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PARTICLE ACCELERATOR DIVISION

Summary Report

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3 PARTICLE ACCELERATOR DIVISION

Summary Report

I. PUBLICATIONS AND REPORTS

L. C. Teng, "Linear Theory of Betatron Oscillations in Sectorial Cyclotrons." Rev. Sci. Instr. 27, 1051 (1956).

E. A. Crosbie and L. C. Teng, "Coupling Between Betatron and Synchrotron Oscillations in an A.G. Synchrotron." Bull. Amer. Phys. Soc. 2, 10 (1957).

E. A. Crosbie, M. I. Ferentz, J. P. FitzPatrick, M. H. Foss, E. F. Frisby, J. J. Livingood, R. H. Lykken, D. S. Manson, J. H. Martin, L. C. Teng, and R. A. Trcka, "Report to the United States Atomic Energy Commission on the Design Characteristics of the 12.5-Bev Synchrotron for the Argonne National Laboratory." March 20, 1957.

E. A. Crosbie, M. I. Ferentz, M. H. Foss, M. H. Hamermesh, J. J. Livingood, J. H. Martin, and L. C. Teng. "The Argonne 12.5-Bev Proton Synchrotron," CERN Symposium (1956), Vol. 1, p. 42.

II. ABSTRACTS OF ANLAD REPORTS

ANLAD-31 "Radiation Damage in a Plastic Chamber"
Edwin A. Crosbie, Oct. 2, 1956

The main source of radiation damage in the chamber is assumed to be due to those protons which are injected into the machine but are not accelerated due to their not being picked up in stable phase oscillations. These 50-Mev protons, striking the walls of the chamber at right angles, would penetrate about 0.8 inch. If we assume a 6-inch amplitude for the betatron oscillations the protons will penetrate about 4 mils. Taking 5 ma as the injection current, 5/6 of this as the total loss, 4 sec as the repetition rate, and 100 turns as the time of injection, gives an energy loss in a 4-mil layer of the plastic of 0.29 joule/sec in.³ or 9.3×10^6 joules/year in.³. The equivalent radiation required to produce the same energy loss per unit volume corresponding to one year of operation is 39 ma sec/in.² for 10-Mev protons, 19 ma sec/in.² for 20-Mev deuterons and 2.4 ma sec/in.² for 40-Mev alphas.

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ANLAD-32 "Adiabatic Damping of the Radial Width of the Synchrotron Beam," L. C. Teng, Oct. 11, 1956.

General formulas for the adiabatic damping of the synchrotron, betatron, and error amplitudes in a weak focusing synchrotron are derived. It is shown that under the adiabatic approximation the synchrotron oscillation amplitude is proportional to $\frac{\gamma}{\eta^2} \left[\frac{\eta^2}{\gamma \left(\frac{1}{\alpha} - \frac{1}{\gamma^2} \right)} \right]^{1/4}$, the betatron oscillation amplitude is proportional to $\eta^{-1/2}$, the field and momentum error amplitude is constant, and the frequency error amplitude is proportional to $\left(1 - \frac{\alpha}{\gamma^2} \right)^{-1}$, where the symbols have their standard meanings. When applied to the Argonne synchrotron with parameters given in ANL-5630 the following results are obtained:

γ	Total beam radial width (in.)
1.0533 (injection)	36.0
1.3	20.5
1.5	17.6
2.0	14.5
5.0	10.2
14.323 (final)	8.0

ANLAD-33 "Resonances Between Voltage Ripples in Magnet Circuit and Synchrotron Oscillation." L. C. Teng, Dec. 31, 1956.

The ripples in various polyphase, rectified and unfiltered d.c. voltages are first analyzed. These voltage ripples in the magnet circuit will cause time ripples in the magnetic field, space ripples being eliminated by the generator arrangement proposed in ANLAD-30. Certain harmonics of these field ripples will resonate with the synchrotron oscillation at various energies during the acceleration cycle. The effects of the resonances are studied under the adiabatic approximation. The results indicate that for a 6-phase unfiltered d.c., assuming the free oscillation frequency of each magnet (octant) to be of the same order as the fundamental ripple frequency, the increments of the synchrotron oscillation amplitude ΔR during resonance with different harmonics N of the field ripples are

N	γ	ΔR (in.)	N	γ	ΔR (in.)
5	14.23	0.275	9	4.27	0.029
6	9.85	0.134	10	3.40	0.021
7	7.20	0.074	11	2.73	0.016
8	5.47	0.045	12	2.19	0.014
			13	1.71	0.015

All effects of these resonances may be completely eliminated by frequency self-tracking and beam radial positioning devices.

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ANLAD-34 "Proton Synchrotron R. F. Cavity Design"
John H. Martin, Jan. 17, 1957

Some of the details are presented for the design of a tunable radio-frequency cavity which may be used to supply the accelerating voltage for the protons in the ring magnet. To keep up with the proposed magnetic guide field rate of rise of 20,000 gauss per second, the particles must gain about 8000 electron volts of energy per turn around the machine. The peak value of the R.F. potential across the cavity will be about twice this. The frequency of this signal will be determined by a master oscillator and the cavity will be tuned to be approximately in resonance at all times. At the fourth harmonic of the proton orbit frequency the signal will sweep from about 2.1 megacycles per second at the time of particle injection to about 7 megacycles at the highest particle energy.

Calculations and material studies indicate that the required cavity characteristics can be obtained by carrying nearly all the R.F. magnetic flux in one of two available types of ferrite. To carry this flux around the 6 inch by 36 inch particle chamber about 1500 kilograms of one kind of ferrite is needed. Losses in the material are such that a peak R.F. power of 75 kilowatts is required. The proposed plan calls for slicing the ferrite into 4-cm thick slabs and cooling them by forced air. The swing in ferrite permeability required to produce the desired change in resonant frequency requires a magnetic bias of about 8000 ampere turns. The load impedance presented to the R.F. driver changes less than 50% throughout the entire program.

ANLAD-35 "The Effects of Current Distribution in the Coil on the
Magnetic Field." L. C. Teng, Feb. 22, 1957

At low fields the magnet of the Argonne synchrotron may be approximated by a two-dimensional rectangular cavity in a medium with infinite permeability. The magnetic field in such a cavity for simple current distributions may be derived by conformal mapping. This is applied to study the effects on the field due to gaps and misalignments in the coil and the magnet return yoke. Results for several special cases are given. As general conclusions one can state that horizontal air gaps, arbitrary in number and location in the return yoke, totaling less than 0.5 inch in width, produce negligible perturbation in the useful region of the magnetic field. Insulation between layers of coil should not be thicker than 0.02 inch, and top and bottom layers of insulation on the outer boundaries of the coil should not be greater than 0.03 inch.

III. THEORETICAL WORK

A. Motion of Ions in Singly Periodic Magnetic Fields

L. C. Teng

In a general magnetic field which is periodic in one arbitrary generalized space coordinate q , the equilibrium orbits (defined as those orbits which are periodic in q) of ions with given e/m_0 and different momenta define a two-dimensional surface - the orbit surface. The position of a point on the orbit surface is conveniently expressed in the orbit coordinate R , defined as the length of equilibrium orbit in one period divided by 2π , and specifying the particular equilibrium orbit on which the point lies; and θ , defined as the distance measured along an equilibrium orbit divided by R and specifying the position of the point on that equilibrium orbit. The equilibrium orbits are completely determined by two parameters:

$$\mu(R, \theta) \equiv \frac{R}{\rho(R, \theta)},$$

$$\nu(R, \theta) \equiv \frac{R}{\tau(R, \theta)}$$

where ρ and τ are the radii of curvature and torsion, and the relative positions of points on neighboring equilibrium orbits are specified by three parameters $\xi(R, \theta)$, $\eta(R, \theta)$ and $\zeta(R, \theta)$, which are expressible in terms of μ and ν . These parameters, as well as the magnetic field on the orbit surface, are periodic in θ with period 2π . The equilibrium orbits together with an added parameter $B_t(R, \theta)$ determine uniquely the behavior of small oscillations about the equilibrium orbits. The equations of these two coupled small oscillations are derived and expressed in terms of the six parameters μ , ν , ξ , η , ζ , B_t . Ultimately, one should be able to express ξ , η and ζ in terms of μ and ν , and these equations in terms of the three parameters μ , ν , and B_t . The special case of $\nu = B_t = 0$ and q a cylindrical angle coordinate corresponds to that of the sectorial cyclotron (Rev. Sci. Instr. 27, 1051, (1956)). Applications of this general theory include the derivation of focusing conditions in sectorial cyclotrons without median plane and in linear or helical systems. This work will be continued and will be written up in ANLAD reports.

B. Coupling Between Betatron and Synchrotron Oscillations in AG and Argonne Synchrotrons

E. A. Crosbie and L. C. Teng

In a previous paper [Phys. Rev. 98, 233 (1955) and MAC Report MAC-1, (August 1954)] Crosbie and Hamermesh studied the effects of coupling between betatron and synchrotron oscillations for a constant gradient synchrotron using systems of linear difference equations to represent the coupled oscillations. An error in this paper which neglects the damping of

the betatron oscillation was corrected. The technique was then applied to a general AG synchrotron with arbitrary half-sector width-ratio and field gradients. To lowest order terms in the ratio of energy gain per RF cavity to total energy, the results gave the well-known uncoupled behaviors of these oscillations. The higher order terms, however, appreciably modified the frequencies and dampings of both the betatron and the synchrotron oscillations for certain ranges of machine parameters. Application of this technique to the Argonne synchrotron is now in progress. Preliminary results indicate that the damping of the betatron oscillation amplitude is more seriously modified than for either the constant gradient or the AG synchrotrons. This work when completed will be written as an ANLAD report.

C. Parameters and Focusing Conditions for a Zero-Gradient Synchrotron with DC Magnets for Orbit Shifting
E. A. Crosbie, L. C. Teng

Martyn Foss has recently proposed using four tunable short DC magnets located in the middle of the short straight sectors to serve (1) as the correcting magnet for field errors, (2) as a tuning element to adjust the betatron oscillation frequencies at the beginning and the end of the acceleration cycle, and (3) as a bending magnet so that the high energy orbits will be radially tilted relative to the more strongly bent low energy orbits. The following advantages would result: (a) It allows the insertion of a stationary Piccioni magnet placed radially inward of one of the DC magnets for the extraction of the 12.5-Bev particles whose orbits are now separated from the low energy orbits (see Fig. 1).

FIGURE 1

τ

(b) The tilted high energy orbits wandering radially across the gaps of the main guiding magnets (built to follow the low energy orbits) tend to average out local radial field gradients which are present at high fields even after correction. (c) A weaker Piccioni magnet is needed to tilt the already tilted orbits at 12.5 Bev to effect extraction.

Formulas for the betatron oscillation frequencies have been derived and the parameters of the synchrotron have been chosen in accordance with the following requirements: (1) At injection (50 Mev) $\nu_x \cong 0.75$, $\nu_z \cong 0.875$. (2) At extraction (12.5 Bev) $\nu_x \cong \nu_z$ for both radial and vertical refocusing after passing through Piccioni target. (3) The amplitude of tilt of high energy orbits should be $\cong 5$ inches to obtain effective averaging of local radial gradients of the magnet field in the main guiding magnets. (4) The field of the DC magnet should be > 500 gauss so that it operates in the region of constant permeability. (5) The total straight sector length should be maximized. (6) The field in the main guiding magnets should be $\cong 21.5$ kilogauss at 12.5 Bev. A preliminary set of machine parameters and the corresponding operation parameters are given in the following table.

	Injection	Intermediate			Extraction	
K.E. (Bev)	0.0500	0.1095	0.5000	1.0000	12.5000	∞
γ	1.05329	1.11668	1.53293	2.06586	14.32319	∞
η	0.33080	0.49697	1.16184	1.80769	14.28824	∞
S_1 (ft)	53.465	53.505	53.554	53.568	53.591	53.594
ρ_1 (ft)	71.248	70.214	69.072	68.772	68.305	68.238
ψ_1 (R)	0.75040	0.76203	0.77534	0.77893	0.78458	0.78540
B (kG)	0.47673	0.72678	1.72716	2.69901	21.4791	∞
θ_2 (R)	0.17885	0.17885	0.17885	0.17885	0.17885	0.17885
θ_4 (R)	0.17885	0.19048	0.20379	0.20738	0.21303	0.21385
F_2 (ft)	394.112	388.389	382.075	380.414	377.831	377.460
F_4 (ft)	394.112	364.139	334.229	326.860	315.772	314.213
S_3 (ft)	1.6577	1.6678	1.6731	1.6753	1.6788	1.6793
ρ_3 (ft)	47.362	71.248	166.348	258.818	2045.72	∞
ψ_3 (R)	0.03500	0.02337	0.01006	0.00647	0.00082	0
θ_3 (R)	0.06985	0.05822	0.04491	0.04133	0.03568	0.03485
F_3 (ft)	676.905	1222.37	3701.34	6259.05	57318.5	∞
S_2 (ft)	10.0000	10.0276	10.0591	10.0676	10.0809	10.0829
S_4 (ft)	5.0000	4.9581	4.9110	4.8985	4.8789	4.8761
d (ft)	0	0.1549	0.3320	0.3797	0.4550	0.4659
R (ft)	89.283	89.316	89.378	89.394	89.419	89.422
α	0.5564	0.5924	0.6332	0.6442	0.6614	0.6639
ν_x	0.7500	0.7744	0.8013	0.8083	0.8193	0.8209
ν_z	0.8750	0.8447	0.8257	0.8234	0.8222	0.8223

where

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- K.E. = kinetic energy of proton
- γ = total energy of proton (in unit of m_0c^2)
- η = momentum of proton (in unit of m_0c)
- S_1 = length of orbit in main guiding magnet
- ρ_1 = radius of curvature of orbit in main guiding magnet
- ψ_1 = angle of turning of orbit in main guiding magnet
- B = magnetic field of main guiding magnet
- θ_2 = angle between orbit and normal to end of main guiding magnet at long straight sector
- θ_4 = angle between orbit and normal to end of main guiding magnet at short straight sector
- F_2 = focal length of end of main guiding magnet at long straight sector
- F_4 = focal length of end of main guiding magnet at short straight sector
- S_3 = half-length of orbit in DC magnet
- ρ_3 = radius of curvature of orbit in DC magnet
- ψ_3 = half angle of turning of orbit in DC magnet
- θ_3 = angle between orbit and normals to ends of DC magnet
- F_3 = focal length of ends of DC magnet
- S_2 = half-length of orbit in long straight sector
- S_4 = half-length of orbit in short straight sector
- d = distance between accelerated orbit and injection orbit at ends of main guiding magnet measured along the ends.
- R = equivalent radius of orbit
- α = momentum compaction
- ν_x = number of radial betatron oscillations per revolution
- ν_z = number of vertical betatron oscillations per revolution

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Since the magnets are built to follow the orbit at injection, the machine parameters are then:

$$\left\{ \begin{array}{l} \text{Length of main guiding magnet} = S_{10} = 53.465 \text{ ft.} \\ \text{Radius of main guiding magnet} = \rho_{10} = 71.248 \text{ ft.} \\ \text{Angles of main guiding magnet ends} = \theta_{20} = \theta_{40} = 0.17885 \text{ R.} \\ \text{Field of main guiding magnet at injection} = B_0 = 476.73 \text{ G.} \\ \text{Field of main guiding magnet at extraction} = B_f = 21.4791 \text{ kG.} \end{array} \right.$$

$$\left\{ \begin{array}{l} \text{Length of DC magnet} = 2 S_{30} = 3.3154 \text{ ft.} \\ \text{Radius of DC magnet} = \rho_{30} = 47.362 \text{ ft.} \\ \text{Angles of DC magnet ends} = \theta_{30} = 0.06985 \text{ R.} \\ \text{Field of DC magnet} = B_d = 717.16 \text{ G.} \end{array} \right.$$

$$\left\{ \begin{array}{l} \text{Length of long straight sector} = 2 S_{20} = 20.0 \text{ ft.} \\ \text{Length of short straight sector} = 2 S_{40} = 10.0 \text{ ft.} \\ \text{Equivalent radius of accelerator} = R_0 = 89.283 \text{ ft.} \end{array} \right.$$

Moreover, since this is not a scaling machine, its operation conditions change as the orbit moves radially away from the middle of the magnets. Thus, for example, at injection energy for an orbit which is 16 inches outside the central orbit (given in the above table) measured along the end of the main guiding magnet at the short straight sector, the operation condition is $\alpha = 0.5654$, $\nu_x = 0.7521$, $\nu_z = 0.8781$; and at extraction energy for an orbit 9 inches inside the central orbit (given in the table above) measured along the end of the main guiding magnet at the short straight sector, the operation condition is $\nu_x = 0.7989$, $\nu_z = 0.8210$.

The details of this work will be presented in an ANLAD report.

D. Remarks on Magnet Design for Argonne Synchrotron Martyn Foss

1. Effect of Curvature of Magnets on the Desired Uniformity of Field

It is clear that the curvature of the guide magnets can have no appreciable effect on the uniformity of field as long as the permeability of the iron is very large compared to unity. At very high fields this condition will not hold, and it is anticipated that slightly differently sized shimming holes in the iron may be required at the inside and outside of the magnet gap. The magnitude of the necessary correction will be determined in curved models.

//

2. Reduction of Saturation Effects in Fringing Fields

If the magnet gap height remained constant from end to end of a sector, there would be severe saturation of the iron at the ends. On the other hand, by supplying a flare to the gap, so that its height increases in the last foot as the magnet end is approached, the flux density in the end can be kept at a value very close to that existing in the bulk of the magnet. This technique will, therefore, make the fringing field almost independent of field strength.

3. Control of Fringing Field Across the Gap

The magnet is designed so that the fringing field has the same shape across the entire radial width of the gap. Under the usual methods of construction, the field at the center of the chamber is less dependent on the position of the azimuthal conductors than is the field near these conductors. In the present design, these conductors are so shaped that the equipotentials in their neighborhood are very similar to the equipotentials existing in the gap center.

In order to bring this shape into being in a manner consistent with easy engineering practice, the azimuthal conductors will also follow a flair as the magnet ends are approached, and a pair of radial iron lips will exist above and below the gap at a position just beyond the radial cross connections. This will cause the equipotentials to have a simple shape which is very closely the same across the entire gap width.

The chamber (and coils) will also be flared radially at the magnet ends. This not only facilitates beam extraction, but by putting the coils radially further away from the beam envelope, reduces any disturbances in the end focusing effects due to errors in conductor location at these regions.

4. Effect of Interturn Insulation in Coils

The ideal coil structure would consist of a solid bar of copper with uniform current density throughout. For practical reasons, one must compromise with individual conductors pierced with water holes and separated by layers of insulation. For 8 layers this results in field irregularities which fall off as $e^{-\frac{16\pi\Delta r}{g}}$ and $e^{-\frac{32\pi\Delta r}{g}}$, where Δr is the distance to the point under consideration and g is the gap height. With the insulation thickness under consideration, these irregularities will be of no consequence, particularly since the vertical and radial betatron oscillations will average out the effects.

Lower order effects, such as are due to a gross displacement of the coil bundle as a whole, do not die out so rapidly in the radial direction, and can cause displacement of the median plane. Corrective measures can be taken by not activating one or another of the conductors farthest removed from the vacuum chamber, but it is doubtful if such measures will have to be taken, if any reasonable care is used in the coil construction. Furthermore, about one inch of space next to the coils will not be available for ions (due to coil support structure and vacuum chamber wall) and in this distance many of the perturbations will have died out.

IV. MODEL MAGNET STUDIES

M. Foss, H. B. Phillips, D. McMillan, R. D. Orr

For reasons of economy in both the power supply and the magnet iron, it is desirable to operate with a high magnetic field, say 21 or 25 kilogauss. At these fields, however, the upper and lower magnet yokes are becoming saturated, causing the central field region to be depressed with respect to the field near the side walls of the vacuum chamber. With the poleless magnet design, there is, of course, due to symmetry, a low "n" region about the center of the chamber; because of adiabatic damping, the high-energy beam is compact and can be made to occupy this low "n" region. For beam extraction, however, it is desirable to have the "good" field occupy as much of the radial width of the chamber as possible.

We are attempting to so design the magnet that at high fields the gradient will be of an acceptably small value from one side of the chamber to the other; any errors that this procedure may cause at low field strength, or those which then exist due to eddy currents and residual fields, can be compensated by the use of auxiliary magnets (placed in four straight sections) embodying a multiplicity of windings so that corrective gradients can be introduced where necessary.

Magnetic measurements have been carried out on 29 different magnet configurations, using three different exciting coils. A typical magnet, either of Armco iron or type 1010 steel, is $8\frac{1}{2}$ inches high, 14 inches wide, and 12 inches long, with a gap 1 inch high x $6\frac{1}{2}$ inches wide. There have been variations made in the outside dimensions of different models, but the same gap size has been retained throughout. In most of the models used to date, the ends have been guarded by 3 inch thick laminated sections which are so constructed as to produce a field which is essentially flat, in the azimuthal direction, at the region midway between the ends; for example, at 23.7 kilogauss, the field varies only 2 gauss over an azimuthal distance of ± 1.2 inches.

Three different exciting coils have been used. The first was composed of 16 turns of flat conductors, each conductor having a copper cooling tube hard-soldered to one edge. The coil was made in two parts, the upper and lower halves being potted separately with an epoxy-type resin. Because

of a defect in a solder joint of a cooling tube, the coil failed at a high current and was destroyed. Coil #2 was made of 12 turns of 1/4 inch diameter (1/16 inch wall) copper tubing which had been squared by rolling; again the upper and lower parts were potted separately. Coil #3 consists of 12 turns of squared 1/4 inch diameter tubing as before; it is made as one unit (not in halves) and has more accurate spacing between conductors.

Very encouraging results in the attainment of an acceptably flat contour (in the radial direction, from coil to coil) at high field strengths have been obtained by boring holes in the upper and lower yokes parallel to and in the vicinity of the exciting coils. Due to the lack of a good analytical method for solving the non-linear problem involved, an empirical approach has been used, salted with intuition. A hole is drilled and its effect noted by field measurement. In the light of the result, additional holes are drilled or plugged and the effect measured. Figure 2 shows a typical set of holes, and Fig. 3 the effect of these holes, at various field strengths, in terms of the deviation from the value at the chamber center; the abscissae have been scaled up to full size. Without the holes, the flatness of field is acceptable up to 17,600 gauss; with the holes, it is good up to 21,900 gauss. (In order that the operating point shall not move to the resonances at $\nu_x = \nu_z = 1$, then n can differ from zero by not more than about 0.2, which, for the dimensions chosen, represents a gradient of 40 gauss in 10 inches, at 20 kilogauss.)

MODEL MAGNET WITH
FIELD CORRECTING HOLES
FIGURE 2

4-1-57

In the DC model made of 1010 steel (without shimming holes) the residual field at the chamber center is about 11 gauss, and 8.5 gauss near the coils. With the shimming holes, the dip is not quite so bad. It is anticipated that the eddy current effect in a laminated pulsed model will tend to counteract this dip - and, perhaps, over-correct it. In any case, it is expected that corrections will have to be applied at injection time, for if the fullest advantage is to be taken of the scheme to avoid hitting the back of the injector, one must be sure that ν_x and ν_z are very close to the desired values. With the small values of ν_x and ν_z to be used, it is only the values of $\int H d\ell$ which must be corrected around the orbit, so that reverse gradients may be introduced in small magnets located in the straight sections. Since residual field errors and eddy current effect will be static (for constant dH/dt), so also may be the corrections applied by these small magnets.

Since the machining of small diameter holes through a large solid block of steel is difficult to do accurately and is very time-consuming, a new magnet structure has been made. This magnet consists of 3/16 inch thick laminations which may be drilled individually, or in groups, using fixtures. Additional studies will be made using this drilling technique.

A second method of field flattening is now under preliminary investigation. This procedure utilizes auxiliary windings buried in the upper and lower magnet yokes, which windings carry a programmed current. The little data obtained so far indicate that adequate correction can indeed be achieved up to 22.6 kilogauss.

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A new search coil manipulator, designed by E. C. Berrill, has been completed. This device consists of a carriage which can be advanced along a precision rack in discrete steps by means of a driving motor. The stepping mechanism can also be locked so that the scan is continuous.

Several new search coils of various shapes and areas have been constructed, and a few modifications have been made in the recording servo fluxmeter. The principal change has been the addition of a remote control panel, by means of which the fluxmeter operator is enabled to control the search coil motion.

V. CONTROLS FOR MODEL MAGNET POWER SUPPLY

E. F. Frisby and J. F. Mech

Extensive use has been made of the generators, installed for powering the model magnets, since the time of the last report. No difficulty has been experienced in their operation and the control system has been adequate. One incident occurred in which the protective devices used to safeguard magnet operation were put to the test. A short circuit in a magnet winding was promptly interrupted by means of the interlock between the magnet and the generator.

The battery "filter" was placed in operation and has been used to filter the generator voltage, removing much of the "noise" produced by the generator.

A maintenance and operation log is being kept on the generator and on the battery.

Difficulties were experienced in making magnet field measurements, due to the necessity for high precision in the measurements and in the regulation of the generators. It was felt necessary to resort to some type of automatic control device to regulate the generator voltage or current to a fairly high degree of accuracy. The amount of power necessary for control was considerably more than was possible to produce by the usual electronic methods; hence, a design was sought which would incorporate a DC power supply continuously variable from 0 to 125 volts and capable of developing a current of 3 amperes. A controlled thyatron rectifier is such a device and was employed for the purpose. The DC voltage ripple was a possible source of error, but in practice the ripple was effectively eliminated due to the large time constants of the generator fields, and the rectifier was put into service without a filter. A DC voltage amplifier was then constructed and the regulating system was installed. The usual methods for system stabilization were employed. Control of either voltage or current was possible to the extent of one part in a thousand. This method of control proved satisfactory for some time.

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A need for greater precision arose, however, and with this need a difficulty due to the inherent characteristics of a thyatron rectifier became apparent. The model magnet study group is housed in a building containing considerable machinery operated on a common 440-volt power distribution system. Consequently the power lines contain many perturbations and are quite "noisy." Existing line voltage regulators would not eliminate this "noise" to the required degree. The noise was then directly coupled into the regulating system and, since this system was inherently a slow system, would appear on the output of the system somewhat reduced in magnitude.

A new system was then designed based on the use of an amplidyne and the exciting generator (Lincoln Welder) in a closed feedback loop. This part of the system replaced the controlled thyatron rectifier and was made to respond very rapidly. The use of feedback and the isolation of the amplidyne output from the line due to the inertia of its rotating parts completely eliminated the effect of line disturbances. System operation was somewhat faster and control was improved. Control of voltage and current is possible over the ranges 1 - 70 volts and 100 - 6000 amperes on the model magnet to the extent of one part in 5000.

Construction is proceeding on a device to reduce voltage ripple on the generator under varying voltage conditions. This will be a feedback system and is based on a high-powered electronic amplifier which will be capable of driving the low impedance of the generator and the model magnet. It is anticipated that voltage ripple will be reduced by a factor of 20 by means of this model.

Plans have been made and material is being procured for a switching system to pulse a laminated core model magnet utilizing the generators now in use as a power supply. The principal problem is to secure the necessary accuracy in timing to obtain a reproducible pulse of current in the magnet. It is now proposed to fire an ignitron to initiate the pulse and to open a circuit breaker after a predetermined interval. Accurate initial voltage control should insure that the current at this time will be reproducible. When the breaker is opened, the stored energy will be dissipated either into the generator or into a storage battery through unilateral conduction devices (silicon diodes). The proposed model will have a stored energy (ca. 25,000 joules) which is not excessive, so that the operation is not expected to be hazardous.

VI. INSTRUMENTATION FOR DYNAMIC MAGNET AND RADIO FREQUENCY STUDIES

Dean McMillan

After an initial survey of the problems involved in using oscilloscope techniques for pulsed model magnet measurements, it was apparent that these techniques are very laborious, time consuming and limited in accuracy to about 1.0%. A further investigation disclosed that there are several fast analogue to digital converter systems available commercially which can perform all the functions we will need. These functions are: to sample simultaneously at least four channels of analogue voltage signals at a rate of 1000 samples/sec/channel, convert these to digital information, put the digital values into a fast storage medium, and later read these values out on punched cards and/or punched tape for direct entry into any of the digital computers at Argonne. A conservative estimate of the available over-all analogue to digital accuracy of such a device is $\pm 0.25\%$ (maximum error at full scale).

With this type of equipment it is envisaged that it will be possible to get magnetic field data from several pick-up coils while at the same time monitoring such things as magnet voltage, current, etc. By requesting provisions for also putting in digital data from gated scalars, etc., it will also be possible to use this equipment to get very accurate measurements of the radio frequency program for the accelerating cavity. Of course, this equipment is also ideally suited for dynamic strain gauge measurements if the need should arise in connection with the mechanical design of structural components of the synchrotron.

After a thorough investigation of possible suppliers of such equipment, it was decided to purchase the machine indicated by block diagram in Fig. 4 from J. B. Rea Company, Inc. of Santa Monica, California. Delivery of this machine is expected by early August, 1957, which is just about the time it is expected that all the bugs will be out of the first pulsed model magnet and that the master oscillator for the RF cavity will be ready for initial trials.

In the years to come it is thought that this equipment will be very useful in testing the final magnet blocks for optimum distribution around the ring. It may also be useful in "tuning up" the synchrotron and in logging the synchrotron with the idea of following preventive maintenance procedures.

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VII. ACCELERATING VOLTAGE FREQUENCY CONTROL

John H. Martin

To attain the desired accuracy of tracking of the accelerating voltage frequency with respect to the guide field, it is believed that neither time nor the guide field current is sufficiently reliable as an index. Consequently, experiments are under way to employ the Kerr and the Faraday effects to produce a voltage which is directly proportional to the guide field.

This voltage will be used to control the bias current in the ferrite of the main inductance of the master oscillator to produce a first approximation to the desired frequency characteristic.

A second approximation will be made by applying a bias to the ferrite in a second inductance (in series with the capacitor of the oscillator), this bias being derived from a function generator also controlled by the field data derived from the Kerr-Faraday equipment.

A third correction will be supplied by a diode network again controlled by the guide field.

Analysis indicates that this scheme should give a frequency which is correct to about $\pm 0.03\%$.

The elaborate system proposed above is to afford some insurance of accurate tracking when the beam, for one reason or another, is too small to permit self-tracking techniques to be employed. Provision for this latter method will also be incorporated. Possibly the beam will be chopped at the pre-injector, to produce appropriate bunches in the synchrotron even at the beginning of its accelerative cycle.

It is planned to hold constant the phase of the particles with respect to the accelerating voltage by frequency control. Energy errors, detected by sensing the radial position of the ions, will be handled by control of the voltage amplitude. Such separate control systems will facilitate directing the particles onto internal targets and into the Piccioni jump target.

VIII. READOUT OF PULSED MAGNETIC GUIDE FIELD

John H. Martin

Certain steps have been made toward developing a fast and accurate method for reading out the instantaneous value of the pulsed guide field in the ring magnet for the proton accelerator. The idea is to produce a voltage output which is accurately related to the pulsed field strength. This signal will then be fed through a fast analogue computer containing a master oscillator which will produce the resonant frequency for particle acceleration with an accuracy of about $\pm 0.03\%$. In any event this signal will be needed at the beginning of each acceleration period until the particles are suitably bunched in their orbits. Following this, it may be better to employ self-tracking techniques in which signals from the beam itself are used to govern the frequency program. In the cases of malfunction of the accelerator, the master oscillator driven from the magnetic guide field will be used to develop the entire RF program.

The method under study involves the Faraday rotation of the plane of polarization of light passing parallel to the magnetic field in certain media. To the first approximation the angle of rotation is linearly related to the field strength. This rotation may be returned exactly to zero by passing the light also through a rotating Kerr cell with a suitably applied electric field. (In this case the term "rotating Kerr cell" is used to refer to the type of cell usually employing a crystal which rotates the plane of polarization of light as a function of an electric field applied to the crystal in the same direction as the direction of propagation of the light.) Again,

to a first approximation the angle of rotation is proportional to the applied electric field. Thus, the Kerr cell voltage necessary for a net rotation of zero should be proportional, to a first approximation, to the Faraday cell magnetic field strength.

To obtain the necessary stability and accuracy of about $\pm 0.01\%$ the plan now under consideration involves splitting a filtered beam of light from a single source to follow two nearly identical paths. Along one path the Kerr rotation will be counterclockwise and the Faraday rotation will be clockwise. The other path will be the same except that the directions of rotation will be reversed. The Faraday cells will be in immediately adjacent magnetic fields and the rotating Kerr cells will have the same applied voltages. The light intensity in each path will be modulated by a Kerr cell chopper operating at a few megacycles per second. One Kerr cell chopper will be 180° out of phase with the other. The cathode of a single photomultiplier will be illuminated with the light from the final optical analyzers of each path. The photomultiplier signal will be pulsed at twice the Kerr cell chopper frequency and will contain no fundamental component if the contributions from each path are balanced. The photomultiplier signal will be filtered to pass the fundamental. This signal plus one from the Kerr cell chopper will provide the magnitude and sense information for servoing the rotating Kerr cell voltage to equal light intensity at the photomultiplier from each path.

From investigations already made it seems that the best rotating Kerr cell material is either z-cut ammonium dihydrogen phosphate or potassium dihydrogen phosphate crystal slabs. They may also be the best for wide aperture Kerr cell choppers. A single slab can produce about 90° of rotation before danger of voltage breakdown becomes serious.

Investigations for a suitable Faraday cell material have dealt mostly with three types of dense lead glass. Verdet constant values ranging from 41×10^{-3} to 117×10^{-3} min per cm per gauss have been obtained. A nitrobenzene sample yielded 22×10^{-3} min per cm per gauss. The most dense glass contained 65% lead silicate and a 1.16-cm thick sample produced a light intensity loss of 65% at a wavelength of 4358 angstroms, where the measurements were made.

The values of the magnetic field to be measured range from 500 to 22,000 gauss. Studies are now under way to understand more clearly the properties of the materials which may be used, e.g., temperature effects, proximity to absorption bands, linearity, magnetostriction, strains and birefringence. It is not yet clear as to the total amount of rotation which may be necessary to permit the desired accuracy. This will depend upon optical, electrical and mechanical stability and upon the effectiveness of RF shielding.

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IX. MEASUREMENTS OF THE PROPERTIES OF FERRITES

John Dawson

At the end of the summer the ferrite Q measurements at high flux densities were complete only for the Philips IV-H ferrite. These measurements did not seem to be reliable, so the work was repeated. At this time the measuring technique was revised, and subsequent investigation revealed that the previous data were not of sufficient accuracy. When the measurements of the Philips IV-H parameters were completed, a redesign of the ferrite driver to incorporate a 4-1000A was undertaken to provide the higher power necessary to test the Steatit-Magnesia C 131/5 rings. At the close of the Steatit-Magnesia C 131/5 tests, all the information necessary for the selection of ferrite had been obtained.

After the ferrite tests were concluded, some analytical work was done on the problems of biasing the oscillator and cavity. This resulted in a two-inductor method of providing the oscillator program, and a transient technique for biasing the cavity.

Recently a permanent ferrite testing installation has been designed. This provides 1,000 amperes of DC for biasing the ferrite, and about 200 watts of RF power to drive the rings. The unit is bandswitched from 2-18 mc in three bands. The permanent ferrite testing installation is currently under construction and should be ready for operation about June 1, 1957.

X. R. F. MASTER OSCILLATOR

Lachman Wadhwa

Since the permeability vs magnet field characteristics of the magnetic ferrites seemed to present some attractive possibilities for realizing the required radio frequency program for the Argonne 12.5-Bev Proton Synchrotron, it was decided to test a few of the available ferrites with a view to selecting a suitable one having the desirable characteristics. The ferrites tested were: Philips IV-H and IV-A, General Ceramics type G, and Allen Bradley type R-01. Of these four types, Phillips IV-H was found to be quite suitable because it has a reasonably high initial permeability and is moderately soft but not too soft to be very "lossy." Also, the frequency range from about 2.1 Mc to 6.7 Mc can be obtained by application of not too high a magnetic bias.

A model ferrite-loaded RF oscillator was designed and built using Philips IV-H ferrites in the form of toroids as cores for the tank circuit inductance.

Experimental observations of this test oscillator under biased conditions indicated that to obtain the desired frequency program with a certain

minimum tank circuit Q (for reliable functioning of the oscillator) the ferrites had to be operated with a certain initial fixed bias H_0 and that the tank circuit had to contain an auxiliary inductance.

An analytical approach was made in an attempt to find a possible method for simulating the desired frequency program. The details of this theoretical investigation, which are contained in the Internal Report LW-1, dated February 15, 1957, may be briefly summarized thus:

In order to realize the desired frequency program of Fig. 5, the oscillator tank circuit of Fig. 6 is visualized, where L_0 is

FIG. 5 DESIRED FREQUENCY PROGRAM

FIG. 6 OSCILLATOR TANK CIRCUIT

a fixed inductor, L is a biased ferrite inductor and C is a fixed capacitor.

To determine the magnitudes of various parameters of the tank circuit the boundary conditions were arbitrarily chosen at the start of the acceleration cycle, when $f = f_0$, $\left. \frac{df}{dt} \right|_{t=0} = \lambda$ at $H = H_0$, where H is the bias on the ferrite and τ is a normalized time variable, and a point on the knee where $f = f_1$ at $\tau = \tau_1$ (Fig. 5). If the biasing field be assumed a linear function of time, then the oscillator frequency can be made to fit the desired frequency curve during the initial part of the program, but at the end of the acceleration cycle the deviation of oscillator frequency from the desired frequency will be very large. To satisfy the final boundary condition a third controllable parameter is needed. This suggests the employment of a biasing field of the form

$$H = H_m (1 - e^{-\gamma t}) + H_0$$

instead of the field which is a linear function of time. By proper choice of γ a close fit can be realized. In fact, with this exponential bias program, calculations show that the maximum deviation of the theoretical curve from the desired curve is about +8% and occurs a little before the knee of the curve is reached; for the major portion of the acceleration cycle

the fit is closer than 1%. The deviation, which is monotonic, from the desired program can be easily compensated to within 0.01% by means of some corrective network, for example, a multipoint diode switching network.

In order to check the frequency stability of the oscillator, a constant temperature enclosure was built; the ferrite-loaded tank and the associated oscillator circuit were housed in it. The temperature of the enclosure was maintained to within $\pm 0.05^\circ \text{C}$ by circulating temperature-regulated water through it.

Preliminary observations indicated that the oscillator had a frequency drift of about -0.054% per hour (warm up time of about 15 minutes). This is probably due, in great measure, to the poor temperature regulation in the constant temperature water circulator.

It has not been possible to make any reliable observations of the frequency stability under bias conditions due to the lack of adequately well-regulated power supply for obtaining bias currents. The need for a low voltage-high current (2 v - 10 amp) constant current supply regulated to within 0.05% or better was acutely felt. Since such power supplies are not commercially available it has been decided to build one.

An all-transistor current regulator (4 volts, 5 amperes) has first been designed and built, and the preliminary tests on the regulation accuracy of this device seem very encouraging. The current-handling capability will be increased to 10 amperes as soon as the required components are received.

It is expected that shortly some important and conclusive results will be obtained from the tests on the frequency stability of the oscillator.

XI. VIDEO POWER AMPLIFIER AND GENERAL INSTRUMENTATION

Henry A. Kampf

A. Power Amplifier

The prototype video power amplifier to drive the accelerator cavity is in the process of being designed, and the low level stages are being mechanically laid out. Most of the power supplies for the amplifier will be built locally; however, the construction of the power supply for the final stage probably will be contracted to some company specializing in this type of power supply design.

The performance of the power amplifier must be well defined in phase and gain versus frequency characteristics to insure a signal of the proper frequency, amplitude and phase at the accelerating gap of the

synchrotron. Two instruments are being constructed which will aid this part of the design. The first is a phase shifter of high accuracy which, when used with a suitable oscillator, will measure phase shift with an accuracy of better than ± 1 degree throughout the operating range of the power amplifier. The other instrument is a variable frequency signal generator whose frequency is controlled by a function generator to be within 1% of the actual frequency sweep of the synchrotron. It is felt that this frequency program should be more than adequate to describe the dynamic transfer characteristics of the power amplifier. The dynamic transfer characteristic must be known before the power amplifier can be designed into a servo-loop.

B. Phase Measurements

These phase measurements are made by using a precise phase shifter operating at audio frequencies. The RF phase shift is found by beating an oscillator against the RF signal to produce an audio signal. This beating oscillator frequency can be locked in with a control loop to keep the audio beat frequency stable enough to make phase measurements. Since the phase relationship of the RF signal is maintained after mixing, the audio beat frequency signal will exhibit the same phase shift as the RF signal. Then, two readings of phase will be made, one to calibrate the equipment on a reference signal and the second to get the relative phase shift.

Part of this equipment is built and operating. The audio phase shifter using an oscilloscope and an oscilloscope null detector, has an accuracy of better than ± 0.5 degree. The audio frequency phase shifter uses an autosyn resolver connected as a phase shifter. The position of the resolver shaft determines the phase shift of the signal passing through the instrument, and it is this shaft which is used to tune for a null reading.

C. Dynamic Gain vs Frequency Measurements

A ferrite-controlled transistor oscillator has been designed and built to furnish a sweep frequency signal from 2.2 to 7.3 mc. The output frequency is controlled by a DC input voltage. The 0 to 2-volt DC input signal is amplified by a two-stage, push-pull transistor amplifier and fed to the bias coil of the ferrite-tuned oscillator tank.

The oscillator is of a two-stage feedback type employing high-frequency transistors. The power for the oscillator and its control amplifiers is supplied by a regulated power supply using power transistors and zener voltage reference diodes. It will supply 30 volts at 300 milliamperes with 0.5% regulation. The output stage is a gated cathode follower which has a frequency calibration tank in the cathode circuit.

The instrument used to drive this sweep oscillator at the desired frequency program is a ten-point function generator. An examination of the transfer characteristics of the oscillator and the theoretical curve of $f(t)$ desired for the accelerating gap showed that a 9-point function (approximation by eight straight lines) would be sufficient to give a frequency program within 1% of the desired program.

The function generator consists of a linear sawtooth oscillator operating at a controlled repetition rate of from 7 to 30 cycles per minute to allow testing on both sides of the desired rate of 15 per minute. This linear voltage is then shaped into the calculated curve required for the proper frequency program by a feedback DC amplifier and biased diodes. The DC amplifier has a gain of 500 and a bandpass which is more than adequate for this application.

Two additional circuits are included in this instrument to provide variable delayed output pulses to facilitate examination of specific points along the sweep.

D. Vacuum Gauges

Two vacuum gauge systems were designed. A six-channel ion gauge system was adapted from a commercial design to allow six ion gauges and six thermocouple gauges to be used instead of just one.

Another 24-gauge system has been constructed and is now being checked and calibrated. This system can use as many as 24 ion gauges and 12 thermocouple gauges; it provides for automatic, unattended recording of all 24 ion gauges. It will automatically switch from one to another at a rate adjustable from one per minute to one per hour. The range of the ion gauge meter circuit is automatically set to be between 0.1 and 0.9 of full scale (except on the end ranges). The output from the electrometer tube and DC amplifier is automatically zeroed every five minutes by a zero-seeking servo-amplifier. The time required for zeroing is approximately 10 seconds. If, because of some component failure, this is not accomplished, an additional indication is placed on the record by an error-sensing circuit and an error lamp lights up on the panel.

In addition to this, the system includes regulated power supplies and a high pressure safety relay.

E. Peaking Strip Equipment

Accurate timing pulses developed from the rising field of the synchrotron guide magnet are required to time other pieces of equipment, such as RF sweep starting time, etc. In order to build peaking strips to do this, special nickel-iron alloys were purchased from four different

manufacturers. These alloys have a very high (dB/dH) characteristic which enables them to change from magnetic saturation in one direction to magnetic saturation in the other direction very quickly. It is also necessary to have a very small cross-sectional area to restrict eddy current effects. The thinnest sample of these alloys is a ribbon 0.000125 inch thick.

In order to secure the largest output signal from the sample, it is necessary to have the magnetic field parallel to the direction of rolling grain and to have the sample under tension. A machine was built to do this and a signal increase of about 3 to 1 was observed for the correct stress, which was about 40,000 lb/in.². It is felt that an additional increase of signal can be obtained by hydrogen annealing the sample before applying the stress, since this would eliminate past stress history that the sample may have experienced. An audio frequency, 15-watt driver was built to drive the test coils. The driver can supply this power to any impedance from 0.7 to 500 ohms.

F. AC Voltage Regulation Measurement

A method was devised for measuring small changes of AC line voltages accurately. The problem came up when it was necessary to check the regulating efficiency of an AC line voltage regulator. This scheme uses a DC voltage and a clipping diode. The DC voltage on the clipping diode is varied until only the very peak of the AC waveform is allowed to pass on to the oscilloscope. Further adjustment of the DC voltage gives a DC voltage exactly equal to the peak of the AC wave. The DC voltage is then read by a meter at high accuracy. Two such readings, one without line load and one with the line load, are required to find the line regulation. The maximum practical limit of accuracy is about 0.2% per centimeter of oscilloscope presentation. Any further increase of gain only shows up the peak to peak variations of regulation which make the determination of the actual AC peak voltage difficult.

XII. MODEL R. F. CAVITY DESIGN

John H. Martin

A decision has been made to place the two R.F. cavities for accelerating the protons in the ring magnet into the same long straight section that contains the system for inflecting the particles from the linac. This arrangement results in a decrease in the total space required for cavities as compared to what it would be if four cavities were located in four different short straight sections. This, also, results in a considerable reduction in the complexity of the driving system for the R.F. cavities. It has become possible to place the accelerating cavities in the same straight section with the inflector system by dividing the latter into two parts with the cavities functioning as a drift space for the particles on their way in.

The present plan calls for the two cavities to be closely spaced and driven in parallel and in phase. Toward testing this method a model cavity, electrically and magnetically the equivalent of one of these, has been designed and is ready for construction. Arrangements are being completed for the purchase of 980 kilograms of Type Keraperm C131/5 ferrite from Steatit-Magnesia Corp. of Porz, Germany, for use in this model. Plans are completed for operating this cavity under full power conditions with a prototype of the R.F. driver which is expected to be used in the final machine. Plans are completed for testing both a single-turn method as well as a multi-turn method of biasing the ferrite.

The preliminary program for testing ferrites has now been completed. It considered five different ferrites from four different manufacturers as probable suppliers. For the reasons of high R.F. losses and/or high dielectric constant, having at the same time suitable permeability characteristics, all types were eliminated except two, viz., Type IV-H by Philips and Type Keraperm 131/5 by Steatit-Magnesia. The latter was chosen because of a considerably speedier delivery program and because of a 15% saving on the space required for the necessary quantity of ferrite. The cost of the total quantity of ferrite needed will be almost exactly the same for either type.

In the model, twelve rectangular frames of ferrite will be fabricated, each from twelve rectangular slabs, 4 cm thick and 10 cm wide. Each frame will have a window size of 36 x 112 cm. Details of the calculations on the final double cavity employing twenty-four such frames are in Report ANLAD-34. In this it can be seen that an R.F. magnetic flux density of 90 to 27 gauss is chosen in the frequency range of 2.1 to 7 megacycles per second (fourth harmonic of the orbital frequency). For producing the required 16,000 peak R.F. volts on the double cavity, a ferrite flux cross section of 960 cm² is required. This calls for about 1500 kilograms of ferrite when the frame size is as mentioned above. The amount of R.F. power for driving such a double cavity would range from 65 to 74 kilowatts. If the two halves of the double cavity are connected in parallel, the load impedance at resonance would range from about 430 to 625 ohms. The amount of DC bias required to carry the ferrite permeability through the required program would range from 800 to 8000 ampere-turns. The calculated conditions as to cooling, thermal stress, mechanical strength, etc. appear to be within safe limits. The model of one of the double cavities is expected to test the above.

XIII. MAGNET POWER SUPPLY

E. F. Frisby

Studies have been made on power supply requirements for various magnet parameters and guide field intensities appropriate for 12.5-Bev protons. When the maximum guide field flux density varies from 20 kilogauss to 26 kilogauss, the calculated peak power requirements imposed

upon the ring magnet excitation equipment decrease over the flux density range of 20 kG to 23 kG and then increase as the flux density is changed from 23 kG to 26 kG. Maximum ampere-turn requirements and average power requirements both rise over the increasing range of flux densities, while the stored energy decreases. The relationship of these calculated values is shown in the following table.

<u>Flux Density (Kilogauss)</u>	<u>Peak Power (Kilowatts)</u>	<u>Average Power (Kilowatts)</u>	<u>Ampere- Turns (NI)</u>	<u>Stored Energy (Kilojoules)</u>
20	131,000	3,800	350,000	54,200
21	127,000	3,900	355,000	51,100
22	125,000	4,000	365,000	50,500
23	124,000	4,400	381,000	49,100
24	125,000	4,900	406,000	47,700
25	126,000	5,600	436,000	46,400
26	130,000	6,700	479,000	45,100

An investigation into the estimated cost for the ring magnet power supply under the different flux density considerations indicates that the purchase cost would be slightly less at the higher field intensities, the difference being about 10 per cent of the higher cost. However, the cost of operating power would increase with increased flux densities. From a power supply standpoint, at the present time, the optimum value for maximum flux density appears to be between 21 and 22 kilogauss.

Some analyses have been made concerning the most suitable type of power supply system for meeting the requirements of ring magnet excitation. These requirements are unique for many reasons, among which are:

- (a) The load is pulsed and the ratio of the peak power to the mean power is high.
- (b) The load is highly inductive.
- (c) The energy flow must be reversed as quickly as possible at peak load.
- (d) Succeeding pulse patterns must be reproduced independently of variations in frequency and voltage of the incoming power supply line.
- (e) Particle injection and ejection may require a specially controlled guide field at the beginning and end of the power pulse.

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Taking the above factors into consideration, it appears that mercury-arc converters would be best suited for conversion equipment under a wide range of operating conditions. Associated with the converters would be other main equipment components, such as: wound rotor drive motor for supplying system and load losses, flywheel for storing energy mechanically, and alternator for supplying pulsed AC power.

Efforts in determining the type of converter circuit to be utilized have required some consideration of current and voltage requirements, permissible amount of ripple in DC voltage, and the simplicity and reliability of the system as a whole. Since there are voltage and current limitations on individual rectifier tanks, it follows that for high voltages more tanks have to be connected in cascade (series) and for high currents more tanks must be run in parallel. The amount of ripple permitted in the DC voltage will determine the number of phases of alternating current to be rectified. Also, the reliability in service and the simplicity of circuitry depend on the number of tanks utilized and the manner in which the rectifier units are connected. Several connection schemes have been analyzed for adequacy in satisfying the operating requirements. One such scheme is shown in Fig. 7. This scheme has the advantage of having the DC power supplied at four successive locations around the ring magnet, and the midpoint of the magnet coil between power supply locations being grounded through current limiting resistors. This connection makes possible an operational potential between coil and ground of about one-eighth of the total accumulated terminal voltage. If 32 turns were used in the magnet coil, the accumulated terminal voltage (at full load) will be slightly less than 10 kv, and the nominal voltage between coil and ground would be less than 1.25 kv.

The alternators in this scheme are mounted in tandem on the same shaft, which means that the AC power for all rectifying units can be held mechanically to a definite phase relationship, and space ripple can be avoided in the excitation current of the magnet coil.

Another advantage of using four alternators is that, in the event of failure on either an alternator or a rectifying unit, the accelerator could be operated at half power with only two alternators and rectifier units while repairs on the faulty equipment are being made.

Among the other connection schemes being considered is a scheme utilizing phase-shifting transformers between the alternators and the rectifying units. Also, a scheme which would utilize two way rectification is being studied. The final parameters of the ring magnet will be the main determining factor in the selection of the most appropriate power supply system.

FIGURE 7

XIV.. MECHANICAL DESIGN OF MAGNET

Robert Lykken

During the past few months efforts have been made to determine the most feasible methods of fabrication and assembly of the ring magnet, vacuum chamber, and coils. The principal problems involved in the designs will be considered separately with the solutions that at present seem most practical.

(1) It is necessary to laminate the magnet to reduce eddy currents, while at the same time it is desirable to have as high a proportion of steel to insulation as is possible. It is also necessary to fasten all laminations together rigidly. Studies of available machining equipment, tolerances of commercial rolling practice, and experiments with insulations and adhesives lead to the following design and laminating technique. The magnet will be made of S.A.E. 1010 Steel obtained from the mill as hot-rolled, flattened-annealed, 1/2 inch thick plates. These will then be edge-milled to size and any holes necessary will be punched, locating from the finished edge. The plates will then pass through a Hill-Acme sheet grinder which will grind each plate flat on both sides while removing all scale and drag from the punching operation.

The next operation is the laminating to make a slab of about 15 plates. The plates will be placed in a fixture, alternating with insulating sheets of fibre-glass cloth impregnated with epoxy-resin. The fixture will very accurately align the plates and provide the necessary laminating pressure for the curing cycle.

A method of curing from the inside out by induction heating allows the resin to flow evenly before curing, so that the final slab is reasonably flat and each plate insulated with from 0.005 inch to 0.010 inch spacing. The bond between plates should be at least 1000 psi in shear.

(2) Referring to Fig. 8 it is obvious that a magnet octant must be made in subassemblies both for ease in handling and to make it possible to assemble the coils and vacuum chamber. If the magnet is divided into a top and bottom pole and an inner and outer yoke as shown in Fig. 9, it is obvious that very little steel will be wasted in scrap, and final finishing of the gap surfaces can be in the direction of the lamination, thus reducing the number of shorts due to machining.

Calculations based on the dimensions shown in Fig. 9 indicate that a division of the upper and lower poles into 9 blocks, each about 5.9 feet in azimuthal length, will give blocks weighing about 24.5 tons each. The upper and lower blocks will be identical except for the weldments and lifting gear on the exterior surfaces.

TYPICAL SECTION OF MAGNET
FIGURE 9

In order to obtain the necessary arc these blocks will be tapered with an included angle of 5° each. This taper will be obtained by rough machining the faces of the slab, after laminating (see paragraph 1), to a $1/2^\circ$ included angle. Ten slabs will then be stacked in a fixture with the necessary insulation and room-temperature cured epoxy adhesive between slabs to form one block. This fixture will accurately locate and hold the slabs during curing and during the welding of steel straps on the exterior surfaces, as shown in Fig. 9. The plates will be stacked so that alternate plates project $1/2$ inch on the exterior surfaces, allowing testing and clearing of shorts after assembly. The tapered faces of the blocks will then be finish machined to close tolerance. It is estimated that the plates can be aligned so closely on the gap edges that machining of the gap surface may not be necessary. A full size model of a slab is now being built to study this question further, as well as to perfect the laminating technique.

Variations of the above technique will be necessary for the end blocks of each octant in order to provide a different face angle and the necessary bell-mouthing of the gap both horizontally and vertically.

(3) After the blocks are machined to size they will be preassembled for match marking or doweling the top and bottom poles and inner and outer yokes. On arrival at the site the block assemblies of top, bottom and side pieces will be tested for magnetic characteristics and their position in the ring determined to randomize variations.

The lower poles will be brought into the ring and located on a supporting girder. Small jacks between block and girder will be used for leveling the blocks. A compressible insulation will be used between blocks to seal up the necessary gap due to machining tolerances. When an entire octant of lower poles is properly level and accurately aligned radially, tie beams will be welded on the bottoms and sides to effectively produce a monolithic structure.

The gap surface will then be covered with a layer of 0.002 inch stainless steel in short lengths which are insulated from the laminations by fibre-glass cloth and epoxy resin to seal the entire lower gap face and provide a good clean vacuum surface.

The next step may then be to bring in the potted coil assemblies so that their tension straps (as shown in Fig. 10) may be properly located in the slots provided in the side yoke blocks. These side yokes will then be placed and accurately located, fastened together and to the lower poles by the weldments previously mentioned. The coil assemblies will then be accurately located and the lower seal between the inner coil wall and the bottom gap surface installed.

SECTION THRU MAGNET GAP

FIGURE 10

The upper poles will now be brought in and accurately positioned. They will be insulated from each other and sealed as previously described. The upper blocks will be fastened together to form a monolithic octant length beam with appropriate weldments in such a manner as to allow their dis-assembly should it be necessary for coil replacement or repair.

The upper pole will now be lifted vertically 24 inches or 30 inches by hydraulic cylinders located along its length. When raised, the upper gap surface will be sealed with stainless wallpaper as was the lower surface and the gasket joint installed to seal the roof to the side walls when the upper pole is lowered into place.

A. Vacuum Chamber Studies

A vacuum chamber designed to fit the proposed magnet cross section (see Fig. 10), the required inside dimensions of this vacuum chamber being 32 inches wide by $5\frac{1}{4}$ inches high, rules out the use of a separate, self-supporting thick-walled chamber. Such a chamber would require an allowance of one inch per side for wall thickness and deflection, reducing the usable gap height to $3\frac{3}{4}$ inches.

This magnet cross section combined with the proposed method of laminating, presents a ready-made vacuum chamber, utilizing the magnet steel for strength and the new epoxy resins for their great adhesive qualities and low out-gassing rates.

A test chamber, having laminated top and bottom plates, has been built in this manner. The side numbers are simply steel bar stock with a gasket groove milled into two opposite surfaces. The laminations were allowed to open in several places in order to test the ability of a wall-papered stainless steel liner to seal off any leaks between laminations. This chamber has been pumped down to a better than 1×10^{-6} mm Hg, indicating such a technique is feasible and reducing the outgassing rate of exposed gasket and epoxy to a minimum.

The present choice of magnet gap dimensions is predicted on the theory that the above magnet assembly with the stainless steel lining can act as the high vacuum container. If this technique should fail in further test assemblies, then a thin-walled inner chamber (shown in Fig. 10) can be constructed and supported by a rough vacuum maintained in the above chamber formed by the magnet. The inner chamber will be constructed of fiber-glass and epoxy, and will be lined with 0.002-inch stainless steel in much the same manner as CERN'S.

Various other chamber designs have been proposed; some have been modeled. Basically they require multiple gasket joints with "Tee" or "Cross" joints between blocks. Modifications of these designs are possible,

but they require considerably more machining and induce systematic irregularities in the field. Should some unforeseen difficulty with the present design arise, these offer alternative solutions.

Experiments have been made with various epoxy-resin formulations and fiber-glass fabrication techniques to obtain the best combination and to learn the new skills necessary in such work. Several 3 foot long fiber-glass and epoxy chambers about 9 inches by $1\frac{1}{2}$ inches in cross section have been made with walls thick enough to withstand atmospheric pressure without collapsing; they have been pumped down to pressures as low as 4×10^{-6} mm of Hg. These chambers have inner areas of exposed epoxy of approximately 6 sq ft, which represents a much larger area of epoxy than would be exposed in a stainless steel-lined chamber.

Additional experimental work is now in progress to improve our techniques and find the best epoxies for vacuum characteristics and strength. Another steel-lined chamber is being fabricated to further test the feasibility of this design.

XV. MAGNET COIL DESIGN

W. A. Siljander

The coil will consist of 36 water-cooled conductors along each side of the gap (see Fig. 11 for cross section). The outside layers will be utilized for field corrections so that there will be 32 turns normally energized. At either end will be water-cooled jumpers bolted on the side conductors and passing equally over the top and bottom of the gap. The side conductors will be potted separately to the point of end connection (see Fig. 12 for side coil assembly). The end jumper conductors will be potted as an assembly. The whole coil assembly consists of the two sides and the four ends (see Fig. 13).

It is the intention to hold the coil assembly securely. The sides will be tied to the yokes by means of stainless steel cables embedded in the coil sides and passing to the outside of the magnet over and under the side yoke blocks through slots cut in the laminations. There they will be tension-fastened in such manner that they can be re-tensioned periodically as required. On installation into the magnet the ends will be shimmed with insulating material, then epoxy-impregnated so that the ends will be held securely between the magnet ends and the separately mounted magnet end guard.

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COIL CROSS SECTION
AFTER POTTING
 FIGURE II

PLAN VIEW

SIDE ELEVATION

COIL ASSEMBLY
FIGURE 13

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XVI. TEST VACUUM SYSTEMS

John Moenich, Richard Trcka, Kenneth Weberg

The need for vacuum pumping stations to test models of various vacuum chamber designs and to back up and start large volume pumps for evacuating the chamber of the accelerator necessitated considerable activity in this department.

A "Veeco" portable high vacuum station, Model VS-9, was purchased in 1956. It contains a 2-inch, air-cooled, oil diffusion pump backed by a 5-cfm capacity mechanical pump. Auxiliary equipment includes a liquid nitrogen refrigerant-type cold trap and a rack-mounting ionization gauge and 2-station thermocouple gauge control. Circuit breakers and pilot lights are provided for diffusion pumps and mechanical pump protection.

A pumping station containing a type MCF-700, 6-inch oil diffusion pump, backed by a 13 cfm Welch mechanical pump has been designed and built. Its auxiliary equipment includes a liquid nitrogen refrigerant-type cold trap, and a rack mounting 6-station ionization gauge and 6-station thermocouple gauge control. Water flow, thermal and vacuum interlock safety switches are installed for pump protection.

Another pumping station consists of an Evapor-ion pump, a 2-inch air-cooled oil diffusion pump and a 13-cfm Welch mechanical pump, plus related controls and valves. The primary purpose of the diffusion pump is to lower the pressure in the Evapor-ion pump to the point where it can be started. Since the Evapor-ion pump need not be backed up after it is started, as diffusion pumps do, the station is so designed that once the Evapor-ion pump is started the rest of the system can be utilized for pumping elsewhere. It is with this Evapor-ion pumping station that we hope to determine the feasibility of using Evapor-ion pumps to evacuate the chamber of the accelerator.

The Evapor-ion pump is a getter type pump. It is being considered because of its many advantages over the diffusion pumps. The Evapor-ion pump has no refrigerated baffle, no compressor, no forepumps, and no automatic valves. The total power input is a few hundred watts as compared to two or three thousand for a comparable diffusion pump. If trouble occurs in the Evapor-ion pump there is no working fluid that needs to cool down and no trap that needs to warm up. Maintenance periods are short.

Extensive tests by Brookhaven National Laboratory with the Evapor-ion pump resulted in recommended changes for more reliable operation. These changes were incorporated into our pump in the latter part of December 1956. Continued failure of the feeding system to function properly resulted in minor changes in feed spring and annealer tube design before satisfactory operation was achieved.

One of the changes in the Evapor-ion pump recommended by Brookhaven was the elimination of the primer circuit. This circuit cuts down considerably the starting time of the pump. The increased maintenance due to frequent shorting brought about by the excessive amounts of titanium evaporated by the primer more than offset its one advantage. Elimination of this primer lowered the starting pressure to the point where highly efficient and costly "Roots" blower pumps or diffusion pumps are required. This fact plus feeding problems outlined above have resulted in considerable thought as to the possibility of a redesign to offset the above problems. Present thought indicates such design is feasible with very little change in the existing pump.

A test chamber is now being designed. It will consist of an 8-inch diameter steel pipe, 24 feet long, and suitably flanged to mount to the Evapor-ion pump. Rough pumping of this chamber will be possible from either end to shorten pump down time to the starting pressure of the Evapor-ion pump. Thermocouple and ionization gauges periodically arranged along the length of the tube will indicate pressure gradients at various stages of pump down. From this system outgassing rates, pump down times and pump characteristics under various conditions will be determined.

Efforts are being made to automatize the system where necessary. Two circuits have been added to the system. One of these circuits takes advantage of the surge of post current that occurs during a glow discharge, caused by too high a pressure in the pump. This surge trips a relay, cutting off power to the pump. With such a safety device the pump can be left unattended. It is quite evident that restoration back into operation can be automatic also. The second circuit in operation at present maintains the chamber pressure at some predetermined level.

To save time in locating minute leaks in chambers and other evacuated apparatus a Mass Spectrometer Leak Detector, model MS-8, made by the Vacuum Electronic Engineering Company, was purchased in late 1956. For the same purpose, a General Electric type H-1 freon leak detector has also been acquired.

XVII. SOIL STUDIES

D. Deere (U of Illinois), Richard Trcka

The test pile program recently carried out at the proposed site for the Particle Accelerator gave information regarding the driving resistance encountered by four 10-inch diameter steel pipe piles and three 12 BP53 steel H-piles, as well as the load-settlement and time-settlement relationships under various static loads of four piles driven to varying resistances. Although hard driving resistances were encountered (from 40 to 100 blows per ft), both the thin-wall pipe (0.279 in.) and the thick-wall pipe (0.365 in.) could

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be driven with no damage to the pile other than slight buckling at the top. The H-piles also encountered some buckling at the top and cover plates had to be welded to the upper 2 ft of the web to prevent excessive buckling. The pipe piles were driven to depths ranging from 55 to 74 ft and the H-piles from 76 ft to 95 ft.

The load tests showed that the piles driven to high resistances settled only slightly, even under the 100-ton load (approximately $1/4$ in.), and that most of that was recovered elastically upon unloading. On the other hand, piles driven to lower resistances (27 and 41 blows per ft) could be expected to settle 1 in. or more under the 80-ton load and break into the ground several inches under higher loads. These same piles showed very small settlements under loads less than 60 tons. The pile driven to 27 blows per ft was tested with a static load of 50 tons for a 3-month period. The time-settlement relationship was found to be a straight line on a semi-logarithmic plot, i.e., a decreasing rate of settlement with time. A similar relationship was found under the shorter term tests. This relationship is used in predicting future settlements by extrapolation.

On the basis of the results of the test pile program it is recommended that a pile foundation be considered for supporting the ring magnet, Linac injector, and proton deflecting magnets. Ten-inch diameter pipe piles (0.279 in. wall thickness) are recommended with a design load of 30 tons per pile. The piles should be driven with a flat point and with a hammer having 26,000 ft lb of energy to a resistance of 50 blows per ft for four consecutive feet. The average pile length will be of the order of 60 ft. The expected settlements are approximately 90 mils in 2 weeks, an additional 14 mils at the end of 6 months, 3 mils the next 6 months and 5 mils the second year.

The concrete shielding in the Meson Experimental Area should also be pile-supported to prevent horizontal and vertical displacements of the piles supporting the ring magnet when the shielding is moved around. Steel H-piles may be considered as well as pipe piles.

Additional borings will be needed for checking the subsoil conditions at various critical points when the final layout of the magnet and other units becomes fixed. A long-term load test on one pile, or a cluster of three piles, under the design criteria should be considered to check on the extrapolated predicted settlements.

XVIII. SHIELDING CALCULATIONS

E. A. Crosbie

Some considerations have been given to the shielding requirements for the proton accelerator. Some of the results of this work have been presented in the weekly reports and a complete report will be presented at

the Shielding Conference in New York on April 13, 1957. The calculations seem to require of the order of 20 feet of earth for the magnet sections and 30 feet of earth for the straight sections in front of personnel.

XIX. DIGITAL COMPUTER WORK

W. C. Davidon, M. I. Ferentz

Several subtle errors have been discovered and corrected in the synchrotron oscillation code; particle orbits have now been traced through a "perfect" machine and the results compared with hand calculations. These results, while not interesting in themselves, are essential for future orbit traces in imperfect accelerators.

The code is general enough to analyze the effects of arbitrary radio frequency and magnetic field programs upon proton orbits in a large class of accelerators, so that accurate calculations may be made of the effect of failing to track exactly the R.F. with the magnetic field schedule.

In recent weeks, work has started on writing a code for the IBM 650 computer that will reduce the data coming from the model magnet studies. Data obtained from the DC model will be hand punched, while the pulsed-magnet information will be punched directly onto IBM cards by the REA analogue-to-digital conversion system now on order. The data reduction code will accept the cards and perform the necessary arithmetic operations on the raw data to punch out and print the pertinent information.

XX. BUILDINGS

John P. FitzPatrick

The design of the buildings required for housing the proton synchrotron and its ancillary equipment depends almost entirely upon the design of the machine. The design of the buildings needed to house the equipment that is required to conduct experiments with the machine depends almost completely upon the proposed experimental program. The organization of the various buildings into a complex requires considerable knowledge of the site and the necessary inter-relationship of the various buildings. During the past six months, site location studies, machine design studies, consideration of the proposed use of the machine and some study of building inter-relationship have progressed far enough to permit the compilation of a "Proposal for a 12.5-Bev Proton Synchrotron Facility." This proposal was prepared to acquaint prospective Architect-Engineer firms with the scope, requirements, time scheduling and estimated cost of the work that they would be expected to perform. At the present time the Business Manager's Office and the Plant Operations Division are reviewing the proposal, and it is expected that discussions with Architect-Engineer firms will start in the immediate future.

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During the period of April through September 1956, a paper titled "Preliminary Design Requirements - 12.5-Bev Proton Synchrotron," was prepared and issued. The proposed scope of the Architect-Engineer was established along the tentative building designs and some building requirements. The new "Proposal" is based upon this paper plus a considerable amount of new information concerning inter-relationships required of the various buildings, building requirements, area assignments, site orientation, floor levels and beam height.

Using the tentative design shown in the "Preliminary Design Requirements," a paper was prepared on "Estimated Construction Cost of Proposed 12.5-Bev Proton Synchrotron." This report was issued November 1, 1956. The cost estimates covered the building program as well as estimated costs for the synchrotron itself. Subsequent reviews of these cost estimates, using data obtained from various sites and considering the effect of refinements in the basic design of the synchrotron, have shown that the cost estimates obtained seem reasonable and sufficient. A revised form of these cost estimates have been incorporated in the "Proposal."

A considerable amount of effort has been spent in developing design and construction schedules for the proton synchrotron facility. These schedules are based upon dates on which funds are expected to become available (according to information received from the Atomic Energy Commission), scheduling leads necessary on purchased equipment, estimated design and construction time for specialized equipment, availability of manpower and a serious attempt to avoid peaks in professional manpower. An attempt has also been made to distribute the Architect-Engineer and construction contractor load as evenly as possible. Condensed forms of these schedules have been included in the "Proposal" and may be summarized as follows:

Architect-Engineer

Starts work - July 1957
Design completed - July 1959
Supervision completed - July 1960

Constructors

Start work - July 1958
Completed - July 1960

Proton Synchrotron

Start development - Under way
Start construction - July 1958
Start installation - July 1960
Start testing - July 1961.

XXI. OPERATIONS

D. S. Manson

In October 1956, the technicians were organized into a pool under Kenneth Menefee as Chief Technician. From this pool the Technicians are assigned to specific jobs. This has proved to be more efficient than assigning technicians permanently to individual staff members because the work load can be balanced by advanced scheduling of assignments. The technician force has increased by three people since the last report and we hope to add three more shortly, to cover the increasing work load.

The machine shop has been staffed with two machinists, and additional machine tools have been added to perform required machine operations. One technician is being assigned as an instrument maintenance and repair man for the Division to insure that the equipment will be kept in top operating condition.

Some remodeling was done in Building 805 to gain 200 square feet of much needed office space. If progress continues as expected, more laboratory and office space (about 6000 sq ft) will be needed to house the additional people and test and development work now planned. It is hoped that this space will be made available by the early summer of 1957, by rehabilitating and remodeling Building 817, part of which building (about 2000 sq ft) we had already planned to allocate to the Architect-Engineer.

XXII. DRAFTING

Roy Tuma

In September 1956, the formal organization of a drafting room took place within the Division to undertake the job of producing the major part of the mechanical drafting work that is to be required for the preliminary study and final construction of the machine. During this organizational period, systems were developed for various aspects of drafting room operations, such as a drawing numbering system, filing system, a print distribution scheme, and a record system that will coordinate drawings of all parts of the machine during and after the construction period.

At the present time, the drafting room consists of two designers and two draftsmen, one of whom is the Group Leader, providing approximately 675 man hours of drafting time per month to the Division for its various drawing requirements. The major part of this time has in the past been used for drawings of various types of instrumentation required for all phases of study being carried out. In addition to this type of work, several high vacuum systems have been developed, along with several types of

magnet probes, mechanical measuring devices, model magnets, magnet iron and coil conceptual drawings, and miscellaneous "gadgets" used in the research program. A number of conceptual drawings on building structures and arrangements have also been produced.

XXIII. LINEAR ACCELERATOR

Due to the courtesy of the administration and staff of Brookhaven National Laboratory, Rolland Perry has been in residence there for the past three months, working with the linear accelerator group, in order to become familiar with the design problems of this instrument.

XXIV. PERSONNEL ADDITIONS

Staff

R. David Orr - Oct. 1, 1956
 J. P. FitzPatrick
 Associate Division Director - Nov. 19, 1956
 William A. Siljander - Feb. 18, 1957
 Konstantine Burba - Feb. 1, 1957
 Resignation: Henry Berman - Sept. 1956

Technician Pool

Arthur Neubauer - Oct. 15, 1956
 Michael Otavka - Nov. 1, 1956
 Carlos Richards - Dec. 10, 1956
 Clarence Senders - Jan. 21, 1957
 Jerry McCorkle - Jan. 24, 1957
 Resignations: Milford Eck - Feb. 15, 1957
 Almon Muehlhausen - Feb. 1, 1957
 (to Army)

Drafting Room

Roy Tuma, Group Leader - Oct. 8, 1956
 Frank Klun - Dec. 14, 1956

Machine Shop

John Sendera - Dec. 3, 1956
 Nicholas Calaianni - Jan 14, 1957