ANL-6427

ANL-6427

MASTER

325
12-18-61

Argonne National Laboratory

PARTICLE ACCELERATOR DIVISION

SUMMARY REPORT

April through September 1960

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or*
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.*

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

*Price \$1.25 . Available from the Office of Technical Services,
Department of Commerce, Washington 25, D.C.*

ANL-6427
Particle Accelerators and
High-Voltage Machines
(TID-4500, 16th Ed.,
Amended)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

PARTICLE ACCELERATOR DIVISION

Summary Report

April through September 1960

Albert V. Crewe,	Director
John P. FitzPatrick,	Associate Director
Martyn H. Foss,	Associate Director
David S. Manson,	Assistant Director

Previous Summary Reports:

ANL-6152	May 1959 through March 1960
ANL-6032	November 1958 through May 1959
ANL-5956	April 15, 1958 through October 1958

Operated by The University of Chicago
under
Contract W-31-109-eng-38

TABLE OF CONTENTS

	<u>Page</u>
PUBLICATIONS.	3
I. ORBIT THEORY.	6
A. Effects of the Field at the Magnet Edges.	6
B. More Precise Calculation of the Parameters of the Extraction Beam	7
C. More Precise Frequency Program with the Hard-edge Parameters.	8
D. Longitudinal Space-charge Limit.	8
E. Acceleration due to Induction in a Synchrotron.	9
F. The Consequences of Liouville Theorem on the Configu- ration Space Density of the Ion Beam.	10
G. Compiler into GEORGE Assembly Routine	10
II. INJECTOR STUDIES.	11
A. Theory.	11
B. Tuning-up Procedures.	13
C. The Injector System	15
D. Present Status of the RF Ion-source Program.	18
E. Pick-up Current Transformers.	20
F. The Duoplasmatron Ion Source Program.	20
G. Drift-tube Quadrupole Testing	21
III. RING MAGNET	24
A. Support System	24
B. Accelerated Aging Effects of Ring Magnet Steel.	25
C. Capacitance Network.	25
D. Filter for the Prototype Power Supply	26
IV. THE VACUUM SYSTEM.	28
A. Operating System.	28
B. 25-foot "Spacemetal" Chamber Behavior under Vacuum .	39
C. The 32-in. Pump Test Program	40
V. THE RADIOFREQUENCY SYSTEM	43
A. Study of Characteristics of the Power Amplifier and the Radiofrequency Cavity Including Effects of Beam Loading	43
B. Synchrotron Radiofrequency System.	43

TABLE OF CONTENTS

	<u>Page</u>
VI. BEAM EXTRACTION	46
A. Theory of Resonant Extraction from Sectorial Cyclotrons.	46
B. Magnet Problems.	46
C. Proton Beam Transport.	48
D. Meson Beam Production and Transport	48
VII. TARGETRY.	50
A. Study of Multiple Traversal of an Accelerated Beam in a Synchrotron through a Thin Target	50
B. Beam-Target Interactions	52
C. ZGS as a Source of High-energy Neutrinos	53
D. Kinematics of $\pi^- + p \begin{cases} \rightarrow \pi^0 + n \rightarrow 2\gamma + n \\ \rightarrow \pi^0 + \pi^0 + n \rightarrow 2\gamma + 2\gamma + n \end{cases}$	53

PARTICLE ACCELERATOR DIVISION

Summary Report

PUBLICATIONS

Abstracts of ANLAD Reports

ANLAD-60 "Hamiltonian Formulation of the Motion of Ions in a Sectorial Cyclotron or Synchrotron," Lee C. Teng
(May 31, 1960)

The complete motion of an ion in a sectorial cyclotron or synchrotron is studied by a general Hamiltonian formulation. Starting from the general Hamiltonian function for the motion of an ion in an electromagnetic field possessing a median plane and expressed in the spatial "orbit coordinates" R, θ, z , and the time coordinate t , we first transform it to θ as the independent variable. The "betatron approximation" is, then, made to decouple the R and z motions from the t motion. The R and z equations give the betatron oscillations. They allow, in the first place, the solution $R = \text{constant}, z = 0$, namely the equilibrium orbit. We then expand the Hamiltonian function under the "betatron approximation" or the betatron oscillation Hamiltonian function about the equilibrium orbit. This gives the Hamiltonian function in expanded form of betatron oscillation in a general sectorial circular magnetic accelerator expressed in "orbit coordinates." The t equation gives the phase oscillation. Under the "betatron approximation" we substitute the equilibrium orbit parameters in the t equation to decouple the t motion from the R and z motions. For a sectorial cyclotron the now decoupled t equation can be easily transformed to a closed canonical form and a closed phase oscillation Hamiltonian function can be easily constructed. But for a sectorial synchrotron the transformation to canonical form can only be carried out in expanded form. This gives the phase oscillation Hamiltonian function in an expanded form. Throughout this paper efforts are made to retain as much mathematical rigor as possible in the development and to state explicitly the assumptions and approximations made at each step.

ANLAD-61 "Magnet Excitation for a Proton Accelerator,"
G. O. Calabrese (March, 1960)

The power required by the magnet excitation and the requirements of the radio frequency system of a particle accelerator are affected by the manner in which the voltage e_1 applied to the terminals of the magnet coil varies with time. In the design of a particle accelerator it then becomes necessary to calculate $i, e_1, di/dt, B, dB/dt$, etc., under different assumptions for the shape of e_1 as a function of time.

This report outlines two methods applicable respectively to longhand and computer calculations which, in addition to the time variation of e_1 , permit taking into consideration the variation of the incremental inductance L_s with saturation.

From the discussion it will be apparent that any desired degree of accuracy can be attained.

Internal Memoranda

M. E. Abdelaziz

MEA-1	Theory and Performance of the Radio Frequency Ion Source	4/14/60
MEA-2	Part II of Above - Extraction of Ion Beams from the RF Plasma	9/1/60

A. V. Crewe

AVC-1	Possible Alternative to Quadrupole Magnet Focusing	5/6/60
AVC-2	Tuning up the ZGS	5/10/60
AVC-3	Quadrupole Magnets and Their Uses	8/19/60
AVC-4	Hydrogen Supply and Safety Considerations for the ZGS	9/28/60

H. Lucks

HL-JSM-1	Spacemetal Chamber	8/24/60
----------	--------------------	---------

J. Moenich

HL-JSM-1	Spacemetal Chamber	8/24/60
----------	--------------------	---------

J. R. Simanton

JRS-CHMT-1	A Basis for the Design of a Simple Induction Electrode System Using a Calibrating Wire	7/18/60
JRS-CHMT-2	Notes Relating to the Development and Design of a "Split" Radial Induction Electrode System Using a Calibrating Wire	7/22/60

L. C. Teng

LCT-19	Revised Injection Procedure into ZGS	6/7/60
LCT-20	ZGS as Source of High-Energy Neutrinos	6/20/60
LCT-21	Acceleration Due to Induction in a Synchrotron	7/5/60

C. H. M. Turner

CHMT-10	Notes on Equivalent Circuits of Induction Electrode Systems	4/13/60
JRS-CHMT-1	See above	
JRS-CHMT-2	See above	

A. Yokosawa

AY-4	A Study of a Focusing Electrode	6/13/60
AY-5	II. Extraction System for an RF Ion Source	6/20/60
AY-6	Trajectories of Protons in a Cylindrical Three-Electrode Einzel Lens	8/26/60
AY-7	An Analysis on the 300 kv Accelerating Electrodes	9/6/60

External Publications

Radio-Frequency Self-Tracking in a Synchrotron
L. C. Teng and E. A. Crosbie
Bull. Am. Phys. Soc. 5 225 (April 1960)

Pulsing Hall Probes for Greater Output
D. L. Shirer
Rev. Sci. Instr. 31, 1000-1001 (September 1960)

I. ORBIT THEORY

A. Effects of the Field at the Magnet Edges (E. A. Crosbie)

The coded program derived for use with GEORGE to integrate the proton orbit around the ZGS magnetic field, incorporating the effects of the soft fringing field at the edges of the main guide magnets (the octants) and those of the field of the DC magnet, has been outlined in ANL-6032, page 8, and ANL-6152, pages 39 and 40. The octant field is assumed to be uniform inside, and the soft fringing field is taken to be of the form

$$B_1(s) = \frac{B_{10}}{2} \left(1 + \tanh \frac{s}{\epsilon_1} \right) \quad (1)$$

on the median plane, where B_{10} is the uniform "interior" field and s is the perpendicular distance from the edge. The DC magnetic field is assumed to be of the form

$$B_3(x, s) = \frac{B_{30}}{2} \left(1 + \sum a_n \frac{x^n}{n!} \right) \left(\tanh \frac{s + s_0}{\epsilon_3} - \tanh \frac{s - s_0}{\epsilon_3} \right) \quad (2)$$

on the median plane, where B_{30} is the "central interior" field, x is the radial distance from the central curve passing through the reference point WP-S, and s is the azimuthal distance from the middle of the magnet with radial and azimuthal directions defined by the edge angle. The coefficients a_n give the radial dependence of the field and s_0 is the central half-width of the DC magnet. The parameters ϵ_1 and ϵ_3 define the "softness" of the octant and the DC fields, respectively.

The computing program calculates the orbit of a proton with a given momentum in the magnetic field described above, either by direct Runge-Kutta integration or by simple transformation wherever possible, to reduce the computation time and to retain accuracy. The computed orbits, the position of the equilibrium orbit, and the behaviors of the betatron oscillations may then be evaluated.

Throughout the study, the DC magnet edge was assumed to be parallel to the adjacent octant edge, and, for practical simplicity of construction, the radial dependence of the DC field was assumed to be given only by a_1 and a_2 . The parameters B_{30} , s_0 , a_1 , and a_2 were adjusted for a given set of "softness" parameters ϵ_1 and ϵ_3 to give (1) the central orbit following the center line of the vacuum chamber, (2) a value of $\frac{7}{8}$ for the frequency ν_y for this central orbit, and (3) values $\nu_x = \frac{3}{4}$ and $\nu_y = \frac{7}{8}$ for an outer orbit approximately 15 in. from the central orbit. The results are given in the following table:

ϵ_1 (ft)	ϵ_3 (ft)	s_0 (in.)	B_{30} (kgauss)	a_1 (ft ⁻¹)	a_2 (ft ⁻²)
1/2	0.3	14.29	1.0108	-0.15248	0.02858
1/2	0.2	15.05	0.9599	-0.14618	0.02632
1/2	0.1	15.82	0.9150	-0.14039	0.02432
1/3	0.3	15.24	0.9482	-0.14493	0.02594
1/3	0.2	16.05	0.9020	-0.13898	0.02391
1/6	0.3	16.33	0.8866	-0.13722	0.02337
0	0	19.85	0.740	-0.112	0.019

Values in the last row (that with $\epsilon_1 = \epsilon_3 = 0$, corresponding to the case of an infinitely hard field edge) were obtained by linear interpolation from results given in the rows above. These values are in agreement with values previously calculated¹ for the case of fixed ν_y : $s_0 = 19.84$ in., $B_{30} = 0.734$ kgauss, $a_1 = -0.120$ ft⁻¹, $a_2 = 0.021$ ft⁻², and $a_3 = 0.005$ ft⁻³, thus giving confidence in the correctness of the GEORGE program. The best present estimates of ϵ_1 and ϵ_3 are those given in the first row of the above table. If, however, the softnesses of the octant and DC magnets turn out to be different, the above table may be used to give an immediate set of design parameters.

B. More Precise Calculation of the Parameters of the Extraction Beam (L. C. Teng)

A calculation was made to take into account the bending of the orbit by the DC magnet and the effects of the edge angles of the octant guide magnet, both of which were neglected in the calculation made in LCT-10.² Soft-edge effects, however, were still neglected. For the orbit-field parameters, we used the hard-edge fixed- ν_y design values given in LCT-14.¹ It should be noted that, although the softness of the magnetic field edges play an important role in the betatron oscillations, it should not influence the position of the extraction orbit significantly. Therefore, this calculation made under the hard-edge approximation should be a fairly good one. The important resulting engineering parameters are as follows:

Position of Center of Bending of Piccioni Magnet

Radial distance from the reference point WP-S = 17.54 in.

Azimuthal (perpendicular to radial) distance from WP-S = 39.00 in.

¹ L. C. Teng, Design Parameters for the DC Magnets of the ZGS, Internal Memo LCT-14 (August 12, 1959)

² L. C. Teng, Beam Position after Passing through Piccioni Magnet, Internal Memo, LCT-10 (December 29, 1958)

Angle of Bending of Piccioni Magnet

Angle	= 2.006°
Field times length of Piccioni magnet	= 51.29 kgauss-ft

Position and Angle of Beam Exit from Octant

Distance along iron edge of octant from reference center	= 18 in.
Angle from direction of long straight section	= 1.675°

C. More Precise Frequency Program with the Hard-edge
Parameters (L. C. Teng)

A more precise calculation of the proton circulation frequency ($\frac{1}{8}$ that of the radiofrequency) versus octant magnetic field was made for the ZGS. Hard-edge field parameters^{1,3} were used. The hard-edge field approximation, although not very good for evaluating the precise design parameters of the DC magnet, should give adequately precise values for parameters of the equilibrium orbits. In particular, it may be expected to give the equivalent radius (the only quantity needed in the computation of the frequency program) to within 0.1%. Previous crude calculations for injection capture have been improved, and a more realistic and practicable frequency program was worked out. The entire calculation was made using the new computing machine, Recomp II.

D. Longitudinal Space-charge Limit (L. C. Teng)

The longitudinal space-charge effect on the ion beam in a circular magnetic accelerator has been studied in detail by C. E. Nielsen and A. M. Sessler.⁴ Beam behaviors similar to longitudinal space-charge instability have been observed in proton synchrotrons with Van de Graaff injectors (Cosmotron and Saturne) and electron synchrotrons (Cal Tech synchrotron). Uncertainties still exist, however, in the proper interpretation of these observed phenomena. In view of the vital importance of the longitudinal space-charge effect on the target beam intensity of 10^{13} protons per pulse for the ZGS, a critical study and improvement of Nielsen and Sessler's work was made. For weak-focusing synchrotrons operating above the transition energy, the effect of electrostatic repulsion between

³L. C. Teng, Parameters for 12.5-Bev Synchrotron, Internal Memo LCT-1 (May 6, 1957); EAC-LCT-2.

⁴MURA Reports Nos. 413, 441, 442, 480, and 488; Rev. Sci. Inst. 30, 80 (1959).

ions in the azimuthal direction is to cause a uniform circulating beam to bunch longitudinally into short clusters with azimuthal length approximately of the same order as the transverse dimensions. This longitudinal bunching effect is counteracted by the existing energy spread in the beam. For a given energy spread ΔE there exist a maximum number, $N_{\max}$, of ions in the beam beyond which the beam will be longitudinally unstable. When applied to various proton synchrotrons, the numerical results were as follows:

Cosmotron

For $\Delta E = 6$ kev	$N_{\max} = 5 \times 10^{10}$
For $\Delta E = 50$ kev	$N_{\max} = 3.6 \times 10^{12}$

Saturne

For $\Delta E = 9$ kev	$N_{\max} = 5.2 \times 10^{11}$
------------------------	---------------------------------

ZGS

For $\Delta E = 150$ kev (Expected energy spread in the beam from the Linac)	$N_{\max} = 4.6 \times 10^{12}$
For $\Delta E = 414$ kev (Width of RF bucket at end of injection if the modified injection procedure described in Section II, A.2 above is employed)	$N_{\max} = 3.5 \times 10^{13}$

From the last number we see that with the modified injection-capture procedure,* the longitudinal space-charge limit does allow the attainment of the projected beam intensity of 10^{13} protons per pulse for the ZGS.

E. Acceleration due to Induction in a Synchrotron (L. C. Teng)

This study is an offshoot of the study of the Hamiltonian formulation for the betatron- and phase-oscillations in a synchrotron. The time-varying axial magnetic field produces an azimuthal electric field which accelerates the ions in the synchrotron in addition to the applied rf accelerating electric field. In a betatron this acceleration due to induction is the sole mechanism of accelerating the electrons, whereas in a proton synchrotron this effect is expected to be small. This effect is studied here in general.

*See See Section II, A.2 of this report.

The general formulas obtained were applied to several specific examples. In particular, when applied to the ZGS at injection with the rf off, it shows that the gain of momentum of the proton due to induction when the beam moves from the extreme outside of the vacuum chamber to the middle (magnetic field rising) is only 0.006% of the total momentum, and that the error made in neglecting the effect of induction acceleration in calculating the percentage rate of shrinkage of the orbit radius at the extreme outside and inside of the chamber is only $\pm 1.5\%$.

F. The Consequences of Liouville Theorem on the Configuration Space Density of the Ion Beam (L. C. Teng)

The Liouville Theorem states that "for an ensemble of particles executing Hamiltonian motion, the density of phase points in the neighborhood of and moving along with any phase point remains constant in time." For practical application, in many cases, one is interested in the time variation of the configuration space density of particles, which is obtained, of course, by integrating the phase space density over the canonical momentum coordinates. In general, the Liouville Theorem is unable to supply any inference for the configuration space density because of the complex nature of the integrations over the momentum coordinates. However, in special cases for which the dependencies of the phase space density on the momentum coordinates are particularly simple, general behaviors of the configuration space density can be inferred from the Liouville Theorem. Such studies lead to theorems of the "invariance type" for the configuration space density and, in particular, make "ultimatum type" of statements on the electromagnetic handling of charged particles.

G. Compiler into GEORGE Assembly Routine (R. George)

When preparation time is important in the writing of computer programs, it is desirable for the programmer to make his code as automatic as possible, via assembly and compiler programs.

CIGAR is a compiler now being written for the GEORGE computing machine. When completed, it will read in statements belonging to a subset of the FORTRAN language statements and from this it will create a GAR language program which may then be assembled in the usual manner to yield a machine language code for GEORGE. CIGAR will create calls for library subroutines as required by the FORTRAN-like code. The original FORTRAN statements are carried along as remarks in the GAR code.

This compilation program is partially complete, and it is possible to use it to produce workable programs. At this time, it is necessary for the programmer to use a mixed FORTRAN-GAR language with control statements given in FORTRAN and arithmetical statements in GAR.

II. INJECTOR STUDIES

A. Theory

1. Matching the Linac and the Synchrotron (E. A. Crosbie)

The work described in ANL-6152, p. 40, is nearing completion. The following procedure has been found which leads systematically to the parameters for a pair of quadrupole magnets transforming given initial x- and y-phase ellipses to desired x- and y-phase ellipses (the beam is assumed to be moving in the z direction).

Starting with a convenient and practical set of values of magnet lengths and drift-space lengths, the final ellipses are calculated from the given initial ellipses for various values of the field gradients in the quadrupole magnets. From these results, one pair of field gradients is chosen to give final ellipses closest to the desired ellipses, the criterion being that the major and the minor axes of the corresponding ellipses should fall inside the same phase octants. This set of parameters (namely, magnet lengths, drift-space lengths, and field gradients) are then adjusted in steps to give final ellipses closer and closer to the desired ones, taking care at each step to select the set which is physical (all lengths are positive) and in which all quantities are practical in magnitude. (This is possible because there are more parameters than conditions.) When the desired final ellipses are reached, a complete search is made in the neighborhood of the set of parameters arrived at through this iterative procedure, and the most convenient and physically practical set is chosen. The entire procedure has been coded for IBM-704 and is now being applied to finding the necessary quadrupole magnets for matching the output beam from the Linac to the ZGS.

2. Revised Injection Procedure into the ZGS (L. C. Teng)

The commonly used procedure of injection into synchrotrons of turning on the radio frequency after the chamber is filled with ions from the injector has two drawbacks: (1) The capture efficiency is low; for a synchronous phase of, say, $5\pi/6$, the stable rf phase area extends only about π radians. The capture efficiency is, therefore, smaller than 50%. (2) Ion loss due to space charge; after one-quarter of a synchrotron oscillation, the longitudinal bunching of the captured ions greatly reduces the transverse space-charge limit. A major portion of the already captured ions may be lost by the transverse space-charge effect at this moment.

A modified procedure of injection capture is proposed whereby the radio frequency is turned on during injection. The injected ions are captured immediately into rf buckets with such a rate of frequency modulation that the synchronous phase is π , the stable phase region extends over 2π radians, and the ions do not gain any energy on the average. Near the end of injection, the rate of frequency modulation and the rf voltage

are adiabatically changed over to that corresponding to synchronous phase $5\pi/6$ and the normal rate of energy gain per turn. This procedure eliminates effectively both of the defects of the old injection-capture procedure mentioned above.

Approximate frequency- and voltage-modulation programs were worked out for the equivalent synchrotron of the ZGS. With this modified procedure of injection capture and adequate injection beam current from the injector Linac, one should be able to obtain a 12.5-Bev beam from the ZGS close to the space-charge limits of $2-5 \times 10^{13}$ protons/pulse.

3. Trajectory Calculations for Ion Source (J. Dick, R. George, and A. Yokosawa)

In conjunction with experiments by A. Yokosawa on accelerating-electrode systems, a program has been written which traces the path of a number of particles through a mathematically simulated electrode system. The numbers of surviving protons, and their positions and velocities as they approach the Linac have been calculated for different beam currents and for a number of proposed electrode arrangements. The program was written for the IBM-704 in two parts.

4. Simulated Injection Tuning Experiments (R. George and D. Cohen)

It is believed that the injection tuning of the ZGS will require the aid of a computer to minimize the tune-up time. Whether this be analogue or digital, it is apparent that insight into the problem may be gained by simulation of a number of possible variants of the ZGS machine and performing upon these simulated machines the start-up experiments.

Assuming that the proton orbits obey certain equations and that measurements of the position of a beam are subject to normal distributions, the programming to perform these preliminary experiments has been initiated. The GEORGE computing machine will be used.

5. Theory and Mechanism of the Low-pressure Plasma in RF Ion Sources (M. E. Abdelaziz)

A theoretical study has been made of the rf plasma in the low-pressure (1 to 10μ) range, in which the mean free path is so large that some electrons will collide with the wall surfaces before undergoing collision with gas molecules. Secondary electrons are emitted as a result of such wall collisions. Thus the electron distribution in the plasma will be governed, not only by the applied rf field, but also by the secondary emission. It has been found that the electron concentration is given by a Bessel function of the zero order, with a maximum density at the center of the tube.

Expressions were derived for the electron concentration, the plasma current, and the rf power absorbed by oscillating electrons. The theoretical results lead to the suggestion that it might be possible to obtain intense ion beams if extraction were effected at a point near the tube center. It is on this basis that the so called radial-extraction ion source is designed.

A study of the processes whereby a hydrogen molecule is ionized and dissociated in the rf plasma was also made. The results have been used to explain the variation of proton concentration with rf power and gas consumption.

6. Extraction of Ion Beams from the RF Plasma (M. E. Abdelaziz)

The analysis of the extraction problem in a rf source was considered in three sections:

1. Design charts of the exit canal from the source were prepared by taking into account:
 - a. the maximum space-charge-limited current which can be transmitted through a cylindrical canal, and
 - b. the gas flow which creates the suitable pressure difference between the source and the high-vacuum region.
2. The focusing properties of the beam between the plasma boundary and the canal were analyzed by means of a theory of conical flow of proton beams between spherical surfaces. From such analysis, the dimensions of the beam-forming cathode shield were determined for different canal sizes.
3. The theory of radial potential distribution in an intense beam⁵ was applied to determine its effect on design calculations from the first-order theory. This gives an estimate of the resulting loss in the beam current inside the canal due to space-charge effects.

B. Tuning-up Procedures (D. Cohen)

Since the protons injected into the ZGS must miss the inflector for eight turns before being swept inward by the rising magnetic field, the radial and vertical oscillational frequencies, ν_r and ν_z , at injection must be accurately known and controlled. The control will be achieved primarily with DC magnets. It would be desirable to measure the frequencies with an accuracy of ± 0.005 .

⁵Smith and Hartmann, J. App. Phys., 11, 220 (1940)

The initial ideas⁶ for a measuring system have been studied and extended, and it now appears that the actual tuning up will closely resemble the following procedures. All are directly or indirectly related to measuring ν_r and ν_z .

(a) The first few octant magnets, powered with small DC, can be used for analysis of the energy and direction of the injected beam.

(b) With the octants in normal pulsed operating condition and with the inflector set for injection on the median plane, median plane errors can be minimized.

(c) If solid-state detectors at the end of radial probes in seven straight sections are used to detect the injected pulses, the equilibrium orbit can be made symmetrical with respect to the straight sections. This is done by noting the relative radial detector positions for that condition in which they collide with the detectors at various radii.

(d) Fluorescent screens, which will pass about 80% of the beam, will be situated across the beam area in all long straight sections except L2. In addition, there will be a small aperture at the exit end of the inflector and a plate with narrow slits and/or holes which are distributed radially in L2. The beam side of this plate will be fluorescent. The injected beam thus encounters an aperture, either an aperture or a stopper, three screens, and one stopping plate. Closed-circuit storage television cameras, called Permachons, will view the three fluorescent screens and one fluorescent plate, and the resultant images will be monitored in the control room. The images will consist of bright radially distributed spots superimposed on a grid, thereby allowing rapid and accurate determination of the radial and vertical spot positions. These numbers will be remotely fed to either the GEORGE or the IBM-704 computer where a least-square fitting program will yield ν_r and ν_z as a function of equilibrium orbit position. A complete determination should take less than ten minutes.

Computer studies have been made of random and systematic errors in the spot positions, and the necessary accuracy of ± 0.005 for ν_r and ν_z is obtained if the spot position errors do not exceed ± 0.1 in. Experiments with a Permachon system and various fluorescent materials with the 21-Mev deuteron beam from the Argonne Cyclotron indicate the equipment will work if care is taken in applying the fluorescent powder to the screen correctly. Since energy spreads of greater than ± 10 kev in the injected beam result in spot sizes which are too great, the beam tests were made at currents appropriate to a very low-intensity Linac beam. The small energy spreads can presumably be obtained by lowering the electric gradient in the Linac tank, with resulting loss of intensity.

⁶A. V. Crewe, Tuning Up the Zero Gradient Synchrotron, Internal Memo AVC-2 (May 10, 1960).

- C. The Injector System (M. Abdelaziz, R. Castor, D. Cosgrove, J. Froehlich, P. Livdahl, J. Mech, W. Myers, R. Perry, and A. Yokosawa)

Construction of most components of the Injector have been started. Deliveries are scheduled to begin in early November with completion of most equipment by April 1961. Following is a resumé of the present status of major components.

1. Injector Building: The Injector Building has reached about 60% completion during this period. Occupancy is scheduled for mid-January 1961.

2. 800-kv Power Supply: Assembly and testing of this equipment is underway at the Emile Haefely Co. plant in Basel, Switzerland. Acceptance tests are scheduled for early December, with delivery about February 1, 1961.

3. Ion Source and Accelerating Column: No assembly work on these items has as yet started; however, some components of the assemblies have been ordered and detail mechanical and electrical designs are presently being completed. Ion source development has continued and will be discussed later in this report.

4. Linac Tanks: Rolling and welding of all eleven linear accelerator tank sections have been completed by Lukens Steel Co. Machining of the tanks has started at the Cleveland Diesel Co. plant in Cleveland, Ohio. Delivery of the first section is scheduled for mid-December with all tanks due by April 1, 1961.

5. Drift Tubes: The machining of drift tubes and stems is being done in ANL Shops and will be completed by November 1. Completion of the drift tube assemblies is awaiting further experimentation of an electron beam welding technique for closing the drift tube bodies.

Figure 1 is a photograph of the finish-machined number 2, 60 and 124 drift-tube bodies.

6. Drift-tube Quadrupoles: Fabrication of the quadrupoles is also being done by ANL Shops. Machining of the quadrupoles will be completed by November 1, and the coil winding and potting will be completed by December 1.

Figure 2 is a photograph of various quadrupole parts, an unpotted coil, and a completely assembled Group VI magnet.

Fig. 1

Partially Assembled Drift Tubes #2, 60 and 124

Fig. 2

A Bare Quadrupole, Coil, Potted Coil
and Assembled Quadrupole (Group VI)

Figure 3 is a photograph of one magnet from each group and a Group I coil. No coils were assembled for Groups IV and V at the time of this photograph.

The status of quadrupole testing is described elsewhere in this report.

Fig. 3

One Quadrupole from Each Group

7. Linac RF System: The 5-Mw, 200-Mc rf power system, which will drive the Linac cavity, is under construction at Continental Electronics, Dallas, Texas, and is approximately 85% complete. Preliminary operational check-out has been accomplished on all major units with the exception of the A2346F super power triode final amplifier. This stage is in final mechanical assembly.

On October 10, 1960, the contractor reported satisfactory continuous eight-hour operation of the 4-W-20,000A Driver at an output power of 200 kw. Previously, the series-parallel ML5682 Modulator was operated at full power, 9.2-Mw peak at approximately 37 kv.

Some difficulty had been experienced with what is literally termed "pulse stretching," caused by what is believed to be grid emission

in the ML5682 Switch Tubes. Not all tubes have exhibited this phenomena. Machlett has been consulted relative to this problem, and some progress has been made.

At the present time, it appears that final acceptance tests on the system into a resistive load will be conducted in Dallas sometime in December 1960. Installation at ANL is to be completed by April 1961.

8. Linac Vacuum System: All components of the vacuum system are now on order except the piping. Final drawings of the piping, shop drawings of pumping equipment, and checking of these items is underway. Delivery of some components has started and all items are scheduled to be on hand by March 1, 1961.

D. Present Status of the RF Ion-source Program

Two types of plasma containers were used in the development work on the rf ion source. The first has the geometry of the CERN type but is different in material, since Pyrex is substituted for ceramic. It is found that, under the same running conditions, much less rf power is required for a Pyrex envelope than for a ceramic envelope of the type manufactured by the same makers of the CERN tubes. (There is no guarantee, however, that it is the same ceramic.) In addition, Pyrex is known to have the best surface for a plasma container, since it has the smallest surface recombination coefficient compared with other insulators. Performance of the source was improved by increasing the rf power, properly matching the source to the transmitter, eliminating the undesirable plasma in the gas line, and improving the beam focusing into the exit canal by using the proper cathode geometry. Beam currents in excess of 100 ma could be extracted for considerable lengths of time.

A 100-ma beam has been accelerated to 240 kv using the Harrison-type electrostatic lens. The beam emittance is measured at 8 millirad-inch by means of a beam-scanning device. Magnetic analysis of the beam current indicates a proton percentage of about 85%. Figure 4 shows some of the characteristic curves for this source.

The second type of rf source takes advantage of the fact that maximum ionization densities exist at the plasma center. The source is therefore designed with an extraction electrode extending through the plasma in the region close to its center, perpendicular to the tube axis (see Figure 5). Theoretical study (see Sect. II.A.5) shows that the radial density of ionization varies according to a Bessel function of the zero order. Compared with the conventional type of source, the "radial-extraction" source yields a beam current higher by 20 per cent.

Fig. 4

A Sample of Ion Source Characteristics

Fig. 5

Radial-extraction Ion Source

At present the rf source is mounted on a setup using a vacuum pump. A more detailed experimental study of the extraction problem is underway, with the hope of achieving further improvement of source performance. Modifications of the extraction geometry are based upon calculations outlined in Sect. II.A.6.

E. Pick-up Current Transformers

These transformers are designed for the purpose of monitoring the ion beam so that: i) small portions of the beam current admitted through the slit mechanism can be detected with reasonably high sensitivity (for measurements of beam quality), and ii) to measure the total beam current accelerated in the linear accelerator. Satisfactory results are obtained for the detection sensitivity and wave shape of the transformer secondary due to a pulsed current in a single-turn primary representing the beam current. It is hoped to get a similar behavior with the actual beam current.

One of the current pulse transformers is completed and its calibration curve has been determined.

F. The Duoplasmatron Ion Source Program

During early stages of testing of the Duoplasmatron ion source, difficulties were encountered in maintaining sufficient voltage (at least 60 kv required) at an anode-to-accelerator spacing of 5 mm. These difficulties were removed by use of a nickel extractor electrode and an improvement of the pumping speed of the vacuum system.

Various shapes of aperture were used, and it seems that an aperture of the type shown in Figure 6 delivers much more current than the one with a 70° opening. However, these apertures were not tried at an extraction voltage higher than 60 kv.

A peak ion current of 200 ma has been extracted through a 0.050-in. aperture at 60-kv acceleration. Current output was limited to this value by the extraction power supply and the tantalum filament. As there has been no recent difficulty in maintaining 60 kv between anode and extraction electrode, an increase of the extraction voltage, up to 80 kv if possible, will be attempted. The diameter of the beam was at most 16 mm measured at the end of a field-free region, 1 in. from the 5-mm extraction electrode. The beam was accelerated up to 250 kv through the accelerating column. The measured beam diameter was 1 cm at the exit of the last electrode. More exact measurement of beam divergence will be done by the method described in ANL-6152, p. 49.

Based on H. Frohlich's source,⁷ a modification of the present source will be made to seek a higher ion current and better ion optics.

⁷See discussion in A. Yokosawa, An Ion Source Which Produces a Hydrogen Ion Current of 1,000 MA, Internal Memo AY-2 (Feb. 12, 1960).

Fig. 6

Special Electrode

G. Drift-tube Quadrupole Testing

During the early phases, considerable time and effort was spent in reworking the Bridgeport milling machine which formed the nucleus of the testing equipment, and in building and debugging the associated electronic gear. Much experimentation with the search coils and with the brush-and-slip-ring assembly was done. Extensive preliminary testing was carried out using the prototype magnets, and as a result several improvements were made to expedite the testing.

The first production magnets were delivered and tested during the middle of July. To date, 10 Group I, 12 Group II, and 4 Group III quadrupoles have been tested. None of the magnets delivered for testing have been rejected for mechanical or magnetic faults; one magnet was rebuilt because of questionable electrical insulation.

The criteria which are used as a basis for accepting or rejecting a quadrupole magnet are:

1. electrical insulation >20,000 megohms;
2. pole windings correctly ordered;
3. water flow and water temperature rise normal at operating pressure;

4. harmonics due to errors in the magnet, each $< 1.5\%$ of the second harmonic at a distance $\frac{1}{4}$ in. off the center;
5. quadrupole field agrees closely with prototype values to insure uniformity of steel; and
6. displacement of the magnet ends from their prescribed position by less than 0.003 in. for Group I to 0.006 in. for Group VII.

Rotational alignments are made mechanically using markings affixed on the quadrupole during machining.

One small and one large search coil are used to accommodate the range of magnet length and bore diameters. The values of field obtained with this equipment for the prototype magnet in Group I agree to better than 0.2% with those taken on the same magnet using very accurate flux-meter data. The second harmonic frequency is maintained at 120.0 ± 0.1 cps at all times by means of a synchronous motor and special drive.

Requirement (6) above involves measurement of (a) how far the magnetic axis is displaced from the geometrical center, and (b) how much the magnetic axis is tilted with regard to the geometrical axis. The centering and tilting measurements are performed by nulling of the first harmonic signal, which is isolated by a sharp filter. Because of the insensitivity of the first harmonic to nutation of the search coil, it is also used for absolute calibration of the plots of quadrupole field versus current which will be used to set the magnetic gradient in the Linac.

Requirement (4) is checked using a Panoramic harmonic analyzer which allows viewing of any desired harmonic signal.

Dials on the milling machine can be read directly to 0.0001 in., and the sensitivity of the electronics is such that changes of 0.00002 in. in the magnet position is easily detected for Group I quadrupoles.

The average time required for the complete testing of a new magnet is approximately $2\frac{1}{2}$ hr. Until recently, the number of magnets tested per day has been somewhat lower than expected because of unforeseen deficiencies in the mill, for which corrections had to be made.

Table I below gives some approximate results of the magnetic testing thus far, as well as the maximum and minimum for each group.

Table I

Group	Quantity Tested	Magnetic Axis				End Displacement, in.	
		Off Center		Tilt Angle			
		Max	Min	Max	Min	Max	Min
I	10	0.00063	0.00014	8'	2'	0.0018	0.0006
II	12	0.00086	0.00000	7' 30"	2'	0.0021	0.0006
III	4	0.00051	0.00014	8'	5'	0.0024	0.0017

The same tests described above will be repeated after encapsulation of the magnets in the drift tubes. In addition, a B vs. I curve will be run. The same equipment will be used and accurate alignment of the drift tubes in the Linac tank will be insured by using the same reticule holders on the drift tubes for both testing and installation in the tank.

III. RING MAGNET

A. Support System

1. General Description

Each octant of the ring magnet has its own independent supporting structure. The principal components of the supporting structure are as follows:

a. A base weldment consisting of four curved 12-in. channels joined together with appropriate structural members. Separated by a one-in. grout, this weldment is placed on the concrete beam octant.

b. Forty-four special mechanical jacks, each rated at 25 tons. A quarter turn of approximately 1000 in.-lb will raise a 25-ton load 2 mils. Each jack is bolted to a steel plate which, in turn, will be welded to the base weldment at final positioning. Each jack has a special cap which has a polished hardened surface. This is the mating surface of the following item.

c. DU Glacier Plate - a low-friction bearing material described as a "tin-plated steel sheet on which is sintered a thin lining of spherical bronze impregnated with a mixture of TFE fluorocarbon plastic and lead and having a thin surface layer over the top of the bronze spheres of the same TFE-lead mixture." A test is planned to determine the actual coefficient of friction of this material against steel. The manufacturer's rating of the coefficient of friction for this type of loading ranges from 0.08 to 0.15.

d. Straight structural "rails." These rails, are welded to the underside of each magnet block, and serve to maintain the ring magnet at a prescribed elevation and to distribute the concentrated load of the jack over a wider area.

e. One radial restriction assembly. This is a guide which will limit any movement of the ring magnet in a radial direction due to heating.

f. Two azimuthal restriction assemblies. These are guides which will limit any movement of the ring magnet in an azimuthal or tangential direction due to heating.

2. Status

The design calculations, the layout drawings, the detail drawings and the specifications have been completed. The project is in the stage of being sent out for bids.

Several jacks have been ordered. When obtained, they will be used in an evaluation of several other components of the support system, among them, the DU Glacier Plate and a specially-designed clamp which will be used in positioning the magnet blocks. The evaluation test will be conducted primarily to confirm several assumptions and calculations used in the design of the support system.

B. Accelerated Aging Effects of Ring Magnet Steel

By means of the $\frac{1}{7}$ -scale model magnet, measurements of the residual field after different baking times were made with sample plates that had the same composition and heat treatment of the steel to be used for the ring magnet. The residual field was determined for the plates as they were received, and then measurements were made after heating at 110°C for various periods, with the following results:

Total Bake Time, hr	Residual Field, gauss
0	13.1
22	13.5
87	13.8
249	13.9

It has been estimated that the longest baking time would be equivalent to operation for 30 years at 25°C.

For purposes of comparison, a similar study will be made with steel of high carbon content.

C. Capacitance Network (G. O. Calabrese*)

Calculations previously made of the capacitance network of the magnet of the proton synchrotron have been revised to account for the latest changes in the design of the coil. The coil conductor arrangement, dimensions, and insulation are as shown in Figure 7. With reference to this figure, it was assumed that the lower two turns (1, 1) adjacent to the anchor plate

*Summer Student Aide, A. Burger, made the necessary calculations.

IV. THE VACUUM SYSTEM

A. Operating System (J. S. Moenich, H. Lucks, and K. Weberg)

With the decision to use eight isolation valves (PV-R1), and with the pumping equipment broken up into eight separate stations, one beneath each straight section, the ring vacuum system can be ideally split, both physically and control wise, into eight similar segments, (see ANL-5956, p. 45). Each segment will include one octant and one straight section, with a pumping system consisting of two or three 32-in. oil diffusion pumps, two 130-cfm mechanical pumps, one 1000-cfm mechanical blower, valves, piping, and controls, that can be independently operated.

The unique feature of segment control enables any one segment to be brought up to atmospheric pressure for corrections without destroying the high vacuum in the others and thus assuring return to average operating pressure in a short time.

Because of the extreme caution that must be exercised, inasmuch as the inner vacuum chamber is sensitive to differential pressures (see Sect. IV, B), and because the oil in the diffusion pump is susceptible to oxidation, a number of protective devices have been provided. These require extensive and complicated circuitry.

To minimize the extent of the interlocking, a technique of step control was suggested by the Controls Group. This involves the use of a Master Selector Switch at the Control Panel which would control the valves of each segment through various steps until normal operating conditions are reached.

To illustrate the operation of such control, let us follow a segment in "normal" operating position through the four steps necessary to bring it from a vacuum to atmospheric pressure and then to return it again to normal operating conditions. Refer to Figure 9 for valve locations.

1. Master Selector Switch to "OFF" Position

a. When the Master Selector Switch of a segment is turned to "OFF" position:

(i) Valves associated with this segment have or assume the following positions and remain so during this master selector position when and if interlocking is satisfied:

Fig. 9

Ring Magnet High Vacuum System St. Section (Plan IV)

Valve	Location	Position
PV-1, PV-2	Straight section	Closed
PV-R1	On opposite ends of segment	Closed
PV-3, PV-4	Outer chamber line	Closed
PV-5, PV-6	Outer chamber	Open
PV-7, PV-8	Finishing line	Closed
PV-9, PV-10	Diffusion pump outlet	Open
PV-11, PV-12	Diffusion pump inlet	Closed
PV-13	Outer chamber line (on either side of segment)	Closed
PV-14	Finishing line (on either side of segment)	Open
PV-15	Bypass valve	Open
PV-17, PV-18, PV-19, PV-20	Gas inlet valves	Monitoring differential pressure between inner and outer chamber
PV-21, PV-22	Panic valves	Monitoring differential pressure between inner and outer chamber

(ii) When the valves assume the above positions, the following events occur:

(a) The inner vacuum chamber of the segment, which includes the straight section, becomes isolated from the other segments and from its pumps which consist of two 32-in.-baffled oil diffusion pumps. The two 32-in. pumps, however, continue to operate and are backed by the common finishing line.

(b) The 1000-cfm blower and the 130-cfm mechanical pump, MP-1, are isolated completely from the system. They can also be isolated at any position of Master Selector Switch by the "ON-OFF" switch. When the switch turns off MP-1, the blower circuit is de-energized and valves PV-1, PV-3, and PV-7 close and/or remain closed. The refrigerated baffle in the line just below PV-1 is operative by the "ON-OFF" switch and also goes off when MP-1 is off.

(c) The outer vacuum chamber of the segment and the portion of the roughing line that serves it is isolated from its pump, MP-2, a 130-cfm mechanical pump.

(d) The 130-cfm mechanical pump MP-2 is isolated completely from the system. This pump can also be isolated at any position of the Master Selector Switch by the "ON-OFF" switch. When the switch turns off MP-2, valves PV-2, PV-4, and PV-8 close and/or remain closed. The refrigerated baffle in the line just below valve PV-2 is operative by the "ON-OFF" switch and also goes off when MP-2 is off.

b. Raising to atmospheric pressure:

1. Bleed dry nitrogen through valve PV-19 or PV-20 into the inner chamber. When the pressure in the inner chamber is higher than that in the outer chamber, open panic valve PV-21 or PV-22 between inner and outer chamber.

2. The drop-out valves prevent pressurizing over one atmosphere.

3. The entire segment, except lines on the MP-1 and MP-2 side of valves PV-1, PV-2, PV-3, PV-4, PV-7, and PV-8, comes up to atmospheric pressure (see above).

Once the segment is divorced from the rest of the machine and is up to atmospheric pressure, it is then permissible to enter the straight section of this segment to make necessary changes or repairs.

Since neighboring segments as well as the two diffusion pumps in the segment at atmospheric pressure are still operating, no attempt must be made to open up valves between them and the segment of atmospheric pressure. Doing so may cause considerable harm and loss of time. For this reason, differential switches across critical valves, especially those equipped with key switches, may well be worth the cost.

If a diffusion pump must be entered for some reason, it can be turned off by an "ON-OFF" switch on the Control Panel. Until the oil is cooled down, it will continue to be backed by the common finishing line. This cooling period will be shortened by the flow of chilled water through coils around the pump boiler area when the switch is turned off. Once cooled, the pump foreline valve PV-9 or PV-10, depending on pump in question, can be closed by a key switch so that the diffusion pump can be entered without destroying the vacuum in the common finishing line.

If it is necessary to shut down all eight segments, the operator must be aware that switching of all eight Master Control Switches in the "OFF" position will leave no backing pumps available for the oil

diffusion pumps should it be desired to leave them operating. Thus, when all segments must be shut down, and it is desired to leave the oil diffusion pumps operating, the following procedure is necessary:

1. Leave Master Selector Switch in "Normal" position.
2. Close valves PV-11 and PV-12 in each segment.
3. Raise inner and outer chambers to atmospheric pressure as per Sect. 1b above.
 - a) PV-R1 and PV-R2 close when pressure in inner chamber reaches 1×10^{-5} torr.
 - b) PV-5 and PV-6 close when pressure differential between inner and outer chambers reaches 3 torr.

If it is necessary to shut down all eight segments, including oil diffusion pumps, or if such shutdown is brought about by a power failure, the Master Selector Switch position and let-up procedure, if this is necessary, is identical to that in the paragraph above. Return to operating conditions can be accomplished by first starting the oil diffusion pumps with all MP-1 pumps and the blowers they back. After starting of the oil diffusion pumps has been accomplished, the Master Selector Switch of four alternate segments can then be switched to the "OFF" position and normal pumpdown of these segments can proceed. The oil diffusion pumps of these segments are, meanwhile, being carried by the backing systems of the other four segments. When the first four segments are operating normally, the Master Selector Switch of the remaining four segments can be turned to the "OFF" position to accomplish their pumpdown while their oil diffusion pumps are being carried by the segments in "Normal" operation.

2. Master Selector Switch in "Start" Position

a. Before the Master Selector Switch is turned to the "Start" position, the mechanical pumps MP-1 and MP-2 in the segment should be turned on and the pressure in the lines between these pumps and valves PV-1, PV-2, PV-3, PV-4, PV-7, and PV-8 should be reduced to the point where the baffles below PV-1 and PV-2 can be turned on. Once the baffles are at their operating temperature, the mechanical pumps MP-1 and MP-2 are momentarily turned off.

b. As soon as MP-1 and MP-2 are turned off, the Master Selector Switch can be turned to the "Start" position.

c. When the Master Selector Switch is turned to the "Start" position, valves in the segment are at or assume the following positions when and if interlocking is satisfied:

Valve	Location	Position
PV-1, PV-2	Straight section	Open
PV-R1	On opposite ends of segment	Closed
PV-3, PV-4	Outer chamber line	Open
PV-5, PV-6	Outer chamber	Open
PV-7, PV-8	Finishing line	Closed
PV-9, PV-10	Diffusion pump outlet	Open
PV-11, PV-12	Diffusion pump inlet	Closed
PV-13	Outer chamber line (on either side of segment)	Closed
PV-14	Finishing line (on either side of segment)	Open
PV-15	Bypass valve	Open
PV-17, PV-18, PV-19, PV-20	Gas inlet valves	Monitoring differential pressure between inner and outer chambers
PV-21, PV-22	Panic valves	Monitoring differential pressure between inner and outer chambers

d. Start mechanical pumps MP-1 and MP-2.

1. Overload switches prevent harm due to oil lock.
2. Upon start, solenoid valve opens to allow oil to flow to pump from reservoir.
3. Water-flow switch insures proper cooling.

During the "Start" position of the Master Selector Switch, the mechanical pumps MP-1 and MP-2 will pump simultaneously on the inner chamber, including the straight section, and the outer chamber. Baffles at -40°C below the valves PV-1 and PV-2 prevent migration of mechanical pump oil into the high vacuum chamber.

When the pressure in the segment reaches 3 torr, a pressure switch on the blower inlet side will indicate this by a light on the panel.

3. Master Selector Switch Turned to "Intermediate" Position
When Light on Panel Indicates that Pressure at Blower
Inlet is at 3 torr.

a. When Master Selector Switch is turned to "Intermediate" position, valves are at or assume the following positions when and if interlocking is satisfied:

Valve	Location	Position
PV-1	Straight section	Open
PV-2	Straight section	Closed
PV-3	Outer chamber line	Closed
PV-4	Outer chamber line	Open
PV-5, PV-6	Outer chamber	Open
PV-7, PV-8	Finishing line	Closed
PV-9, PV-10	Diffusion pump outlet	Open
PV-11, PV-12	Diffusion pump inlet	Closed
PV-13	Outer chamber line (on either side of segment)	Opens if PDS is satisfied
PV-14	Finishing line (on either side of segment)	Open
PV-15	Bypass valve	Open
PV-17, PV-18, PV-19, PV-20	Gas inlet valves	Monitoring differ- ential pressure between inner and outer chambers
PV-21, PV-22	Panic valves	Monitoring differ- ential pressure between inner and outer chambers

b. Turn blower on.

- (i) PV-15 closes.
- (ii) Will not come on if MP-1 is not operating.
- (iii) Protected by a water flow switch.
- (iv) Protected by inlet pressure switch.

At this point in pumpdown, the mechanical pump MP-2 is pumping on the 6-in. outer chamber line and is evacuating the outer chamber in the segment through valves PV-5 and PV-6.

The blower, backed by its associated mechanical pump MP-1, is evacuating the inner chamber and straight section in the segment.

When the pressure in the high vacuum chamber drops below 1×10^{-2} torr, it will be so indicated from a controller, such as a thermocouple, monitoring the straight section. This controller will also complete the circuit to open the 32-in. valves above the pumps in the segment when the Master Selector Switch is turned to the "Normal" position, and the 32-in. valve Manual Switch is in "ON" position.

4. Master Selector Switch Turned to "Normal" Position
When a Light on the Control Panel Indicates that the
Pressure in the Straight Section Box is 1×10^{-2} torr
or Less

a. When the Master Selector Switch is turned to "Normal" position, valves are at or assume the following position when and if interlocking is satisfied:

Valves	Location	Position
PV-1, PV-2 PV-R1	Straight Section On opposite ends of segment	Closed Opens when pressure on either side of valve is 1×10^{-5} torr or lower
PV-3	Outer chamber line	Closed
PV-4	Outer chamber line	Open
PV-5, PV-6	Outer chamber	Open
PV-7	Finishing line	Open
PV-8	Finishing line	Closed
PV-9, PV-10	Diffusion pump outlet	Open
PV-11, PV-12	Diffusion pump inlet	Open when Manual Switch is on
PV-13	Outer chamber line (on either side of segment)	Open
PV-14	Finishing line (on either side of segment)	Open
PV-15	Bypass valve	Open
PV-17, PV-18, PV-19, PV-20	Gas inlet valves	Monitoring differential pressure between inner and outer chambers
PV-21, PV-22	Panic valves	Monitoring differential pressure between inner and outer chambers.

(i) Valves PV-11 and PV-12 will open if all conditions for a properly operating diffusion pump are met, such as:

- (a) 48-in.-diameter baffle at operating temperature.
- (b) Proper water cooling.
- (c) Heaters on.
- (d) Foreline valve open.
- (e) Forepressure below the set limiting forepressure.
- (f) Pressure in straight section below 1×10^{-2} torr.
- (g) Manual Switch is in "ON" position.

(ii) Operator should not switch to "Normal" position with Master Selector Switch if pressure on pump side of closed 32-in. valve is not in normal operating range unless Manual Switch for 32-in. valve over this pump is in "OFF" position.

During "Normal" position of the Master Selector Switch, the oil diffusion pumps in the segment, backed by MP-1 through a common finishing line, maintain a high vacuum in the inner vacuum chamber. Simultaneously, MP-2, through a common 6-in. roughing line, holds the outer chamber at a reduced pressure.

The two pumping systems, divorced from each other by the valving arrangement, are monitored by differential pressure switches to prevent rupture of the inner vacuum chamber should one of the pumping systems fail to maintain the proper balance.

Monitoring of the differential pressure between the inner and outer chambers is in effect during all positions of the Master Selector Switch and must remain in effect at all times. For this reason an emergency source of power must be provided to energize the differential pressure-sensing system should the regular power source go out. Failure to do so will result in costly delays.

Besides the continuous monitoring of the differential pressure between the inner and outer chambers, pressure monitoring takes place for other reasons. In the inner vacuum chamber, for instance, flange-type ionization gages or Phillips gages will continuously monitor pressures from the ultimate pressure achieved to 1×10^{-3} torr. From 1×10^{-3} torr to one torr, monitoring will be done by thermocouple gages. When the

pressure anywhere in the inner vacuum chamber rises above 1×10^{-5} torr, the PV-R1 valves will close on either side of the segment or segments affected. If the pressure in the inner chamber continues to rise in the segment or segments affected, the 32-in. valves will close when the pressure reaches $10 \mu (1 \times 10^{-2} \text{ torr})$. Of course, in the event that the pressure in the inner vacuum chamber of the segment or segments rises to 3 torr above that of the outer vacuum chamber, the pressure differential-sensing device will effect the closing of valves PV-5 and PV-6 and open gas-inlet valves to release dry nitrogen into the outer chamber. If release of gas is not sufficient to bring the differential pressure back within limits, a second pressure differential-sensing device will open panic valves between the two chambers when a pressure differential of 6 torr is detected. After the problem is located and corrected, return to normal operation is done through step control of the Master Selector Switch as described earlier in this paper.

The outer vacuum chamber is monitored by the pressure differential-sensing device mentioned above. If the pressure in the outer chamber rises to 3 torr above that of the inner vacuum chamber, valves PV-5 and PV-6 will close, PV-R1 on either side of the segment will close, PV-11 and PV-12 will close, and dry nitrogen gas will be released into the inner vacuum chamber. Should this be insufficient to bring the differential pressure back within limits, a second pressure differential-sensing device will open panic valves between the two chambers when a pressure differential of 6 torr is detected. When the problem is corrected, return to normal operation is done through step control of the Master Selector Switch as described earlier in this paper.

The finishing line requires close monitoring because of the backing requirements for the oil diffusion pumps and also of the effect of a malfunction on all segments. A thermocouple inserted in the finishing line midway between the two diffusion pumps in each segment will monitor the pressure in the finishing line. When the pressure in the finishing line rises to a preset pressure somewhere between the operating pressure ($\approx 3 \times 10^{-2}$ torr) and the limiting forepressure ($\approx 1 \times 10^{-1}$ torr) of the oil diffusion pumps, contact is made in a meter relay. Valves PV-14 on either side of the affected segment or segments will close, and the blower comes on to take over the job of backing the diffusion pumps. The blower continues to back up the diffusion pumps until the problem is corrected; the finishing line pressure drops below the contact point; and the operator presses the reset button. If the blower is not sufficient to hold the pressure in the finishing line of an affected segment, a second contact will be made when the pressure reaches the limiting forepressure ($\approx 1 \times 10^{-1}$ torr) of the oil diffusion pumps. When this contact is made, valves PV-9, PV-10, PV-11, and PV-12 in this segment will close. When the valves PV-9 and PV-10 close, the diffusion pump heaters and refrigeration to the 48-in. baffles above the oil diffusion pumps will shut off.

If the malfunction in the segment which caused the rise of pressure in the foreline is due to a faulty mechanical pump, MP-1, this pump and its related blower can be isolated from the system by merely switching MP-1 to "OFF" position with the "ON-OFF" toggle switch. The diffusion pumps can be returned to the common finishing line by isolating the mechanical pump MP-2 in the segment from the roughing line by a key switch and using it temporarily to reduce the pressure in that portion of the finishing line serving the segment. If the malfunction in the segment is due to some other reason than the backing pumps, return to normal operation after the problem is corrected is done through step control of the Master Selector Switch, as described earlier.

The 6-in. roughing line also requires close monitoring because a pressure rise in the outer chamber of any one segment can, if not isolated in time, cause an interruption in the normal operation of the other segments. A thermocouple gage placed midway between valves PV-5 and PV-6 in the 6-in. roughing line will sense any rising pressure. When a rising pressure in the vicinity of any one of the thermocouple gages reaches ≈ 1.5 torr, the valves PV-13 in the 6-in. roughing line on either side of this gage will close and isolate the outer chamber, and that portion of the 6-in. roughing line that contains the gage, from the rest of the machine. With the PV-13 valves isolating the portion in which the malfunction occurred, the rest of the segments affected will recover. In the troubled portion a continued rise in pressure to 3 torr will, of course, cause the pressure differential-sensing device monitoring the outer chamber in this portion to affect the closing of valves as described previously. Once this occurs, it can readily be determined whether the mechanical pump MP-2 in this segment or the outer chamber itself in this segment is to blame. If MP-2 is at fault, it can be isolated by merely switching MP-2 to "OFF" position with the "ON-OFF" toggle switch. The outer chamber and roughing line isolated by valves PV-13 can be returned to the rest of the system by isolating MP-1 and the blower in this segment from the finishing line by turning the Master Selector Switch to the "OFF" position, and return to normal operation is done through step control of the Master Selector Switch as described earlier in this paper.

Should the problem in the segment be due to some malfunction in the outer chamber itself, return to normal operation after the problem is corrected is also done through step control of the Master Selector Switch.

As was pointed out earlier, the purpose of the Master Selector Switch is to affect given valve arrangements for a selected series of events until a segment is brought to a desired operating condition. Under certain abnormal situations, however, manual control of certain valves would be advantageous and would result in a considerable saving of time.

Control wiring will include provisions for key switching all valves in the segment in case any valve, not initially provided with a key switch, can be so provided should the need arise. Since key switching increases the possibilities of error, provisions will be made for the installation of pressure differential switches across any valve which may require maximum protection against erroneous operation.

B. 25-foot "Spacemetal" Chamber Behavior under Vacuum
(H. Lucks and J. S. Moenich)

A "Spacemetal" (see ANL-6032, p. 13) inner vacuum chamber, 25 ft by 32 in. by $5\frac{1}{4}$ in. and having a total exposed surface area of approximately 25,000 in.² and an estimated nitrile phenolic tape ("Scotchweld AF-31") exposure of 15 in.², was constructed under the supervision of W. B. Hanson. The fabrication procedure has been outlined in ANL-6152, p. 24.

The experimental program for the 25-ft inner chamber was chosen to be analogous to that of the 3-ft chamber discussed in ANL-6152, p. 32, with one notable exception. The chamber was operated at room temperature, because space limitations prevented the placing of heaters about the inner chamber. The average spacing for pumping between the outer chamber, simulating the magnet blocks, and inner chamber is approximately $\frac{5}{32}$ in.

Measurements were made of the times taken to pump down the chamber under the following conditions:

1. chamber exposed to dry nitrogen and evacuated with the aid of a cold finger;
2. chamber exposed to dry nitrogen and evacuated without cold finger;
3. chamber exposed to room air and evacuated without cold finger; and
4. chamber exposed to room air and evacuated with the aid of a cold finger.

Listed below are the results and the important parameters of the system:

Gas	Time (hr) Required to Reach 1×10^{-5} mm Hg	
	No Liquid Nitrogen	Liquid Nitrogen
Room Air	17	4.3
Dry Nitrogen	9.5	2.8
Outgassing Rate: $0.54 \mu\text{l}/\text{sec}$ Leak Rate: $2.94 \times 10^{-2} \mu\text{l}/\text{sec}$ at 1 mm Hg for helium Effective pumping speed of retractable cold finger: $5000 \text{ l}/\text{sec}$		

The time required to evacuate the system to 1×10^{-5} mm Hg is strongly dependent on the amount of condensables present on the surfaces of the chamber. With dry nitrogen, the chamber had the least amount of water vapor present, whereas with room air the chamber had the greatest amount of water vapor present on its surfaces. The 13-hr difference in getting to 1×10^{-5} mm Hg for a chamber exposed to room air indicates the usefulness of the retractable cold finger in removing considerable amounts of condensable vapors from the system.

Assuming that the outgassing rate of the final 54-ft "Space-metal" chamber remains sensibly the same as in the present chamber, then the time required to reach 1×10^{-5} mm Hg from a condition in which the chamber was at atmospheric pressure would be about one hour, since, in the proposed vacuum system, there will be available three times the effective pumping speed that was available for evacuation of the prototype chamber. The ultimate pressure in an octant will probably be about 10^{-7} mm Hg.

In a final series of experiments, the chamber was subjected to pressure differentials, both internal and external, to determine when rupture would occur. The chamber was found to rupture when the external pressure was greater than 44 mm Hg. When the internal pressure was greater, rupture did not occur until the pressure differential was 500 mm Hg; this high value was found because the chamber was somewhat sustained upon expansion by the walls of the outer chamber. There need be no fear of rupture during operation of the ZGS, for the pressure differential between inner and outer chambers will be about 0.2 mm Hg.

C. The 32-in. Pump Test Program (J. S. Moenich and H. Lucks)

Because 32-in. oil diffusion pumps are to be used in the vacuum system (see ANL-6032, p. 18), available pumps of this size were tested under identical operating and gaging conditions to get a relative measure

of their characteristics. Consolidated Vacuum Corporation (CVC) and National Research Corporation (NRC) had such pumps available for test. Kinney Manufacturing Division at the time had such a pump in the developmental stage and willingly let us test it.

Figure 10 shows the comparative speeds of the pumps under conditions stated thereon.

Pump	Consolidated MC-28000	NRC H-32-P	Kinney 32"	Remarks
Backing	KDH 130	KDH-130	KDH-130	
Heat Input	12 kw	10 kw	10 kw	Recommended
Gaging	RG-75	RG-75	RG-75	Heated Envelope-350°F
Limiting Forepressure under load	≈130 microns	≈110 microns	≈45 microns	McLeod Gage
Speed vs Inlet pressure
Pumping Fluid	convoil-20	convoil-20	convoil-20	CVC

Fig. 10

Comparative Speeds of Pumps Tested

Of the three pumps tested, the NRC pump was selected for continuation of the pump and baffle-testing program. The selection of the NRC pump over the Consolidated pump was primarily because it was 24 in. shorter. This is of importance because of the limitations of vertical space beneath the straight sections of the ring vacuum system.

To eliminate the need of additional height which would be necessary to offset entrance impedance caused by the transition from the

48-in.-diameter baffle to the 32-in. pump, the upper portion was expanded to 48 in. The upper portion of the NRC pump was replaced with a frustum of a cone having an altitude equivalent to the 27 in. removed.

Tests with the modified pump showed a considerable reduction in pumping speed, and a few experiments soon verified the fact that the cut was too low. The pump was modified to raise the cut from the 27-in. point to a point 17 in. below the original 60-in. height of the pump. Tests at various heat inputs, however, still indicated some deterioration from the pre-expansion performance and suggested that raising the cut another 6 in. would be advisable.

Based on these observations, specifications were written for the expanded 32-in.-high vacuum oil diffusion pumps to be used for the ring vacuum system of the Argonne Zero Gradient Synchrotron.

The expanded 32-in. NRC pump described above will be used for testing of the prototype 48-in.-diameter baffle.

V. THE RADIOFREQUENCY SYSTEM

A. Study of Characteristics of the Power Amplifier and the Radiofrequency Cavity Including Effects of Beam Loading (C. Turner)

The bunches of protons in the synchrotron are accelerated by the voltage at the gap in the rf cavity. In general, the power absorbed by the beam is a small fraction of that dissipated in the cavity. If the number of ions per pulse is continually increased, eventually the power absorbed by the beam will be of the same order or even greater than that dissipated in the rf cavity. This constitutes a loading of the power amplifier and the rf cavity. The load is variable, depending on the effective "phase" of the bunches of particles with respect to the voltage across the gap.

Assuming that the parameters of the power amplifier and the rf circuit are known, we can examine the way in which the following effects depend on the beam intensity, its phase, and the method of tuning the rf cavity:

1. serious distortion of the rf accelerating waveform; and
2. demands on the power amplifier so as to avoid overloading.

It is anticipated that this study will reveal:

1. whether or not there is an optimum way of tuning the rf cavity; and
2. the maximum number of ions per pulse which can be taken through the entire acceleration cycle (with given phase at injection) without circuit overloading or undue waveform distortion.

B. Synchrotron Radiofrequency System (J. M. Benade, R. Daniels, T. de Parry, J. Dinkel, C. Laverick, J. H. Martin, and J. Simanton)

The master oscillator for control of the frequency has been completed in what possibly will be the final form. It is now undergoing extensive tests in a mocked-up section of the control room. Static tests on stability and repeatability indicate generally adequate freedom from noise and environmental changes. The system has a fixed-frequency stability of better than one part in 10^4 over a period of 30 hr after a warm-up time of 4 hr. The frequency-modulation noise appears to be less than one part in 10^4 . This noise seems to occur primarily at low frequencies, with very little in the region of synchrotron oscillation frequencies. A programmer has been built and is in operation for simulating the synchrotron pulses for testing the master oscillator system.

The final design of the power amplifier has been underway for about a month. The recent requirement that the rf system make up the loss of beam energy in a thin scatter target has necessitated a substantial increase in the power-handling capability of the power amplifier. The demand for peak rf voltage on the cavity was raised from 16 to 20 kv to accommodate the increased rate of rise of the magnetic guide field and also to 30 kv for a 0.2-sec period, when the beam is passing through the target.

Because of this and the deterioration of the Q of the ferrite at high rf flux densities, the power demand during this interval has been raised from about 80 to about 500 kw. Not all the changes to accommodate this increase will be proven on the prototype amplifier, but will be used for the first time on the final version now under design. The preparation of the specifications for the resized power supplies for this power amplifier is essentially complete. Bids for them will be invited within about one month.

The final design of the rf cavity is nearing completion. Water-carrying copper shims will be placed between adjacent ferrite frames for the purpose of heat removal. Bids have been invited for the aluminum oxide frames to fill the gaps across which the rf voltage will appear. Considerable difficulty was encountered by the original supplier of these frames. It may be possible to get one good frame out of their efforts. The supplier of the ferrite frames is in the process of replacing two of the frames which were too far outside the specifications. Thirty-one of these frames are now on hand. Eventually, three more will be received. Thirty will be selected and installed.

The power supply for the cavity bias system has been on hand for some time. The current controller has been tested and found to have certain frailties and inadequacies which are now being corrected. A programmer for testing this system is now in operation. The cooling equipment now in use with this system will be installed in the final arrangement.

Beam induction electrodes for determining the total charge q at a radius R , are being designed to fit the space envelopes available for them. The R_1 electrodes will be placed in straight sections S_3 , L_4 , and S_4 , and the q electrodes in straight sections L_2 and S_2 . The q electrodes and electronic systems are expected to have pass bands somewhat greater than 100 Mc/sec. From the q electrodes will be derived the beam charge information averaged over a few microseconds, the beam charge at a given azimuthal position averaged over a few nanoseconds, and the phase of the beam bunches with respect to the cavity voltage.

Measurements of the proton beam with induction electrodes have identified the areas of validity of the measurements. All measurements refer to steady-state conditions. A chamber for testing these as

well as possibly the R_2 electrodes is nearing completion. In this chamber, pulsed electron beams will be injected with particle velocities and pulse durations similar to those expected in the synchrotron. This will permit the possible development of the R_2 electrodes and the measurement of the dynamic characteristics of the q and R_1 electrodes.

The preamplifiers for the R_1 system are finished and need only to be packaged. The design of the q amplifier chain is finished and awaits packaging. The remainder of the beam tracking and display equipment is at various stages of design and construction.

VI. BEAM EXTRACTION

A. Theory of Resonant Extraction from Sectorial Cyclotrons (L. C. Teng)

Because of the recent interest at ANL in a variable-energy multiparticle isochronous sectorial cyclotron and because of the troubles other laboratories encountered in extracting the accelerated beam from such a cyclotron, a re-examination has been made of the scheme of beam extraction by resonant excitation of the radial betatron oscillation. For a three-sector cyclotron, the radial betatron oscillation together with the most general forcing (excitation) terms is given by the equation

$$\frac{d^2x}{d\theta^2} + (A + B \cos 3\theta) x = \sum_{m=1}^{\infty} \left(\sum_{n=2}^{\infty} a_n^m x^n \right) \cos(m\theta + \phi_n^m) .$$

The condition for isochronism gives one equation of constraint on the coefficients A , B , a_n^m , and ϕ_n^m . The linear terms alone in the equation give a triangular phase diagram without stability limit (limit at ∞). The inclusion of the essential nonlinear terms (terms with $m = 3$) on the right-hand side gives finite stability limit with finite stable phase area. The addition of other terms or alteration of the coefficients of the terms with $m = 3$ will modify the shape and the area of the stable phase region. The object is then to introduce the proper terms to reduce the stable phase area down to zero and to modify the now open phase curves to have only one opening at the desired azimuth, so that the ions will stream out at one azimuth, all the while keeping the isochronism condition intact. Analytically, one treats all the right-hand terms in the equation by first-order perturbation theory and retains the generality (all mn terms) until the last step when specific values of the coefficients a_n^m and ϕ_n^m are suggested by the form of the first-order perturbation solution.

B. Magnet Problems

Systems for delivering particle beams of the required type and momentum from the ZGS to convenient positions in the proton and meson areas, where they can be used for experiments, are being planned. Some calculations have been performed in order to design components and optimize their cost. Momentum analysis, charge separation, and steering of particles can be done with bending magnets. For some experiments mass separations may be desirable. This can be achieved by a combination of momentum and velocity separation. Velocity separation will be studied later.

1. Quadrupole Magnets (P. Kalmus and S. Marcowitz)

Calculations of field gradients, flux densities, current densities, and costs were carried out for quadrupole magnets having the general shapes shown in Figure 11. Design (1) was somewhat limited by saturation at the base of the pole. A good design from the cost point of view would be like (1) with the poles slightly widened at the base. For ease of construction, the yoke would probably be square or octagonal instead of circular.

Fig. 11

Quadrupole Magnet Shapes

2. Bending Magnets (P. Kalmus and S. Marcowitz)

Picture frame bending magnets are being considered. Particles having the full momentum are deflected about 2.5° per meter of path in a field of 20 k gauss. Considerable lengths of bending magnets would therefore be required to obtain the large angular deflections originally desired.⁸ Cost estimates show that the price of these magnets is strongly dependent on the gap width. Furthermore, bending magnets can be more expensive than the quadrupoles used with the same beams. Thus beam-transport systems should be designed in such a way as to keep gaps in the bending magnet small.

3. Beam Systems (P. Kalmus and S. Marcowitz)

Momentum-analyzed beams, focused in the meson area, are being studied. Four systems being considered are:

- (a) a quadrupole doublet followed by a bending magnet;
- (b) a triplet followed by a bending magnet;

⁸See A. V. Crewe et al., Layout of the Experimental Areas of the 12.5-Bev Accelerator, Internal Memo CHKWY-3 (Jan 1958).

- (c) two doublets placed symmetrically before and after a bending magnet; and
- (d) two triplets placed symmetrically before and after a bending magnet.

The spacing, lengths, and energizing of the components of these systems are being varied to give the maximum transmission of particles. The costs will then be compared to decide which system should be used. At present, only the calculations for the third system have been completed.

4. The Optical Properties of Bending Magnets and Quadrupoles (L. Ratner)

The design of a precision wire trajectory system for measuring the "optical" properties of bending magnets and quadrupoles has been completed and components purchased. Fabrication is now under way. Components are such that momentum will be known to $\pm 0.03\%$ maximum deviation and coordinates with respect to magnets to $\pm 0.09\%$ maximum deviation. The probable error in any series of measurements should, therefore, be better than $\pm 0.05\%$.

C. Proton Beam Transport (L. Ratner)

The positions and sizes of the two bending magnets in the L-2 and L-4 straight sections, which lead to the proton areas, have been specified. Bending magnet No. 1 will be the same as the Piccioni ejection magnet and No. 2 will be a "picture-frame" type of magnet, about 12 ft long. The primary proton beam will then pass through the yoke hole of the next octant and enter the switching magnet. It is more economical to break up this magnet into two sections, SW 1 and SW 2, than to make one long magnet. By requiring SW 1 to bend only $\pm 2\frac{1}{2}^\circ$, we can use a 44-in.-long "picture frame" magnet with an 8-in.-wide gap.

Section SW 2 would then have to be a 96-in.-long, "C"-type magnet with the open side toward the machine to allow passage for the $-2\frac{1}{2}^\circ$ and undeflected beams. Then SW 2 would be required to bend the beam only $+5\frac{1}{2}^\circ$ to send it toward the branch tunnel. Although the same power is necessary, we effect a saving of about \$20,000 in copper and steel, and we do not have to consider SW 2 until we are ready to put in use the 30° bending magnet for the secondary proton area.

D. Meson Beam Production and Transport (L. Ratner)

An estimate was made of the number of secondary particles which could be produced by the 10^{13} protons per pulse in the ZGS on an internal target. Target positions and exit channels were reinvestigated in

order to prepare for a magnetic field survey which is soon to be made on the $\frac{1}{7}$ -scale model. It was also determined that if the first element of the beam transport system (a quadrupole doublet) is placed in the L-3 straight section, from which the beam is diverted to the meson area, rather than in the meson wall, we can gain a factor of $1\frac{1}{2}$ in the number of particles transmitted. There is also a reduction of about $1\frac{1}{2}$ in the size of the beam, which leads to a saving of about $\frac{1}{3}$ in the cost of the first bending magnet for the system. There is sufficient space in L-3 for such a quadrupole if we move channel B from 14° to 17° . This does not impair the usefulness of channel B in any way.

VII. Targetry

A. Study of Multiple Traversal of an Accelerated Beam in a Synchrotron through a Thin Target (L. C. Teng)

When a high-energy proton beam goes through a target the non-nuclear interactions produce a 3-fold effect;

- (a) a reduction in the average energy of the beam, $\bar{\Delta}$;
- (b) an increase in the energy spread of the beam with a mean absolute spread $\langle |\Delta - \bar{\Delta}| \rangle$; and
- (c) an increase in the divergence of the beam caused by multiple small-angle scattering with a mean-squared spread $\langle \theta^2 \rangle$.

For various target materials and thicknesses x these quantities have the following values:

Be

x (mil)	$\bar{\Delta}$ (Mev)	$\langle \Delta - \bar{\Delta} \rangle$ (Mev)	$\langle \theta^2 \rangle$ (rad ²)
1	0.00549	0.000788	0.0676×10^{-9}
2	0.0114	0.001575	0.135×10^{-9}
3	0.0175	0.00236	0.203×10^{-9}
4	0.0237	0.00315	0.270×10^{-9}

Al

x (mil)	$\bar{\Delta}$ (Mev)	$\langle \Delta - \bar{\Delta} \rangle$ (Mev)	$\langle \theta^2 \rangle$ (rad ²)
1	0.00793	0.00128	0.327×10^{-9}
2	0.0166	0.00256	0.654×10^{-9}
3	0.0255	0.00383	0.982×10^{-9}

Ni

x (mil)	$\bar{\Delta}$ (Mev)	$\langle \Delta - \bar{\Delta} \rangle$ (Mev)	$\langle \theta^2 \rangle$ (rad ²)
1	0.0257	0.00423	2.19×10^{-9}

The reduction of the average energy $\bar{\Delta}$ can be compensated by the acceleration from the rf cavity. Assuming a peak rf voltage from the cavity of 29.3 kv, we see that if the beam strikes the target every revolution, we can use a Be target up to 4 mils thick, an Al target up to 3 mils

thick, and a Ni target up to 1 mil thick. The allowable thickness of the target can be increased if the target is so small that the beam does not strike the target every revolution, thereby having a much smaller average energy loss per revolution.

The induced energy and angular spreads cause a diffusion-type motion of the phase points in the synchrotron and betatron-oscillation phase spaces, respectively. The number of revolutions, n , before a significant fraction of the beam is lost due to diffusion of the phase points outside the stability limit in the phase spaces are given below.

Synchrotron Oscillation for Be Target

x (mil)	n
1	10×10^6
2	1.6×10^6
3	0.38×10^6
4	0.07×10^6

Betatron Oscillations

x (mil)	n		
	Be Target	Al Target	Ni Target
1	2.8×10^4	5.8×10^3	0.87×10^3
2	1.4×10^4	2.9×10^3	
3	0.94×10^4	1.9×10^3	
4	0.70×10^4		
nx (in)	28	5.8	0.87

Two characteristics of these numbers are significant. In the first place, we note that n for betatron oscillations is much smaller than for the synchrotron oscillation, so that the beam will eventually be lost because of the induction of the vertical betatron oscillation by multiple scattering in the target, causing the beam to strike the top and bottom of the vacuum chamber. In the second place, we see that the equivalent thickness nx of the target passed through by the beam is independent of x for a given target material and is, for all three target materials, of the same order of magnitude as the nuclear reaction length. The most favorable ($nx >$ nuclear reaction length) case is for the Be target.

The cooling of the very thin targets presents a severe problem. Conduction cooling across the target is totally ineffective. The thermal radiation cooling at 1000°C and 2000°C is given below:

	Radiation Cooling
1000°C	$\epsilon(14.8) \text{ watt/cm}^2$
2000°C	$\epsilon(151) \text{ watt/cm}^2$

where ϵ is the emissivity of the surface and can be made to be close to unity. For a Be target and a beam of 10^{13} protons, the total energy ΔE transmitted to the target before the beam is lost is

x (mil)	ΔE (Joule)
1	248
2	258
3	264
4	268

Even if we stretch the total time for the beam hitting the target to 0.2 sec (the duration of flat topping of the guide magnetic field) by making the target small, we still cannot dissipate the heating of a stationary target. Thus, some fancy scheme of moving the target will have to be employed.

B. Beam-Target Interactions (L. C. Teng)

When a synchrotron beam is moved radially either by rf acceleration or by variation of the magnetic guide field onto or off a target, neglecting the energy spread and the small angle multiple scattering caused by the target, the average loss of energy will either damp or induce radial betatron oscillation. This investigation can be broken up into the following parts.

1. Target on inside

a. Beam moved by radio frequency

- (1) Beam moved into the target
- (2) Beam moved off the target
- (3) Beam staying in the target

b. Beam moved by varying magnetic field

- (1) Beam moved onto the target
- (2) Beam moved off the target
- (3) Beam staying in the target

2. Target on outside

(Same subdivisions as above)

In each case we want to evaluate the time behavior of the amplitude of radial betatron oscillation showing the dependence on the rate of beam motion, the target material and thickness, and the initial amplitude of radial betatron oscillation.

C. ZGS as Source of High-energy Neutrinos (L. C. Teng)

It has been proposed by Lee and Yang that high-energy neutrinos could be used as projectiles to study weak interactions. A crude estimate was made for the flux of the neutrino beam obtained from the decay of pions. Assuming an average multiplicity of 2 for the production of pions per nuclear event, an optimistic 12.5-Bev proton beam from the ZGS of 10^{13} protons/sec, and a focusing magnetic system for charged pions with an acceptance of ± 0.1 radian in the Labsy, we obtained a pion current of $0.46 \times 10^{12} \text{ sec}^{-1}$. If the path length of the pions is taken to be 10 m, we get a neutrino current of $2.4 \times 10^{10} \text{ sec}^{-1}$ spread over an area of $7.07 \times 10^4 \text{ cm}^2$ at the position of the detector, which is separated from the pion path by 10-m thick shielding. Taking the theoretical cross section of the inverse β -decay reaction for 1-Bev neutrinos given by Lee and Yang and assuming a 1000-kg detector, we get a reaction rate of about 2 per hour, which is quite good for this type of experiment.

D. Kinematics of $\pi^- + p \rightarrow \pi^0 + n \rightarrow 2\gamma + n$ $\pi^- + p \rightarrow \pi^0 + \pi^0 + n \rightarrow 2\gamma + 2\gamma + n$ (L. C. Teng)

Assuming isotropic distribution for the outgoing π^0 in the Barsy (Baricentric System of Reference) of π^- and p for these reactions (specifically, for the $2\pi^0$ reaction this means no pion-pion interaction in the final state) we see that the angular and energy distributions of the decay γ rays are given entirely by geometrical phase-space considerations. These angular and energy distributions of the outgoing γ rays for both reactions are evaluated in both the Labsy (Laboratory System of Reference) and the Barsy for various incident π^- energies on stationary protons. For the one π^0 reaction these distributions can be expressed in analytical forms, and for the two π^0 reaction these distributions can be reduced to forms containing only one quadrature which may be calculated numerically on the IBM-704.