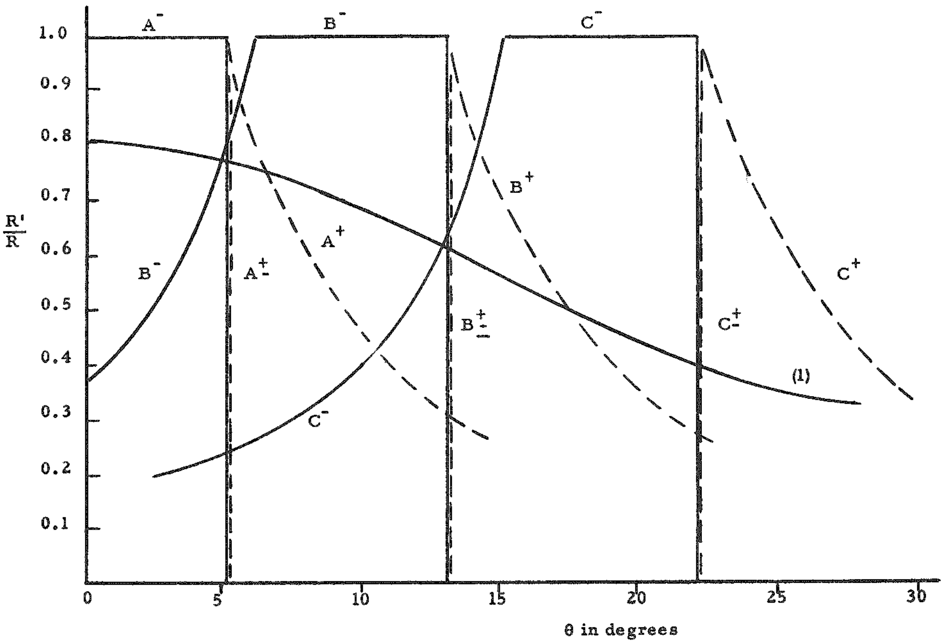


Fig. 23.
Meson Area

We do not recommend the construction of another meson area inside the main circle of the machine. Such an area would provide more experimental space, but access to it would be complicated. Because of the position of the circulating beam and the difficulty of inserting targets well into the upstream magnet octant, it would still be impossible to obtain high-energy positive meson beams produced in the forward direction. Instead we propose that such beams be obtained from the external proton beam in one of the proton beam areas described above.



Curve (1) gives the maximum radius of curvature (R') with which a secondary particle can be emitted at an angle θ in the laboratory system. This is given in terms of the radius of curvature (R) of the primary beam. With the magnet complex of Fig. 23, the areas bounded by solid lines are available for negative secondaries while those bounded by dotted lines are available for positive secondaries. For example, the curve B^- shows the region of acceptable momenta for negative secondaries in the beam "B" of Fig. 23. In arriving at these curves we have arbitrarily restricted the penetration of the targets into the magnet sectors to 3.5° that is, about 5 feet.

Fig. 24.

II. Power Requirements

We estimate that the eventual distribution of power requirements will be as follows:

Proton Beam Handling	2.8 Megawatts
Meson Beam Handling	1.8 Megawatts
Experimental Magnets - Proton Areas	8.9 Megawatts
Experimental Magnets - Meson Area	4.5 Megawatts
Total:	18 Megawatts

III. Beam Characteristics

We suggest the following beam characteristics to make the accelerator useful for a wide range of experiments. We consider the energy and intensity adjustments of the beams as well as the length of the individual pulses.

A. Energy Adjustment of the Beams

An important class of experiments involves the measurement of cross sections as a function of energy. For such experiments, it is usually far better to vary the primary beam energy than to degrade the energy with absorbing materials. In this connection, it is worth noting that to reduce the energy of the proton beam by ionization loss requires so much absorber that multiple Coulomb scattering causes a violent degradation of the angular definition of the beam. Furthermore, the large number of nuclear interaction mean free paths inherent in such an absorber would reduce the beam intensity as well as create a serious background problem. Therefore, the main beam energy should be adjustable from about 1 Bev up to the full energy.

We propose that the energies of the several beams be independently adjustable within one magnet cycle. For example, on a single pulse beam, deliveries might be as follows: 1/4 of the protons at 5 Bev to one proton area, 1/2 of the protons at 10 Bev to strike the internal target, the remaining 1/4 of the protons at 12.5 Bev to the other proton area.

B. Pulse Repetition Rate

It is anticipated that there will be a great demand for machine time. This makes it imperative that the machine put out as many beam pulses as possible. The magnet should spend a minimum of time between beam pulses. Therefore, when the machine is operated at low energies, with a consequent reduction in acceleration time, the pulse repetition rate should be increased correspondingly. At all energies, the programming of the beam should be adjusted to give the maximum useful beam time. We note that this is being done at Brookhaven. Such flexibility is very useful for the adjustment of the injection optics.

C. Adjustment of the Beam Pulse Length

The pulse length must be separately adjustable in the three principal experimental areas. Counter experiments require very long beam pulses with the pulse length variable from 40 to 200 millisec. Even longer pulses would be desirable. It must be possible to make this variation with all the beams independently. Bubble chambers, on the other hand, often require beam pulses as short as a few microseconds.

Rapid ejection has been achieved at Brookhaven with the Rahm ejector. This consists of a large pulsed magnetic field which can deflect the whole beam onto a target or Piccioni magnet during a single turn. The ANL intense magnetic field group is examining the problem of a Rahm ejector for the 12.5-Bev accelerator. We hope they will find it possible, with this method, to deflect only one of the four bunches of circulating beam, without disturbing the other three.

The order in which the pulses are delivered to various targets will depend on the pulse length which is required in the various areas. The beam may be moved rapidly across the machine by using a thin Piccioni target of large radial extent. This will cause a modest increase in the mean vertical oscillation amplitude, but will effect a considerable saving in magnet power.

For the actual control of beam time on the target, the main magnet will have to be programmed by accurate sensing probes. The meson area target will be near the outside of the vacuum chamber, and, in order to push the beam onto this target, the main magnetic field will have to be decreased slowly. The Piccioni targets will be near the inside of the vacuum chamber. A long beam pulse in a proton area will require constant main magnetic field and a plunging Piccioni thin target if the beam is to be monoenergetic.

To make large pulse lengths possible, the beam should first be spread out radially by inducing phase oscillations through noise on the radio frequency accelerating voltage. Brookhaven experience points out the necessity of minimizing magnet power supply ripple if long beam pulses are to be achieved. If only particles with large radial oscillations are used for a long pulse, subsequent rapid ejection of the remaining particles (which have small oscillations) will still be possible by using a Rahm ejector.

Some typical cycles which are contemplated for the machine are illustrated in Fig. 25. Programming of the magnet and the radio frequency voltages are illustrated for these examples.

D. Adjustment of Steering and Focussing Magnets

The steering magnets which switch the external beams should be controlled in such a way that it is possible to deliver a preset number of pulses to either an A or a B area on a pre-arranged schedule. This shifting will allow the concurrent use of these areas as discussed earlier.

When the energy of the beams is varied, all the steering and focus magnets must have their currents suitably adjusted. This adjustment should be part of the central programming of the machine. Suitable sensing and servomechanisms will be required to assure stability from pulse to pulse.

E. Adjustment of Beam Intensity

The beam intensity in the different areas must be adjustable through wide ranges for both the long and the short pulses. For the short pulses from rapid beam ejection, the range of adjustment may be smaller.

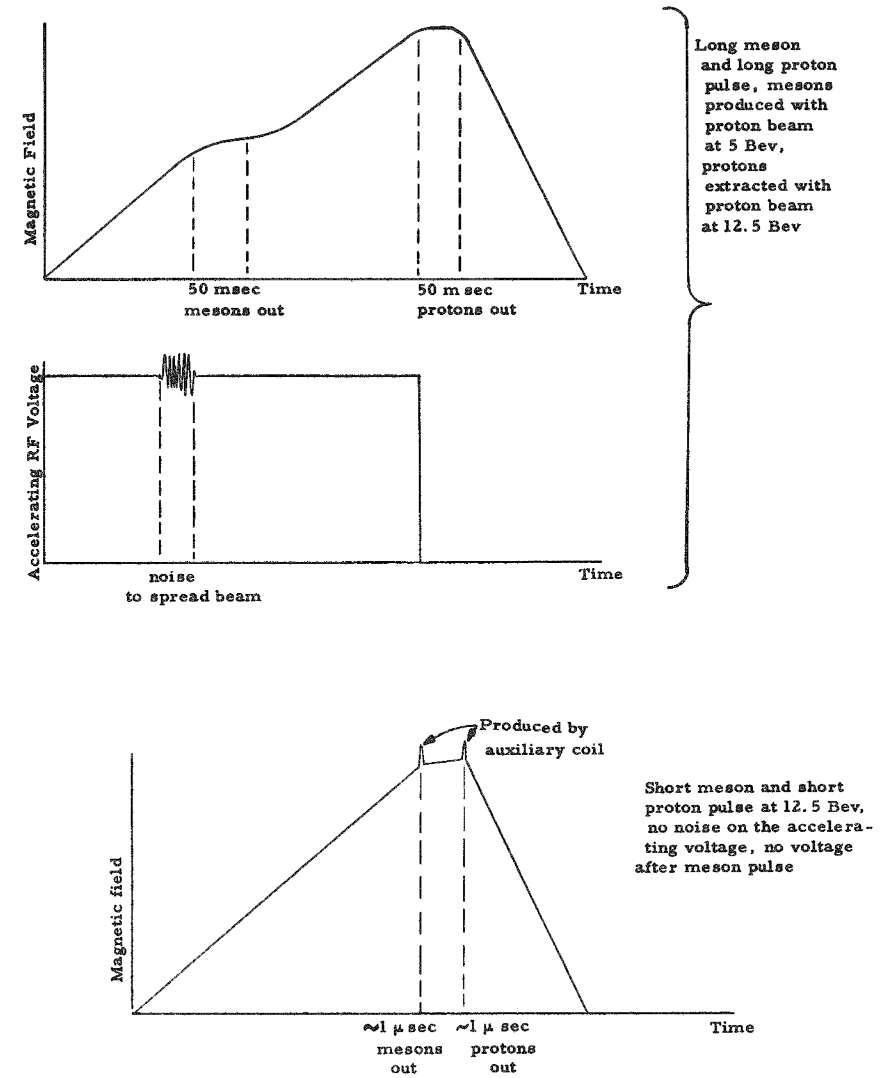


Fig. 25.
Typical Magnet and RF Cycles

The mechanism for varying the intensity of the long pulses onto the Piccioni targets by means of vertical adjustments of target position has been discussed in a previous report, CHKW-2. The beam intensity on the meson target will be controlled by the pattern of noise frequency modulation of the R.F. and the accelerator magnet cycle. The intensity of the beams for rapid ejection will be adjustable only in a crude fashion by selecting a certain number of the circulating bunches.

In order to avoid unnecessary background, the intensity of the injector must be adjustable for each pulse to match the total number of high-energy protons required. This may be done by varying the duration of the injection pulse.

We realize that the requirements we have discussed for long beam pulses imply a substantial increase in the power of the magnet excitation system. However, a high-intensity machine cannot be used efficiently if long beam pulses are not provided. The moderate increase in motor size and rectifier set that the long beam pulses imply will be quickly amortized in terms of the product of the accelerator - good experimental results. We note that pulse lengths of at least 200 millisec are already available at the Bevatron (see UCRL 3608) and lengths of 500 millisec are planned for the Cosmotron.

XXIII. ADDITIONAL TEMPORARY OFFICE AND LABORATORY SPACE

A contract for the rehabilitation and conversion of the 20,000-square foot storehouse, Building 818, into offices, drafting room, additional machine shop, laboratory space and a much needed conference room, was let on February 3, with completion scheduled for mid-May. At that date the offices and drafting space now in use in Building 806 will be turned over to another Division of the Laboratory, and the crowded conditions in Building 805 will be greatly relieved.

In early February, the Vacuum Group and those involved in model magnet assembly work moved into temporary quarters in two rooms of a warehouse, Building 817. As this structure is to be renovated for the use of other Divisions, a shift of the vacuum and model magnet facilities back into Building 805 will occur, probably in the early summer.

A small shack of 300 square feet was moved and placed close to Building 805 in March. This houses the power supplies for the prototype accelerating unit of the synchrotron. This structure will be moved into proximity to Building 818 when it becomes inhabited.

Bids will soon be let for the housing of the new motor generator sets and for their installation close to Building 805.

XXIV. ARCHITECT-ENGINEER SELECTION

J. P. FitzPatrick

After innumerable delays, on December 10, 1957 a Contract Board was established to recommend a firm to perform architect-engineer services for the design of the 12.5-Bev Proton Accelerator. The Board started work at once and held the first formal meeting on December 17, 1957. A list of sixty-five firms was compiled and their qualifications were reviewed, using information available from previous contract boards, AEC Washington, and individual board members. This review resulted in a list of twenty firms that were invited to submit proposals. The proposals received were reviewed and a list of ten firms was selected to be interviewed. The work of evaluating these ten firms was completed and the Board's recommendation was submitted on March 17, 1958. Contract negotiations with the firm that placed first in the Board's evaluation began almost at once, and an agreement was reached with the selected Architect-Engineer on April 9, 1958. The firm selected was Sverdrup and Parcel, Inc., St. Louis, Missouri.

The previously mentioned delays in obtaining authorization to select and retain an architect-engineer have forced a revision of the time schedule reported in ANL-5713. The revised schedule follows:

Architect-Engineer		
Start Work	May 1958	Was July 1957
Design Completed	July 1960	Was July 1959
Supervision Completed	May 1961	Was July 1960
Constructors		
Start Work	April 1959	Was July 1958
Completed	May 1961	Was July 1960
Proton Synchrotron		
Start Development	Underway	
Start Construction	July 1958	
Start Installation	May 1961	Was July 1960
Start Testing	April 1962	Was July 1961

XXV. PERSONNEL

The following additions to the Division have occurred since September 1, 1957.

Staff	
Philip Livdahl	October 8, 1957
Cyril H. M. Turner	November 1, 1957
Robert E. Daniels	December 16, 1957
Reynold J. Krizek	January 6, 1958
Thomas H. McGreer	January 20, 1958
E. Paul Myers	January 23, 1958
Resident Student Associate	
Robert Rothe	March 24, 1958

Technician Pool	
Alphonso McKamey	November 4, 1957
Joseph R. Stapay	December 19, 1957
Julius C. Shell	December 23, 1957
Robert Mandernack	February 20, 1958
Richard Hanchett	February 21, 1958
Rhodin L. Anderson	February 24, 1958
Felice P. Catania	March 27, 1958
Robert Vosecek	April 7, 1958
Max Striegl	April 7, 1958
Donald Fearnley	April 14, 1958
Computers	
Patricia B. Solecki	December 16, 1957
Dorothy Maren	February 19, 1958
Clerk	
Janet Ramuta	February 17, 1958
Draftsmen (Assigned from Central Shops)	
Emmett Tourville	November 1, 1957
Frank Panella	December 1, 1957
Harold Johnson	January 27, 1958
Planning Engineer (Assigned from Central Shops)	
Oren Layton	February 1, 1958
Machinist (Assigned from Central Shops)	
William R. Cole	March 17, 1958
Physicist Consultants (Additional, part time)	
Donald A. Glaser	University of Michigan
Laurence H. Johnston	University of Minnesota
Robert D. Sard	Washington University
Robert W. Thompson	University of Indiana
General Consultants on Accelerator Design	
William M. Brobeck and Associates	February, 1958
Resignation	
David Orr (to return to college)	January 27, 1958

The Division personnel, excluding consultants, now is composed of the following:

33 Staff members, of whom three are at least part time administrative
28 Technicians
4 Secretaries
1 Clerk

2 Computers
1 Planning Engineer, half-time, from Central Shops
8 Draftsmen, of whom 7 are assigned from Central Shops
3 Machinists full time, plus others assigned from Central Shops for specific jobs
2 Co-op students, half-time each
1 Resident Student Associate