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PARTICLE ACCELERATOR DIVISION

Summary Report

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PARTICLE ACCELERATOR DIVISION

Summary Report

I. PUBLICATIONS

Abstracts of ANLAD Reports

ANLAD-48 "Achromatic Bending Magnet Systems"

L. C. Teng, April 8, 1958

For injecting the 50-Mev proton beam from the Linac into the ANL Synchrotron, direction-changing or position-shifting magnet systems must be employed. Because of the energy spread in the 50-Mev proton beam it is extremely desirable that these bending magnet systems be achromatic. The general behaviors of such systems are studied and the conditions for achromaticity derived. Two achromatic systems are designed. The first system changes the beam direction by 110° to enable putting the Linac near the median plane and making a big angle of 110° with respect to the Synchrotron beam. The injection into the Synchrotron will then be from the outside. The second system parallel-shifts the beam to just clear a 2-ft step. This enables putting the Linac either above or below the median plane and tangent to the Synchrotron beam. The injection is now from either above or below. For the first system a minimum of three magnets (elements) is required and for the second system a minimum of four elements is needed. All elements are, for simplicity, designed to have uniform fields of identical magnitude. The focusing properties of these systems are studied. For both systems in the vertical (parallel to magnet field) direction they are simply equivalent to drift spaces, and in the horizontal direction they are equivalent to thick lenses. The practical conclusions of this study are (1) since it is easier to design and build big angle direction-changing achromatic systems than parallel position-shifting achromatic systems, it is recommended that the Linac be put near the median plane at a position roughly perpendicular to the Synchrotron beam and that the injection be from the outside, and (2) it is rather easy to design achromatic systems possessing any required focusing properties in both the horizontal and the vertical direction.

ANLAD-49 "Resonant Excitation and Damping of Betatron Oscillations"

L. C. Teng, June 20, 1958

Resonant excitation and damping of the radial betatron oscillation of the ion beam in a circular accelerator can be employed for beam extraction and injection. The effect of a general resonant-forcing term on

a linear harmonic oscillation is studied by the first-order perturbation method. The resulting expressions are sufficiently general and compact to enable the design of the most efficient extractor and the optimum injector which gives maximum filling of the available phase space area. Several numerical examples are given. In particular, the application of resonant damping for injection into a fixed magnetic field and constant frequency ring accelerator provides a method for continual injection to produce a continuous beam at high energies.

ANLAD-50 "The Choice of the ν_x ν_z Operating Point for the ZGS"
L. C. Teng, June 25, 1958

A systematic search and survey based on rational requirements is made to see what the merits of the proposed operating point, $\nu_x = 0.75$, $\nu_z = 0.875$, for the ZGS (Zero Gradient Synchrotron) are and whether other operating points having more merits exist. The result turns out to be as expected: that this operating point is, indeed, one of the best possible choices except for the fact that it lies on the resonance at $2 \nu_z - \nu_x = 1$. Although there is every indication that this resonance is not at all serious and although extensive studies of its effects are being made with the help of IBM-704 computing machines, it would be reassuring to know that other operating points equally qualified do exist. This investigation shows that there is a sizable region in the vicinity of $\nu_x = 0.75$, $\nu_z = 0.875$ within which all operating points are equally suited for the operation of the ZGS. The boundaries of this region are given and possible alternative operating points, in case the above-mentioned resonance turns out to be serious, are indicated.

ANLAD-51 "Radio Frequency Control System of the Zero Gradient Synchrotron"
L. K. Wadhwa, July 25, 1958

The bias function generator satisfying the precision requirements of $\pm 0.01\%$ and capable of generating the master oscillator frequency program to within the required tolerance of $\pm 0.03\%$ is described. The input for the bias function generator is obtained from quantities such as the guide field flux, B_g ; its rate of rise, $\dot{B}_g$; the guide magnet current, I_g ; and its rate of rise, $\dot{I}_g$.

The total bias function is obtained as a result of adding signals from the (1) B_g simulator, (2) hump generator, and (3) biased diode network.

An analog to digital converter has been used to determine the dynamic accuracy and the precision of the bias function generator and the master oscillator.

ANLAD-52 "The Phase-Amplitude Form of the Betatron
Oscillations in the ZGS"

L. C. Teng, August 22, 1958

The relations between the phase and the amplitude in the Floquet form (phase-amplitude form) of betatron oscillations and the elements of the sector transfer-matrices are derived. The resulting formulas are applied to the ZGS with parameters specified in LCT-1 and LCT-7. The phases, the amplitudes and the parameters defining the sector transfer-matrix elements for both the radial and the axial betatron oscillations at injection are calculated and plotted. The significant result is that the widest radial width of the beam occurs approximately in the middle of a guide magnet. If this maximum radial width is taken to be 32 in., the radial widths of the beam at the mid-point of the long straight section, the guide magnet end at the long straight section, the guide magnet end at the short straight section, the DC magnet end and the mid-point of the DC magnet are, in order, 29.89, 30.01, 30.95, 30.78, and 30.69 in. This indicates that, if the injection occurs at the mid-point of the long straight section, the inflector lip should be placed 1.06 in. inside of the outer vacuum chamber wall.

ANLAD-53 "A Design for an Accelerating Section to Extract and
Control a Large Current of Protons"

H. Fechter, A. Saulys, September 4, 1958

A design has been carried out for a re-entrant electrode structure that produces an approximation to a $z^{4/3}$ axial potential variation. Field data were obtained from an electrolytic tank model; numerical integration was used to solve the paraxial ray equation for beams moving under space charge forces. A 50-mamp beam was traced from the ion source through 330 kv of potential. Net inward radial forces compensate the space charge forces and hold the beam together without allowing it to scallop. Initial beam radius: 1 mm; Final radius: 1.7 mm. Acceleration takes place over 2.8 in.

ANLAD-54 "Modified Program for Computer Studies of Non-Linear
Betatron Oscillations in ZGS"

L. C. Teng, October 2, 1958

The IBM-704 code written as described in ANLAD-38 to integrate particle orbits in ZGS with soft edges has two defects. The program is too slow (approximately five minutes per revolution), and, because the orbits are calculated entirely by point-wise numerical integration, the round-off errors accumulate rather rapidly. Several steps are taken to rectify these defects. Only in the fringing field is point-wise numerical integration necessary. In straight sections where the magnetic field vanishes and in magnet sections where the field is uniform and vertical, the orbit can be

analytically calculated exactly. The choice of the equilibrium orbit as co-ordinate axis makes the interpretation of results simple. Unfortunately, it complicates the equations to be integrated. By using Cartesian coordinates running along the magnet edges, the number of coupled equations can be reduced from 4 to 2, and the forms of the equations can be substantially simplified. The code can be further speeded up by using fixed instead of floating point computation.

Internal Memoranda

G. O. Calabrese

GOC-9	Power Supply for the 12.5-Bev Proton Synchrotron - Effect of the Length of the Pulse on the Motor and Flywheel Requirements (May 5, 1958)
GOC-10	Calculations of the Current in the Magnet of the 12.5-Bev Synchrotron Assuming that the Voltage Decreases Linearly with Time (Aug 1958)
GOC-11	Capacitance Network of the 12.5-Bev Synchrotron (Sept 18, 1958)

D. F. Cosgrove

DFC-3	Report on Visit to UCRL, Livermore and Berkeley and Stanford Linac at Palo Alto (July 3, 1958)
DFC-4	Mechanical Engineering Project Proposal - Mechanical Mock-Up Linac RF Cavity (July 17, 1958)
DFC-5	Mechanical Engineering Project Proposal Wooden Mock-Up No. 124 Drift Tube (July 25, 1958)
DFC-6	Injector System Cooling Requirements (Sept 17, 1958)
DFC-7	Quadrupole Coils for Injector System (Sept 18, 1958)
DFC-8	Project Status Injector Program (Sept 30, 1958)

E. A. Crosbie

EAC-LCT-1	Survival Calculations for Different Gap Sizes in the ANL Synchrotron (May 12, 1958)
EAC-LCT-2	New "Frozen" Parameters of the ZGS (Dec 16, 1958)
EAC-3	New Short Straight Lengths (Oct 22, 1958)

Harry Fechter

- HF-7 Poincaré's Invariant and Particle Optics (Sept 25, 1958)
- HF-8 Derivation of Beam Loading Admittance (Oct 21, 1958)
- HF-9 A Focal Achromatic Bending (Oct 23, 1958)

J. R. Hiskes (Summer Employee)

- JRH-1 Evaluation of Transit Time Factors from Electrolytic Tank Data (July 3, 1958)
- JRH-2 An Injection Optical System for the Argonne Synchrotron (Sept 16, 1958)

H. A. Kampf

- HAK-6 Automatic Vacuum Measurement System (March 25, 1958)

John Moenich

- JSM-3 Ring Chamber Vacuum System (June 6, 1958)

L. C. Teng

- LCT-6 Beam and Chamber Widths and Heights (May 5, 1958)
- LCT-7 DC Magnets with Field Gradient (May 12, 1958)
- LCT-8 Further Considerations of the Vertical Chamber Height of the ANL Synchrotron (May 23, 1958)
- LCT-9 Labsy-Barsy Transformations (Oct 7, 1958)
- LCT-10 Beam Position after Passing Through Piccioni Magnet (Dec 29, 1958)

L. K. Wadhwa

- LW-3 Synthesis of a Special Purpose Hump Function Generator (Sept 22, 1958)
- LW-4 An Estimation of Errors in Frequency Program due to Time-Dependence of the Bias Function for the Master Oscillator (Sept 22, 1958)
- LW-5 An Improved Diode Function Generator (Sept 22, 1958)

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

CHKWY-6 Layout of the Meson Area (Sept 19, 1958)

External Publications

Acceleration and Control of a 50 MA Beam of Protons

H. R. Fechter and A. Saulys

Bull. Am. Phys. Soc. 3, 384 (Nov 1958) Abstract

Computing Programs for Radial Oscillations in Linear Accelerators
with Quadrupole Focusing Magnets

David Cohen, Bull. Am. Phys. Soc. 3, 384 (Nov 1958) Abstract

Electromagnetic Inflector for Synchrotron Injection

H. R. Fechter and Martyn Foss

Bull. Am. Phys. Soc. 3, 384 (Nov 1958) Abstract

Energy Spread from the Linear Accelerator

J. R. Hiskes

Bull. Am. Phys. Soc. 3, 384 (Nov 1958) Abstract

Injection Optical System for the Argonne Synchrotron

Rolland Perry and J. R. Hiskes

Bull. Am. Phys. Soc. 3, 384 (Nov 1958) Abstract

II. THEORETICAL STUDIES

E. A. Crosbie, L. C. Teng

A. Beam and Chamber Widths and Heights (LCT-6)

Calculations have been made of (1) various contributions to the beam width and height at injection, (2) considerations leading to the choice of chamber width and height, (3) acceptance and the expected output of the Synchrotron, and (4) width and height of the beam as functions of the magnetic field intensity, energy and time. The calculations were made with the equivalent synchrotron.

B. New Parameters for the DC Magnets (LCT-7)

In order to get more useful space in the short straight section, new parameters for DC magnets with edges parallel to the adjacent edges of the guide magnets and non-vanishing radial field gradients giving the same operating point were derived.

C. Further Considerations of the Vertical Chamber Height of the ZGS (LCT-8)

As the result of a visit from Dr. L. Jackson Laslett, the adequacy of the chosen chamber height of 5.25 in. was re-examined. The result of the examination shows (1) the increase of the vertical betatron oscillation amplitude due to the A.G. effect is quite negligible, so that the calculation made under the smooth approximation is indeed valid, and (2) the relative chamber height is actually bigger than that of the Brookhaven Cosmotron.

D. "George" Program for the Study of RF Self-Tracking

This program, which was first reported in ANL-5864, was completed. It was expected that by causing the rate of change of the oscillator frequency and the voltage applied at the accelerating electrode to be dependent on the measured average position and phase of the particles in a synchrotron, a stable equilibrium state of operation could be obtained. This program follows the behavior of a random sample of, say, 100 to 200 particles within prescribed limits of initial phase and energy under prescribed coupling conditions. Stable solutions were found and followed for some 1000 revolutions. Whether or not this self-tracking mechanism is practical depends on how well the particles can be bunched initially and how well the average phase and position can be measured. No information was obtained concerning the limits of accuracy required for these measurements. This code can also be used to show the behavior of a system in which position measurements can be used to correct a programmed master oscillator frequency. Further studies with this code are in progress.

E. "IBM-704" Code for Calculating the Frequency Program in the ZGS

The IBM-704 computing machine was employed to calculate the equivalent radius of the particles in the ZGS as a function of energy. This, then, gives the frequency program required. The parameters used for the ZGS are those given in LCT-1, and the magnetic field edges are assumed to be infinitely hard. With the new parameters of the ZGS (see J. below) this calculation should be done over again.

F. Permissible Variations of Betatron Frequencies at Injection

This work was first reported in the last summary report, ANL-5864, and was completed and written up in full as ANLAD-50. The recommended allowable deviations of ν_x and ν_z from the design values of $3/4$ and $7/8$, respectively, to still provide an 8-turn avoidance of the inflector lip are:

$$0.731 < \nu_x < 0.767 \qquad 0.848 < \nu_z < 0.902$$

G. Phase-Amplitude Form of the Betatron Oscillations in the ZGS (ANLAD-52)

The phases and amplitudes of the betatron oscillations in the ZGS have so far been studied only at isolated azimuthal locations under the smooth approximation. In this study the phases and amplitudes in the exact Floquet forms of the betatron oscillations were calculated and plotted for all azimuths. The parameters for the ZGS employed are those given in LCT-1 and LCT-7. The graphs in ANLAD-52 show at a glance the exact shape of the beam with betatron oscillations at any position in the synchrotron. As a result of this investigation it was recommended that the inflector lip should be so located radially that the outside edge of the inflected beam lies one inch inward from the outer vacuum chamber wall. This work should be repeated with the new parameters (see J. below) of the ZGS.

H. New "George" Program for Studies of Non-Linear Betatron Oscillations in ZGS

The IBM-704 code for integrating the exact equations of the betatron oscillations as described in the last summary report, ANL-5864, turned out to be too slow and lacking in precision. Also, the code, as written, is unable to give the equilibrium orbit. These defects are rectified to various degrees in this new program. In straight sections where the magnetic field vanishes and in magnet sections where the field is uniform and vertical, the orbit can be analytically calculated exactly. This new

program integrates the orbit across these sections by simple one-step transformations. Only in the fringing field is the orbit calculated by point-wise numerical integration, where also the number of coupled equations to be integrated is reduced from 4 to 2 by using Cartesian coordinates running along the magnet edges. Fixed point computation is used to further speed up the program. The detailed equations and procedures employed in this program are given in ANLAD-54.

This program is completed, debugged, and checked for accuracy and speed. For an accuracy of five significant figures on the displacements and slopes of the betatron oscillations it takes about four minutes per revolution. This program will be used to study the effects of non-linear and error terms on the betatron oscillations - in particular the long sought for behaviors at the $2\nu_z - \nu_x = 1$ resonance.

I. "George" Study of Synchrotron Oscillations with Frequency Errors

This study was continued during the period covered by this report. The investigation is now essentially completed and the results are being compiled to be presented in an ANLAD report. As expected, the results agree quite well with those obtained analytically under the adiabatic approximation.

J. New "Final" Parameters for the ZGS

The old parameters given in LCT-1 and LCT-7 derived under the approximation of infinitely hard magnetic field edges had to be modified when the "softness" of the magnetic field edges (fringing fields) was taken into account. Before any extensive computing machine study is made of the orbit in the ZGS with soft field edges and DC magnets, the parameters of the DC magnets cannot be fixed. However, based on information obtained from analytical calculations made under the "hard edge" approximation and numerical computations of the "soft edge" effect in the equivalent Synchrotron performed with the IBM-704 code for the study of the $2\nu_z - \nu_x = 1$ resonance, one can safely and rationally choose the parameters for the guide magnets and the straight sections, leaving the final adjustment of the operating point to that of the DC magnets. This was done and the "frozen" ZGS parameters up to date are given below.

Guide Magnet (Octant)

Radius of Curvature = $\rho_1 = 71.2437$ ft

Turning Angle = $\phi_1 = 0.750398 = 42.99465^\circ$

Length = $s_1 = \rho_1 \phi_1 = 53.4611$ ft.

Angle of End at Long Straight Section = $\theta_1 = 0.231358 = 13.2558^\circ$

Angle of End at Short Straight Section = $\theta_2 = 0.124978 = 7.16071^\circ$

Magnetic Field Intensity at 50.0 Mev = $B_0 = 476.763$ gauss

Magnetic Field Intensity at 12.5 Bev = $B_f \cong 21.5$ kilogauss

DC Magnet

Half Turning Angle = $\phi_3 = 0.035000 = 2.00535^\circ$

Straight Section

Half-Length of Long Straight Section = $s_2 = 10.0000$ ft

Half-Length of Short Straight Section (measured on straight line tangent to orbit at guide magnet ends) = $s_4 = 7.00000$ ft

Distances from Center to Accelerator

Center to Guide Magnet End at Long Straight Section =

$L_1 = 88.18032$ ft

Center to Midpoint of Long Straight Section = $L_2 = 87.61147$ ft.

Center to Guide Magnet End at Short Straight Section =

$L_3 = 90.11684$ ft

Center to Midpoint (intersection of straight lines tangent to orbit at guide magnet ends) of Short Straight Section =

$L_4 = 90.08984$ ft

Note: The guide magnet ends are defined to be the ends of the magnetic field. No reference should be made to the iron of the guide magnet.

K. Computer Program for Orbit Computation in the ZGS with "Soft Edges" and DC Magnets

As mentioned in J above the parameters of the DC magnets can only be determined by a detailed numerical electronic computing machine calculation of the orbit in the ZGS with "soft edges" and DC magnets. This computer program will take the experimental data for the fringing field in the median plane of the guide magnet and the assumed median plane field of the DC magnet, evaluate the magnet field away from the median plane, and then integrate the equations of motion for the orbit (at injection). The median plane field, i.e., the parameters, of the DC magnets will be adjusted to give the desired orbit properties. Once the parameters of the DC magnets are determined this program will help to compute orbits at all other energies.

L. Barsy (Baricentric or Center-of-Mass System) and Labsy (Laboratory System) Transformations

Relativistic transformations of kinematic quantities between the Labsy and Barsy for two-particle interactions are frequently useful. The formulas are derived and compiled for convenient reference in LCT-9.

M. Motion of Charged Particles in a Linear Helical Quadrupole Magnet Field

It was suggested by Dr. A. V. Crewe that with an air core a helical quadrupole magnet is simpler to build than the conventional alternating sectional quadrupole magnet. The motion of charged particles in such a magnetic field is studied. An analytical smooth approximation method is developed to study the focusing properties of an infinitely long helix. The imaging properties for a helical quadrupole magnet of finite length are being studied with the help of the analog computing machine.

III. DC MODEL MAGNET STUDIES

Martyn Foss

Field Correction of the Ring Magnet

DC model magnet studies have been continued in order to determine the optimum size and position of correcting holes drilled in the magnet yoke. The presence of these correcting holes allows the magnet to be driven to higher values of magnetic field.

The correction of the main magnet above injection is complicated and facilitated by the complex orbit shape caused by the DC magnets in the short straight sections.

We now have a program for the computer that calculates effective n and $\bar{n}$ for selected orbits in the observed fields and in fields predicted for enlarged correcting holes. Low fields (below 21 kg) must be satisfactory. If any orbit at any low field fails to be inside the low field limits tabulated below, the correcting holes are changed. If all low fields are satisfactory, then the values of $\bar{n}$ for high-field orbits are calculated. After all of the orbits for a particular field are calculated, the values of $\bar{n}$ are compared with the high-field limits tabulated below. If one or more points fail to fall within the limits, then the field at which the first failure occurs is calculated, a card is punched, and the correcting holes are changed. Most of the information on the output cards is indicated in the sample output which follows.

Many factors were considered in selecting the magnet currents, orbit numbers and limits of $\bar{n}$ used in the program. It is clear that the inference that the field is everywhere satisfactory when only a finite set of points is investigated involves previous experience about the behavior between points.

The selection of limits on the allowable contribution of the center blocks to $\bar{n}$ depends on many factors:

1. the anticipated difficulty building the ends;
2. $\bar{n}$ for the entire magnet between orbits numbered -3 and +12 should be between -0.1 and +0.1 at all "low" fields;
3. $\bar{n}$ for the entire magnet between orbits numbered -3 and +8 should lie between -0.15 and +0.15 at "high" fields (Since the stability limits are -0.3 and +0.3, the above may be regarded as a safety factor of 3 at "low" and 2 at "high" fields.);
4. the limits at -6, -7, and -8 are imposed just to keep the beam extraction optics neat; and

5. The weak treatment of the region from 16 to 8 does not seriously hamper the meson area and raises the maximum external beam energy considerably. The forward zero change beam comes from about 8. It is quite probable that many of the very high-energy meson experiments will be done in the external beam where flight times and angles are under better control.

(Note: The orbit numbers stand for the distance in inches from the center of the vacuum chamber in the long straight section.)

TABLE I

Limits of $\bar{n}$ for Center Sections of Ring Magnet Octants

(The contribution of the end blocks must be added to the $\bar{n}$ from the centers.)

Orbit Number	High-Field Lower Limit	Low-Field Lower Limit	Low-Field Upper Limit	High-Field Upper Limit
16	$-\infty$	$-\infty$	∞	∞
13	$-\infty$	$-\infty$	∞	∞
12	$-\infty$ (-0.16)	-0.08	+0.08	$+\infty$ (+0.16)†
11	$-\infty$ (-0.16)	-0.08	+0.08	$+\infty$ (+0.16)†
8	-0.14	-0.07	+0.07	-0.14
5	-0.12	-0.06	+0.06	+0.12
2	-0.10	-0.05	+0.05	+0.10
-1	-0.08	-0.05	+0.05	+0.08
-3	-0.07	-0.04	+0.04	+0.07
-6*	-0.12	-0.08	+0.08	+0.12
-7*	-0.12	-0.08	+0.08	+0.12
-8*	-0.18	-0.12	+0.12	+0.18

The orbit number is its distance from the centerline in the long straight section.

*These are averaged from -3, where it is presumed that the jump target is placed.

†The limits in parenthesis are used for information, not for decision.

TABLE II

Size of Correcting Holes			Sample Output Current below Failure*								Current above Failure*						Field at failure (kg)
Amount of 1st Change	Amount of 2nd Change	Amount of 3rd Change	$\bar{n}$ at 12	$\bar{n}$ at 11	$\bar{n}$ at 8	$\bar{n}$ at -3	$\bar{n}$ at -6	$\bar{n}$ at -7	$\bar{n}$ at -8	$\bar{n}$ at 12	$\bar{n}$ at 11	$\bar{n}$ at 8	$\bar{n}$ at -3	$\bar{n}$ at -6	$\bar{n}$ at -7	$\bar{n}$ at -8	
60	400	100	3	2	2	3	2	2	2	2	2	1	5	3	3	3	22,030
60	400	350	2	1	1	3	2	2	2	0	0	0	5	4	4	3	22,125
60	400	400	2	1	1	3	2	2	2	0	0	0	5	4	4	3	22,134
60	400	375	2	1	1	3	2	2	2	0	0	0	5	4	4	3	22,134
60	600	0	3	2	1	4	3	3	2	1	0	1	5	5	5	3	22,037
60	600	250	2	2	1	3	2	2	2	1	0	0	5	4	3	3	22,129
60	600	350	3	2	2	2	1	1	1	3	3	2	2	1	0	1	21,768
60	600	325	2	2	1	3	2	2	2	1	0	0	5	4	3	3	22,157

- 0 $\bar{n}$ Less than high-field lower limit.
 1 $\bar{n}$ Between high-field lower limit and low-field lower limit.
 2 $\bar{n}$ Between low-field lower limit and zero.
 3 $\bar{n}$ Between zero and low-field upper limit.
 4 $\bar{n}$ Between low and high-field upper limits.
 5 $\bar{n}$ Above high-field upper limit.

*These are averaged from -3, where it is presumed that the jump target is placed.

IV. RING MAGNET CONSTRUCTION

W. B. Hanson, R. H. Lykken

The major design criteria for the ring magnet have been decided. Each octant shall be composed of submodules of ten center blocks and four end blocks. Each block will be made up of a top pole piece, a bottom pole piece, and an inner and outer side yoke piece (see Fig. 1). The top and bottom pole pieces of the center blocks will be identical and can be located anywhere within the octant, depending on the results of magnetic testing. Magnet laminations will be all uniformly tapered with a mean thickness of 0.500 inch. There will be approximately 92 laminations in the center blocks and 42 in the end blocks.

Fig. 1
Cross Section
Ring Magnet

The decision to use all uniformly tapered laminations as compared to using mostly flat laminations and a few tapered ones was made in order to produce a better magnet by having a more uniform magnetic field, a more uniform eddy-current effect, and a better stacking factor because of closer dimensional control.

The dimensions shown in Figs. 1 and 2 are final. The exact location of the magnetic field correction holes shown in Fig. 1 are being determined by the Magnet Group but are not critical to the design at this stage.

Methods of application of interlaminar insulation are still being investigated with the possibilities narrowed down to two methods:

1. use of a pre-impregnated laminate of uncured or B-staged epoxy and fabric with a heat cure after assembly into a block pole piece; and
2. a wet layup of epoxy and fabric also using a heat cure.

A comparison of these methods is now being made with consideration as to cost, electrical short resistance, bond strength, vacuum characteristics, and time and temperature of heat cure. A final decision on this will be forthcoming shortly.

It has been decided that the magnet laminations must be adequately sealed to withstand a rough vacuum pressure at the gap of at least 1 mm Hg. No extensive effort will be made to produce a seal which will withstand high vacuum, since it is contemplated that a double wall vacuum chamber is to be used.

A full scale magnet block prototype program is in process with Blaw-Knox Corporation as the contractor. The purpose of the program is to develop a manufacturing procedure for the final production of magnet blocks which will be both efficient and reliable. Also, one that will give a block free of internal shorts and which is structurally sound. The program is to include:

1. An investigation of tapering plates by various methods of machining or grinding as compared to cold rolling methods.
2. Machining a complete set of plates and rolling a complete set, thereby getting comparative figures on both methods.
3. An assembly fixture.
4. One complete block laid up using the inter-laminar insulation which will have been decided by the time the program has progressed to this point.

One-hundred plates have been taper rolled at Reynolds Metals Company on their 6000 hp rolling mill. The results of this investigation are:

1. The tolerance on thickness must be ± 0.005 . This is permissible since it will not be detrimental to the stacking factor.
2. Tolerance on rate of taper can be held to ± 0.002 which is probably as good as can be held by machining methods.
3. Crown is 0.002 to 0.003 per side. This will hurt the stacking factor and could probably be improved by machining.
4. Bow is rather large but this should be eliminated by stack annealing.

The size and shape of the end blocks are shown in Fig. 3. In general, they will be fabricated in the same manner as center blocks. The problem of magnet support structure has been turned over to the Architect-Engineer and they are working on this at the present time.

Fig. 3

Ring Magnet - End Blocks

V. MAGNET POWER SUPPLY

G. O. Calabrese, E. F. Frisby

A. Calculations of the Current in the Magnet of the 12.5-Bev Proton Synchrotron

These calculations have been made on the basis of the magnetization curve of Fig. 4, derived from the data obtained from the 1/7-scale, DC model No. 5, Mark II, Assembly No. 1, dated September 27, 1957, corrected for the effect of the insulation between plates, assuming that 97% of the azimuthal cross-sectional area is occupied by the iron and 3% is occupied by the insulation. The radial cross section of the magnet to which these calculations refer is shown in Fig. 5. The coil is assumed to have 30 turns.

Fig. 4

Curve No. 1 from 1/7 Scale DC Model No. 5 Mark II
Sept. 27, 1957 1st Assembly 97% Stacking Factor

The incremental inductance as calculated from the magnetization of Fig. 4 is shown in the same figure. The resistance of the coil of the magnet is calculated to be 0.238 ohm. The voltage applied to the terminals can be regulated to follow any desired shape as a function of time by means of appropriate programming. In this report, it is assumed that the voltage

applied to the terminals of the magnet starts at 12,500 volts and decreases linearly with time at the rate of 3,750 volts/sec, thus reaching a value of 8,750 volts at the end of 1.0 sec.

Fig. 5

The results of the calculations are shown in Figs. 6 and 7 giving, respectively:

Fig. 6 Instantaneous variation of current and instantaneous power.

Fig. 7 Instantaneous values of B , $\frac{dB}{dt}$ and $\frac{di}{dt}$.

The method developed for these calculations is adaptable to other methods of programming the voltage at the terminals of the magnet.

B. Magnet Power Supply

The thermal capacity of the power supply for the ring magnet will be based on the following maximum operating condition:

The magnetic field increases from zero to 22.5 kgauss in 1.0 sec, it flat-tops at this value for 0.2 sec, it decays to zero in 1.0 sec, where it rests for a period of 1.8 sec. The pulse duration for this operating condition is 4.0 sec or a repetition rate of 15 pulses per minute.

The characteristics of the power supply for this maximum operating condition are shown in Table III.

Fig. 6

Current and Instantaneous Power Calculated from B vs I Curve No. 1
 $(e_1 = 12500 - 3750 t)$ Volts

Fig. 7

B , $\frac{dB}{dt}$, and $\frac{di}{dt}$ vs Time - Based on B vs I Curve No. 1 $e = (12500 - 3750t)$ Volts

TABLE III

Ring Magnet Power Maximum Operational Conditions

Ampere turns, maximum	329,000
Maximum current, for 22.5 kg	10,950 amp
Voltage (initial)	12,500 volts DC
Voltage (end of rise period)	8,750 volts DC
Voltage during flat-topping	2,600 volts DC
Rise time	1 sec
Flat-top period	0.2 sec
Decay time of magnet field	1.0 sec
Rest time before next pulse	1.8 sec
Total pulse time	4.0 sec
Repetition rate	15 pulses per minute
Stored energy	41.35×10^6 joules
Resistive loss during rise period	9.5×10^6 joules
Resistive loss during flat-topping	5.7×10^6 joules
Resistive loss during decay period	9.5×10^6 joules
Heat loss to be removed from coil	24.7×10^6 joules/pulse
Average power loss in coil	6175 kw
Peak power to magnet	96,000 kw
Maximum allowable line power swing during pulse	5,000 kva
Maximum allowable DC voltage regulation at terminals of magnet	30% no-load voltage
Maximum allowable M-G set speed deviation	10% no-load speed

The thermal limitations as above are such as to permit operating under the following alternative condition:

The magnetic field rises to 21.5 kilogauss in 1.0 sec, flat tops at this value for 0.3 sec, decays to zero in 1.0 sec, and rests for 1.7 sec. Again the pulse duration is 4.0 sec per pulse and the repetition rate is 15 pulses per minute.

It is anticipated that the accelerator will be used to deliver particles of smaller energies than 12.5 Bev. Under these conditions, the repetition rate can be increased to the extent permitted by the thermal capability of the equipment.

The possibility is also contemplated of extracting different fractions of the beams at different energies during the rising period. For instance, on a single-pulse beam, deliveries may 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 an internal target, the remaining $1/4$ of the protons at 12.5 Bev to the other proton area.

This will involve one or more flat toppings during the rising period in addition to the flat topping at the end of the same period. The repetition rates under these conditions will be adjusted so as to remain within the thermal capability of the equipment. At present, it is not known how feasible this method of operation is. Its feasibility will be investigated later.

It is anticipated that, on initial start-up and for a period of perhaps one year, the accelerator will operate as follows:

Flux Density	21.5 kilogauss	Decay time	1.0 sec
Rise time	1.0 sec	Rest time	2.0 sec
Flat topping	0.0 sec		

One possibility is that the major components of the power supply will consist of one 60-cycle induction, wound rotor motor, with an external liquid rheostat in the rotor. The motor drives two 3-phase AC generators, with two flywheels on the same shaft. The generators supply four 3-winding transformers that, in their turn, supply four mercury-arc rectifier banks. The four rectifier banks are connected for 12-phase rectification and feed the magnet at four points. The connections of the transformers and rectifiers at the four supply points are duplicates of one another so that the DC voltages injected at these points are of the same magnitude and their ripples are in phase.

During each pulse, the speed of the motor-generator-flywheel combination is allowed to drop from the initial value at the beginning of the pulse to the final value at the end of the flat topping. The drop will be limited to not more than 10% of the initial speed.

During the rising and flat topping periods, the rectifiers are in the rectify position and energy to the magnet is supplied by the motor and the flywheels through the generators, the transformers, and the rectifiers. During the decay period, the rectifiers are switched to the invert positions; the stored energy of the magnetic field will be utilized to motorize the generators, increasing the speed of the flywheels and thus returning the energy of the magnetic field to the latter excepting for the losses. The average power drawn from the line will be equal to the mechanical, electrical and magnetic losses in the system. Figure 8 gives an outline of the connections of the major components of the power supply under the one possible alternative referred to above. Other possible schemes of power supply are: a) one motor, one generator, one flywheel, and b) two separate motor-generator-flywheel sets electrically in parallel.

Specifications for the magnet power supply are being drawn at present in collaboration with the Architect-Engineer. These specifications will be ready in the spring, at which time we will be able to invite bids from manufacturing companies.

Fig. 8

VI. RING MAGNET COIL

W. A. Siljander

The ring magnet coil program can be considered as consisting of three phases. One phase can be called "the side coil assembly phase," another "the final assembly phase," and the third "the installation and pre-stressing phase."

1. The Side Coil Assembly

There are two side coil assemblies, the inner and outer, and the basic parameters of these assemblies have been decided, that is, the size, shape, and sectional spacing. The permissible tolerances have also been established. These parameters along with those of the final assembly are shown in Fig. 9.

The materials that make up the side coil assemblies have been established in collaboration with the National Electric Coil Company. The copper conductors will be OFHC copper with a minimum tensile yield strength of 30,000 psi, the insulation an epoxy and glass cloth laminate, and the adhesive a filled epoxy formulation.

The anchor-plate material is to be an extruded aluminum of the highest strength extrudable. An initial material, 6062T6, is being investigated at present. This alloy has a tensile yield strength of 40,000 psi and a Young's modulus of elasticity of approximately 10^7 psi. The anchor nuts and stud rods will consist of a high-strength, non-magnetic, stainless steel such as Type 302.

The side coil assemblies will be fabricated in curing jigs constructed of relatively short (approximately 4 feet) sections. Each section will be supported independently of the other sections by support members held by a common concrete foundation. Provisions will be incorporated in the support members to make minor adjustments in the position of the sections by the use of shims and adjusting bolts. This will permit each section to be surveyed into exact position. An approximately 1/16-inch space will be allowed between adjacent sections to permit thermal expansion to occur without disturbing the jig.

The conductors will be pre-formed at the ends and at the start of the horizontal bell-mouth points. The large center-section arc will be formed in the molding jig during assembly.

All component parts of the assembly (conductors, insulation, and anchor plates) will be completely coated with adhesive after the appropriate cleaning and surface treatment has been performed. The parts will

Fig. 9

Coil Parameters

then be laid up layer by layer, paying particular attention to the spacing and perpendicularity on the inner (gap side) vertical row of conductors. This row requires a carefully selective fit.

After the assembly has been completely laid up in the curing jig, it will be clamped snugly to its correct shape and position by the application of a partial pressure, to be followed by the application of heat for curing and additional pressure. Figure 10 shows the clamping features of the jig.

Fig. 10
Coil Clamping Jig

The adhesive formulation, the required curing temperature and pressure, and methods of application for fabrication of the side coil assemblies have been worked out at the National Electric Coil Company.

Mechanical tests to date at the National Electric Coil Company on full-scale cross-sectional models indicate a minimum bonding strength of 700 psi, coil width tolerance of ± 0.081 inch, coil thickness tolerance of ± 0.010 inch, and a perpendicularity at the gap of ± 2 minutes.

Electrical tests indicate that the insulation system will have the following 60-cycle dielectric breakdown strengths using the short-time method:

(a) To ground	55 to 60 kv
(b) Layer to layer	20 to 25 kv
(c) Turn to turn	5 kv

Further mechanical and electrical testing is proceeding at National Electric Coil Company. Particular attention is being paid to the critical transition points along the side coil assemblies.

2. The Final Assembly

The final assembly phase primarily consists of the end jumper securing and insulating. The jumper-securing problem is under study at the present time. A program has been underway on resistance brazing at Sciaky Brothers of Chicago to determine the feasibility of that method. At the same time the brazing method using high-frequency induction is being carried on at PAD and the Lepel High Frequency Laboratories of New York. Either of the above two methods should be fast, clean, and reliable.

The final alignment and insulating problems are also being investigated at the National Electric Coil Company.

3. The Installation and Pre-Stressing Phase

The installation will take place in the tunnel and will utilize the ring magnet for final alignment and securing. Briefly, the procedure would be as follows:

- (a) Install the completed coil assembly in the lower pole and yoke of the ring magnet.
- (b) Adjust for gap at three places along constant center arc. The coil sides will be clamped in these positions using the anchor studs and appropriate insulating shims as required.

- (c) The resulting clearance gap between the side coils and the yokes will then be filled with a filled epoxy along the entire length of the magnet.
- (d) After the top pole of the magnet has been installed along with the associated vacuum chamber parts, the coil is pre-stressed.

The pre-stressing technique to prevent copper fatigue during operation is fully covered in an internal report WAS-4.

It is intended to fabricate a 22-foot prototype coil. This coil will be used to check the pre-stressing technique and establish final design, fabricating, and installation criteria for the ring magnet coil. It will ultimately be used to magnetically check the ring magnet prototype blocks.

VII. RADIO FREQUENCY SYSTEM

R. Daniels, H. Kampf, C. Laverick, J. Martin, C. Turner

A. Accelerating Cavity Design

The ferrite material which is to be used in the accelerating cavity of the Synchrotron has been chosen as Philips Type IV-B ferrite. The required permeability swing for this material of approximately twelve to one is accomplished with a DC magnetic bias field swing of nearly forty oersteds. The quality product, defined as Q times the frequency in megacycles per second, times the relative incremental permeability, exceeds the value of twelve thousand which is required by our specifications. The high value of the quality product indicates a power requirement of about forty kilowatts, which is well below the design value of the power amplifier being built. The magnetic properties of Philips IV-B ferrite are based on measurements taken for small ring samples; proof will be required of Philips Company that they can manufacture larger blocks and frames of material with characteristics as good as the ring samples. Two ferrite frames made up of twenty blocks, each 15.75 cm x 10 cm x 4 cm, are scheduled for delivery about April 1959, and the remaining frames should be delivered at the rate of one per month beginning with the late summer of 1959.

The low-loss ceramic material to be used in the insulating gap of the accelerating cavity has not been chosen as yet, although investigations have begun as to the feasibility of manufacturing it here at Argonne.

B. Radio Frequency Program

The approximate frequency sweep for an oscillator working on the eighth harmonic of the proton revolution frequency is from 4.4 Mc/sec to 14 Mc/sec, and a new master oscillator, incorporating a Clapp circuit, is being designed for this frequency range.

Preliminary tests on the function generator and its associated circuitry using the radio-frequency programming system and the Rea data converter, led to the conclusion that the time dependency of the function generator would probably be too great if step changes in the guide field were contemplated during the guide field rise. The work also led to the conclusion that modifications in the radio-frequency programming system were necessary and that a simpler, but still time-dependent, function generator could be devised. Many of these modifications have been carried out, but the work is not yet complete.

The problem of obtaining a frequency program which is not time dependent has also been considered, and methods of obtaining such programs by the use of notched ferrite cores and by the use of compound,

oscillator tank circuit inductance, each composed of a given type of ferrite core, have been studied theoretically and tried practically. A system which offers the best promise of success is one in which high bias fields are used for the tank-circuit ferrite. Two variants of this idea are:

- (1) to use a portion of the magnet coil current as a source of bias field for one of the tank-circuit inductances and incorporate a second tank-circuit inductance for frequency correction, deriving its bias field from a bias current generator controlled by a diode function generator; and
- (2) to produce the high bias current from a bias-current generator whose output current is controlled by an input voltage ramp obtained from the integration of $\dot{B}$ in the guide field.

Both the above variants are being explored and, if used, would incorporate a bias correction term obtained from a suitable function generator.

C. Noise-Measuring System

A calibrator was constructed to compare experimental results using the noise-measuring system built for the fourth harmonic (2 Mc to 7 Mc) with analytical results. It was found that experimental results using the calibrator are in good agreement with analytical results and that in the noise frequency range of 2 Kc/sec to 7 Kc/sec, which is the Synchrotron oscillation frequency range, frequency deviations as low as forty cycles are observable. The maximum sensitivity obtainable with this method of detecting noise is inversely proportional to the noise frequency

In order to increase the sensitivity of the measuring system, and to accommodate the frequency range of the eighth harmonic, the unit shown in Fig. 11 is under construction. By using two different delay lines the noise-frequency spectrum can be inspected up to 50 kc and noise frequency deviations of 15 cycles should be detectable in the 2-kc/sec to 7-kc/sec noise frequency range. With the tunable oscillator, peak sensitivity can be obtained at any part of the program, and the tunable selective amplifier will allow searching the noise spectrum using various bandwidths and center frequencies.

D. Power Amplifier

The RF power amplifier design for operation at the eighth harmonic has been essentially completed. The broadband type of amplifier will be capable of delivering the full power of 80 kw into the accelerating cavity over a frequency range of 4 to 14 Mc/sec.

Fig. 11

Eighth Harmonic Noise Measuring System

The construction of a full-power prototype has begun and has progressed through the low-level stages. All of the amplifier thus far constructed has worked as well as expected. The construction of the three final stages remains to be completed. These three stages will be grounded grid power amplifiers, which will raise the signal from about 500 watts to full power.

All but one of the power supplies for the amplifier have been built or are under construction. These power supplies are used for converting three-phase alternating current power to the direct current required by the amplifier.

E. Beam Induction Electrodes

Induction electrode systems are being developed to measure the following beam parameters:

- (a) the total charge and azimuthal charge distribution in the bunches of accelerated protons;
- (b) the average radial position of the bunches;
- (c) the average vertical position of the bunches;

(d) the radial width of the bunches; and

(e) the vertical width of the bunches.

The electrode systems are being developed by means of models in which a charged conducting wire is being used to simulate a thin beam of charged protons. Measuring instruments have been obtained and a first experimental model system constructed.

For the calibration of such an experimental system, the charged beam should have a uniform line density. However, a wire, although necessarily at constant potential, will not necessarily have a constant line-charge density.

At the present time, measurements are being taken to find the geometric conditions under which a wire may be used to simulate a charged beam within a known degree of accuracy.

VIII. LINEAR ACCELERATOR

D. Cohen, H. Fechter, J. Hiskes, P. Livdahl, R. Perry

A. Linac Design

Detailed studies have been made of the BNL Linac design and such modifications have been made as are required to meet the specific needs of the ANL injector system.

Because of the long (250 μ sec) beam-injection time, direct current excitation of the quadrupole focusing magnets in the Linac drift tubes was decided upon. This required redesign of the magnets to accommodate water-cooled coils and modification of the drift tubes and supporting stems to accommodate the magnets and their power leads. Six sizes of magnets will be used. Their coils will be made of 7/32-in. O.D. by 1/8-in. I.D. copper tubing, with three turns per pole. Coil leads will be made long enough to thread through the drift tube stems to the exterior of the Linac tank so that no breaks in the water channel will occur in the vacuum envelope.

Prototype coils using 3/16-in. O.D. copper tubing have been made and successfully tested. However, the 7/32 in. O.D. by 1/8-in. I.D. tubing will reduce the power requirement and also give greater security against wall erosion. Average power per magnet is estimated to be about 1.8 kw for the +-+- polarity configuration, or about 1 kw for the ++-- configuration with the 7/32-in. O.D. tubing.

No changes are being made with the BNL drift-tube contours, although the interior of the drift tubes will be modified to accommodate the requirements of the magnets. Modification of the Linac tank design will also be limited to such changes as are required by the magnets plus minor changes recommended by fabricators of the BNL tanks.

Prototypes of a few of the drift tubes will be made in the near future to test the feasibility of all aspects of the design and assembly. In particular, the feasibility of performing all required high-temperature brazing of drift tube parts before machining the outside surfaces will be investigated.

B. RF System

A study of the characteristics of existing, commercially available tubes capable of fulfilling the RF requirements of the linear accelerator has been completed. The frequency and power requirements narrow the selection of tubes down to: a single RCA type A 2346F triode or RCA 15030 triode; two paralleled RCA type A2342A triodes; or four paralleled French triodes, the FTH 470, made by Compagnie Francaise Thomson Houston, Paris, France.

An investigation of the relative merits of these tubes has led to the conclusion that the RCA A2346F system will be inherently simpler and more reliable than any other. Preliminary specifications for the system were sent to prospective suppliers for preliminary engineering proposals and cost estimates. After examination of the proposals submitted, and further examination of the over-all requirements, a set of specifications has been prepared to obtain competitive bids from suppliers for the entire RF system.

The objective specifications to be achieved by the system are as follows:

1. Operating Frequency	200 Mcps (with tuning range of ± 2 Mcps)
2. Pulse Length	Variable from 50 - 500 μ sec
3. Pulse Repetition Rate	Variable from 1 - 10 pulses/sec
4. Maximum Pulse Power Output	5 megawatts
5. Maximum Average Power Output	25 kilowatts
6. RF Rise Time (in 50- Ω resistive load)	Less than 5 μ sec to 80% of full-power output
7. Pulse Firing Time Jitter	Less than 5 μ sec
8. Pulse Length Jitter	Less than 20 μ sec
9. Pulse RF Voltage Amplitude Jitter (Pulse to Pulse)	Less than 0.5%
10. Modulation Voltage Ripple	Less than 0.5%
11. Final Amplifier Plate Voltage Droop within Pulse	Less than 0.5% from 150 μ sec to end of pulse

C. Computing Program

1. Radial Motions

Two computing programs to trace radial motions through the Linac with the IBM-704 have been written and are now working. The first, a purely linear program, was arranged by Mr. Kenneth Hillstrom of the Applied Math Division and is used to investigate the effects of translational magnet misalignments and some general orbit properties. The second, arranged by Mrs. Shirley Steidl of the Applied Math Division, contains x-y coupling non-linearities due to magnet ends and the RF field,

rotational magnet misalignments, space charge, and the presence of the bore; the presence of the bore allows computation of acceptance and output figures in phase space as a function of various phenomena and Linac operating conditions.

Investigations with the linear program were primarily concerned with the effects of misalignments of the type where magnet ends are displaced from the "true" positions. Six sets of random misalignments were chosen from a uniform distribution between 0 and 0.006 in., and the motion of the resulting equilibrium orbits were examined. No serious effects would be present if the bore were allowed to open up, as is called for in the actual Brookhaven Linac design. New misalignments were then chosen; these were of simple alternating polarity of 0.004 in. and therefore deliberately made severe. Under these conditions a disturbing effect was noted; the state of equilibrium orbit on leaving the Linac was a strong function of the time of injection, and hence the output figure in phase space "danced around" the Synchrotron acceptance figure in time. A good fraction of the Linac output could be lost to the Synchrotron in such situations. The result of these investigations was to set the limit of 0.003 in. for misplacement of magnet ends, with the recommendation that care be taken during lining-up procedures so that short-range misalignment be minimized.

A number of phenomena have been studied with the non-linear program. It was found that no significant effects occurred with the non-linearities for bore-limited acceptance and output figures in phase space. Space-charge effects indicated that 0.10 ampere of protons could be injected into the Linac without any significant beam destruction; this linear space-charge treatment involved a circular beam geometry and took into account the loss of particles which originally had improper phases and energies. The calculated forces should be accurate to within a factor of two or so.

One set of random rotational misalignments, chosen from a uniform distribution between 0 and $\pm 1.1^\circ$, was used for the initial investigation of this type of misalignment. Orbits were found to be significantly disturbed, and this particular set was then decreased by a factor of 10. In the latter case, no serious disturbances were seen. Other sets of random angles will be run, but one can tentatively specify a rotational misalignment of ± 10 minutes of arc as a safe upper limit when installing quadrupoles and drift tubes.

2. Phase Motions

A computing program to trace phase motions through the Linac was written by Howard House of the Applied Math Division and is now working. The fundamental equation is non-linear, and the program

has provision for inserting a wide range of initial energies and phase angles, as well as RF gradient fluctuations in space, and some radial coupling effects.

A number of phenomena have been investigated, and results examined via figures in phase space. In particular, output phase and energy spreads have been investigated as a function of random gradient fluctuations, and general gradient "tipping." Many sets of random gradient fluctuations were chosen from a uniform distribution between -2% and +2%, -4% and +4%, and -8% and +8%. Taking into account post-Linac debunching (energy spreads of 400 kv are allowed before the debuncher), no disturbing effects were seen. For space fluctuations only, protons can have their mean output energy shifted by 500 kilovolts, but spreads do not exceed 400 kilovolts for the worst $\pm 8\%$ case. When time fluctuations are inserted with the space fluctuations, however, the output energy spread may become seriously large. Conclusive data on this latter effect are not yet available, but in the near future the magnitude of this latter effect will be evaluated and tolerances set on gradient fluctuations.

Computations with gradient "tipping" ($\pm 10\%$, end to end) indicate an induced energy spread at the output which extends somewhat beyond the allowable range of 400 kv. The computations are continuing in order to investigate a wider range of conditions in which a harmonic analysis of gradient effects may be inserted.

3. Injection Optical System (JRH-2)

The problem of matching the output beam from the linear accelerator to the admittance requirements of the Argonne Synchrotron has been investigated. With a good program of quadrupole field gradients in the Linac, and a particular range of phase oscillations, those particles which, upon injection into the Linac occupy the entire available admittance area in phase space, will emerge from the Linac occupying an emittance area in phase space of about 0.4 milliradian inches, which value is appropriate to either the initially focusing or the initially defocusing plane for the ++-- polarity configuration of the quadrupoles.

Because of misalignments of the quadrupoles in the Linac, the beam will probably emerge somewhat off axis and in a direction not parallel with the axis of the Linac. The first requirement of the optical system, then, is to restore the beam to the extended axis, and to direct it along this line toward the Synchrotron. This can be accomplished by means of two pairs of steering magnets whose four independent field strengths constitute the necessary parameters for aligning the beam in two mutually orthogonal planes. It is also expected that these magnets may be used to pre-compensate for the effect of the earth's magnetic field on the beam in the drift space to the Synchrotron.

After passing through the debuncher, which will reduce the energy spread of the beam to ≤ 75 kev, the beam will be deflected through an angle of 110° by means of an achromatic system of magnets. Working backward through this system from the admittance requirements of the Synchrotron, one finds that the beam at the entrance to the deflecting system must be nearly parallel in the vertical plane, but strongly converging in the horizontal plane with a slope of about 25 milliradians. Inasmuch as the beam emitted by the Linac possesses a slope of only a few milliradians in either plane, it will be necessary to interpose optical elements which will convert this essentially parallel beam into a beam which is parallel in the vertical plane but converging in the horizontal plane.

Work at CERN and BNL suggests that a system of quadrupole doublets and/or triplets might satisfy the requirements. Analysis indicated that a doublet rather than a triplet was clearly to be preferred to match the beam into the deflecting magnet system, with the doublet about 20 inches preceding the entrance to the deflecting system.

Having matched the gross properties of the beam in this manner, there remains the task of matching in detail, in both planes, and restricting the beam diameter in the drift space. For this purpose, a doublet and a symmetric triplet were considered, located about midway between the Linac and the deflecting magnet. Only the doublet has been considered in detail. The parameters of one set of matching lenses has been obtained, as well as the history of the beam through the system in the form of a series of phase space diagrams.

D. Ion Source and Pre-injector

The ceramic RF ion source has been received. A 60-kv, 400-cps power supply was purchased to use for ion extraction.

The design has been completed for a short, 300-kev accelerating section. This section provides a semi-periodic field distribution that has been shown to be suitable for the control of a 50-mamp proton beam. The section, now under construction, will be tested in several months, using the RF ion source of F. Schneider.

A development facility, to be used in the testing of ion sources and accelerating columns, has been designed. Presently, the components for the facility are being constructed and assembled. The 300-kv Cockcroft-Walton-type voltage multiplier has been assembled and tested. The 10-in. mercury diffusion pump vacuum system, with the associated control circuits, is being assembled. Completion of the facility has been held up by delayed delivery of an isolation transformer, which is of such a size that it must be installed before final assembly of the entire equipment can be accomplished.

E. Electromagnetic Inflector

The design of the electromagnetic inflector has been completed. Field measurements show that field errors are sufficiently small in the region of beam travel.

F. Linear Accelerator Vacuum System

Preliminary studies have been started to determine the Linac vacuum system requirements. In order to insure maximum reliability and minimum control system complexity, it has been decided to use a smaller number of larger mercury diffusion pumps than originally planned and to use mechanical refrigeration (-200°F) for cooling the isolating baffles. The use of mercury diffusion pumps is clearly indicated from linear accelerator experience at the University of California Radiation Laboratory, as well as experience in the large vacuum tube industry.

The preliminary design study of this system is continuing and will be completed during the first quarter of calendar 1959.

IX. RING MAGNET VACUUM CHAMBER

W. B. Hanson, R. H. Lykken

The ring magnet vacuum chamber will be of two-piece construction (see Fig. 12). The outer chamber will depend upon the magnet for structural strength and will serve as a rough vacuum chamber. This will enable the inner chamber to be of thin-wall construction, strong enough to sustain its own weight over the width of the gap and such additional atmospheric loading as imposed by the vacuum and controls systems. A double-wall vacuum chamber has the following advantages:

1. Minor leaks in the outer chamber will not necessitate shutdown.
2. The inner chamber may be tested prior to assembly and more easily replaced should damage occur.
3. Sealing the magnet as a single high vacuum chamber, while attractive, involves difficulties which require considerable research and development.
4. Should it be feasible to obtain a high vacuum in the magnet, the inner chamber will provide added insurance of minimum shutdown time and will enable the program to proceed on schedule.

A. Inner Vacuum Chamber

Several methods of fabrication of the inner vacuum chamber have been considered, and the following two types seem most feasible:

1. All Metal One-Piece Chamber

This type would be formed from stainless steel sheet into a rectangular bellows the full length of an octant. All necessary joints would be welded. This design offers the following advantages:

- a. minimum outgassing;
- b. opportunity to heat electrically at assembly to reduce surface contamination and obtain ultimate low pressures rapidly;
- c. maximum rigidity in the event of loss of rough vacuum;
- d. minimum radiation damage to chamber;
- e. less eddy-current effect than continuous flat stainless steel sheet of the same thickness, and
- f. good conductance for rough vacuum.

2. Spiral Wound Stainless Epoxy Chamber

There are several variations of this basic concept which consists of a spiral strip of stainless steel wound on a mandrel with the edges either overlapping or separated by a small gap. In either case the stainless wraps will be insulated from one another. A covering layer of Fiberglas and epoxy is used for mechanical strength and vacuum sealing. The advantages of this design are as follows:

- a. minimum eddy-current effect is possible using narrow strips of thin stainless;
- b. chamber can deflect a considerable amount without permanent damage in the event of loss of rough vacuum; and
- c. opportunity to heat electrically.

Contracts for one or more prototypes will be let. Vacuum tests will be made in our existing 25-foot test chamber, using a simulated rough and fine vacuum system. The comparative advantages of various types of chambers as to outgassing characteristics, radiation-damage resistance, deflections, manufacturing tolerance requirements and end connection design necessary to provide differential pumping shall be a part of this test program.

B. Outer Vacuum Chamber

An experimental program to provide a method of sealing the plates, blocks and octant to obtain the necessary rough vacuum has been started. It will provide the necessary information on the insulation adhesive between plates that will be used in the magnet prototype program, and will test various techniques used in the sealing of the blocks at the pole face surface.

A prototype is being designed and tested that will encompass all of the problems encountered in the final full scale project, including gasketry, overhead application of laminate sealing materials, analysis of stresses and deflections that may occur during assembly and operation of the magnet, as well as limitations imposed by any RF cables, pole face windings, and connections to the pumping system itself.

X. VACUUM PUMPING SYSTEM

R. Trcka, J. Moenich

A preliminary study and design has been made of several vacuum pumping systems for the ZGS accelerator. One pumping system is shown schematically in Fig. 13 as a typical installation for each of the eight straight sections. A straight section contains one rough vacuum connection at each magnet end for the magnet outer vacuum chamber, two vacuum chamber gate valves, one rough vacuum connection, four high vacuum pumping connections, four Freon combination low temperature and -20°F baffles, two cascade refrigeration condensing units, four oil fractionating

Fig. 13

diffusion pumps, one Roots-type mechanical booster pump, one roughing line, one finishing, backing and holding line and a roughing line for the magnet outer vacuum chamber. Three large mechanical vacuum pumps, single stage (duplex design), provide the roughing, backing or holding for all the straight sections. Two mechanical vacuum pumps, single stage (duplex design), are used to maintain a rough vacuum in the magnet outer chamber.

The following requirements were considered in the selection of the vacuum pumping system as shown:

- A. Locate the mechanical rough vacuum pumps in the center pump building.
- B. Provide a differential pumping system in each magnet sector.
- C. All high-vacuum pumping connections to be located in straight sections.
- D. Use Roots-type mechanical booster pumps for roughing main vacuum chamber and backing the diffusion pumps.
- E. Provide a pumping system with sufficient flexibility of operation to conform to accelerator operation.

The location of the mechanical pumps in the center pump building enables the pumps to be centrally located, permits flexibility of operation by using the pumps as roughing, backing or holding pumps, simplifies the exhausting of oil vapors to atmosphere, and an oil reclaimer system can be tied in directly with the pumps for continuous or intermittent operation.

The use of Roots-type mechanical booster pumps is advantageous in that they can be used to rough the entire system from a pressure of 20 mm Hg and also back the diffusion pumps during periods of high gas throughput. During this period of high mass flow, backstreaming of oil from the diffusion pumps to the baffles will occur, and it is desirable to prevent this tendency by using high-capacity backing pumps to maintain a foreline pressure within tolerable limits.

The vacuum pumping system is flexible to the extent that the roughing pumps can be used interchangeably as roughing, backing or holding pumps. The Roots booster pump can be used as a roughing or backing pump and can be shut off and isolated in the system on standby at high vacuum. Any straight section can be opened to atmosphere while the remainder of the diffusion pumps continue to pump, and the four diffusion pumps on the opened straight section are held by the backing and holding pumps.

The possibility of using small holding pumps in the ring building or complete package unit pumping stations in the ring building are being investigated to determine which system is the most suitable for our application.

XI. MISCELLANEOUS

A. Vacuum Properties of Epoxy Plastics - F. W. Markley

The apparatus designed to measure the high-vacuum outgassing of cured epoxy materials, described in the last Summary Report, ANL-5864, has continued to operate satisfactorily. Outgassing rates as low as $5.2 \times 10^{-8} \mu\text{l}/\text{sec}$ have been measured for a sample of Epon 828 cured with Shell hardener Z after vacuum degassing at 170°C for several hours. This sample, of standard size, was a cylinder, 0.437 in. diameter by 4 in. long. Representative data for a low temperature cured epoxy system (Epon 828 with diethylaminopropylamine) are given in Fig. 14.

Fig. 14

Curve No. 1 is the curve of outgassing versus time under vacuum for the unconditioned sample, i.e., as produced. Curve No. 2 is data from the same sample after it has been removed from the high vacuum, exposed to the atmosphere (uncontrolled) for 16.5 hours and then remeasured.

Curve No. 3 was taken after the same sample had been outgassed under vacuum at 100°C for 23 hours, removed from the high vacuum and exposed to the atmosphere for 16 hours, and then remeasured. The outgassing rate measured as soon as the sample had cooled to room temperature, after its 100°C degassing and before it was exposed to the atmosphere, was $1 \times 10^{-4} \mu\ell/\text{sec}$. Since the sample was exposed to an uncontrolled atmosphere, where temperature and humidity may vary within wide margins, the quantity of material adsorbed on the surface of the sample, or absorbed in a surface layer of the sample, may vary widely from one exposure to the next. Such material would have appreciable effect on only the initial portion of the curves. This is believed to be the explanation for the observation that the initial portion of Curve No. 2 was higher than the corresponding portion of Curve No. 1. Therefore, the general features of the curves correspond with theoretical expectations for a low-vapor pressure material containing dissolved gases and high-vapor pressure impurities, throughout its volume, which slowly diffuse out into the high vacuum. All measurements to date indicate that the vapor pressure of the cured epoxies is very low, and the measured outgassing arises only from dissolved gases and impurities, unreacted material, absorbed gases, etc. However, the measured outgassing, even from epoxies of commercial purity, seems to be quite small and can be reduced further by vacuum stripping of the uncured resin and high-temperature degassing of the cured material. Therefore, these materials will probably be quite acceptable for our use.

It should be noted that all of the above data were taken from an ionization gauge and, as mentioned in the last report, this gauge is calibrated for air, not epoxy vapor. It is also true that the ionization gauge acts as a pump for the epoxy vapors. In fact, this is our biggest source of error. However, we have now noticed that ionization gauge pumping saturates during a run, so that the error in the data is not as large as was given in the last report. Our new test system, which incorporates a Knudsen gauge to eliminate these errors, has been finished for a month. Unfortunately, we have not received the glass Knudsen gauge ordered, and we are trying to use a metal one. So far, we have not succeeded in degassing this gauge satisfactorily. These outgassing measurements will be continued, but because of changes in our proposed method of construction of the high-vacuum container, future measurements will concentrate on the high-temperature cured epoxies. It is expected that these materials will have significantly better vacuum properties than their low and room-temperature-cured counterparts, because of a lower concentration of materials remaining unreacted after curing.

B. Evapor-ion Pump Studies - J. Moenich, M. Otavka, C. Senders

Gettering of the common gases like nitrogen, hydrogen and oxygen has always been good with this pump. The problem has been with the noble gases, especially argon, which drastically reduces the pumping

speed for air because of the one per cent of argon present. Ion pumping, the technique for pumping the noble gases in this pump, was known to be quite inefficient and improvements had to be made. The last Summary Report, ANL-5864, describes briefly some of the experiments which resulted in improved ion pumping. Our efforts changed the capabilities of the Evapor-ion pump for pumping air significantly. Where formerly a maximum of 350 liters/sec of air could be pumped, it is now possible to pump between 1000 to 1100 liters/sec.

Since the electron source used for ion pumping was located at the lowest point of the grid, it was felt that possibly only the lower portion of this grid was actually being utilized for ion pumping. An experiment, explained in the last report, to study this possibility was set up. The results in Table IV below indicate that there is a fairly uniform distribution of the electrons over the complete surface of the grid.

TABLE IV

Accelerator Grid Voltage	Grid Voltage	Grid Current (Milliamps)		
		Bottom Grid	Middle Grid	Top Grid
1000	500	75	70	65
1000	625	92	85	70
1000	750	98	98	90
1000	800	100	100	92
1000	825	100	92	85
1000	1000	110	105	100

At the present stage of development, a reasonable number of Evapor-ion pumps could maintain some of the vacuum chambers under consideration for the ring at a pressure of better than 1×10^{-6} mm Hg. The present drawback is one of reliability, and one of the main components responsible for this has been the titanium-feeder mechanism. At present there are two types of feeder mechanism in operation in different pumps and a third is being worked up to the point of a trial run.

The first feeder mechanism is a vertical feeder situated in the top portion of the pump. Vertical motion supplied through a bellows from an outside source feeds the titanium wire down a tube to the evaporating post. Since incorporating a new type of feeder spring arrangement, this feeder has become quite reliable. During one test period, it operated continuously for 20 days in a pump which maintained a 550-liter system at 4×10^{-7} mm Hg.

Figure 15 is a graph of pressure versus the pump down time of the 550-liter system, using first an un baffled 16 in. oil diffusion pump and then the above-mentioned Evapor-ion pump.

Fig. 15

The second feeder in operation is a dipping duck feeder, so called because of its forward and return motion during a feedback stroke. This feeder is a development of Dr. R. Herb at the University of Wisconsin. Its advantages over the first feeder are:

1. The entire feeder mechanism is installed on one frame and removable through a port.
2. The upper regions of the pump are free, allowing the installation of larger grids for ion pumping.
3. No annealer is required to straighten the titanium wire.
4. The starting pressure with the feeder is in the micron range as compared to 0.5 micron with the other feeder.

The dipping duck feeder does not have the record for continuous running as the other, but performance to date suggests that it will do just as good, if not better.

Figure 16 is a graph showing the pumping speed for air of an Evapor-ion pump equipped with the dipping duck feeder. The grid current was kept constant during the run of Curve I and allowed to rise at will with increasing pressure during the run of Curve II. The dashed portion of Curve II is the probable shape if it were continued and is based on previous data.

Fig. 16. Pumping Speed of Evapor-ion Pump

A third feeder arrangement, incorporating a low-powered electron gun as an evaporator, is being readied. It promises to have all the advantages of the dipping duck feeder plus the elimination of the evaporation post and its problems.

C. Water Flow Control - T. H. McGreer

Inasmuch as an unnoticed failure of water flow in a coil of the ring magnet would be disastrous, an investigation of flow detection equipment is being made. The problem is outlined on Fig. 17.

Fig. 17

There are a total of 512 coil sides in groups of 32 to be supervised. The direct approach using 512 flow switches may be used, but it would be desirable to eliminate these from the standpoints of expense, reliability, and maintenance.

An alternate scheme, shown in Fig. 17, has been devised; the large number of contacts are replaced with a smaller number of sensing elements and few, if any, contacts. A laboratory development program is being started to investigate the accuracy and reliability of the circuits and components. Its operation is as follows

1. Normal Flow

The outputs of the inlet flow and outlet flow transducers are balanced and a "normal" signal is emitted by the comparison circuit.

2. System Pressure Changes

The flow will increase or decrease with pressure according to the relationship $q = KP^n$, where q is flow, K is a constant, P is pressure between the main header and the discharge header, and n is a constant approximately equal to $1/2$. The inlet flow transducer responds to the change in accordance with the equation. On the other hand, the response of the coil flow transducer is very nearly in direct proportion to P . Therefore, the flow comparison circuit is weighted to provide a "normal" output signal throughout operationally permissible pressure ranges.

3. Leak Occurs in a Coil

Since the coil is a heavy copper bar with a drawn hole, there is a possibility of a leak occurring only at the headers or in the connecting hoses. If the leak is at the discharge, end flow remains normal and there is no thermal danger to the coil. However, it would be desirable to know that a leak had occurred and whether or not it was more than a dripping leak. If large, shutdown is necessary because of the possibility of damaging insulation.

Since it would be tragic to spray water over adjacent apparatus if a leak develops, the headers and hoses are to be enclosed in a box of some kind. The bottom of the box opens into a two-stage leak detector. The first stage operates on a total leakage of about $1/2$ liter, the second operates on a rate of flow depending upon the orifice size of the overflow. The first provides only an alarm while the second initiates shutdown of the Synchrotron power supply.

A break at the inlet end of a conductor produces a large increase in flow perhaps two or three times normal. This

is easily detected by the large increase in output from the inlet flow transducer accompanied by a smaller drop in the output from the coil flow transducer.

A small leak will be detected by the leak detector as in the case of a leak at the outlet header.

4. Pluggage

Although a properly screened water circuit using demineralized water should not be susceptible to plugging, the circuit shown is effective in detecting such a condition. In case of total plugging of a conductor, the inlet flow is reduced approximately by $1/32$ or 3.1%. This lowers the output from the transducer by a corresponding amount. Since one conductor is a negligible part of the total system, the pressure increase is also negligible. However, any pressure rise will be reflected by an increase in output from the coil flow transducer. Since the transducers can be built to detect flow (differential pressure) changes as low as $1/2$ per cent, there seems no difficulty in detecting a total stoppage or even a 50% stoppage of one coil.

It may be advisable to detect separately any gradual increase in flow resistance such as would be caused by a build-up of scale. An output from the comparison circuit in response to a very slow change in flow will be used for alarm purposes only.

D. Foundation Studies - R. Trcka

Three site areas were considered for the location of the 12.5-Bev proton Synchrotron complex and were designated respectively as Sites A, B and C. Site A had previously been studied with regard to soil conditions by obtaining soil borings, and then a pile driving program, coupled with a pile load test, provided sufficient data to consider a recommendation of friction piles for the foundation support of the accelerator.

Site C was considered because of its proximity to building services facilities and the ANL plant substation; also a study of the limestone ledge contour map indicated that a foundation support could be extended to bedrock in this vicinity. Soil borings were taken to rock throughout this area; however, considerable difficulty was experienced in obtaining samples because two boulder strata consisting of limestone fragments, cobbles and boulders, were encountered and small charges of dynamite had to be employed in order to ultimately reach limestone bedrock at a depth of approximately 90 ft. The first boulder stratum occurred approximately 54 ft to 64 ft below the surface, and the second boulder stratum was generally present at a depth of 72 ft to 78 ft.

In evaluating the possibility of driving piles to bedrock or utilizing a drilling rig for providing a support into bedrock, consideration was given to the use of a unique machine that has been operating successfully throughout the Chicago area on shaft borings and caisson construction. The machine is identified as a Benoto deep caisson excavator developed by a French manufacturer and presently is the only machine of this type operating in the United States. The outstanding characteristics of the machine are that the unit is operational at a job site by utilizing self-contained hydraulic controls and cable crane lift, is capable of moving about under its own power, and can move forward, backward and sideways to the right and left by means of a system of rail wheels, skids propelled by hydraulic rams and four corner jacks acting as movable hinged knee-like supports.

By using a special casing with a cutting edge, applying a vertical thrust and simultaneous reciprocating partial rotation to the casing by the use of two pairs of hydraulic rams and using a hammer grab as a clam shell, the machine is able to penetrate the hardest soils, thereby obtaining a firm anchorage of the caisson base in hard strata with a resulting high bearing capacity. The diameter of the shaft obtainable is from 20 in. to 42 in. and can be driven to a maximum depth of 350 ft.

A contract was let for the purpose of furnishing one 39-in. diameter test caisson at Site C, cored to a depth one foot into rock and poured with concrete that was reinforced with a steel cage of 1 in. reinforcing bars and rings. The caisson was installed during the first week of October. Installation was accomplished without difficulty, in fact the casing progressed through the identified boulder strata without refusal or need of rock crushing tools associated with the Benoto machine. The performance of the machine, based on one test caisson, was very satisfactory, and the possibility of utilizing this machine for caissons to rock for the ring magnet support is encouraging.

It is planned to obtain additional data pertaining to a caisson support by conducting a long-term dead load placed on the test caisson for the purpose of measuring settlement versus time and also data indicating rebound and permanent settlement when the load is removed.