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Quarterly Status Report on the
Medium-Energy Physics Program
for the Period Ending July 31, 1967

UNITED STATES
ATOMIC ENERGY COMMISSION
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I. SUMMARY

Accelerator Structures

Drift Tube Structure--201.25 MHz

A major achievement in the Alvarez accelerator development has been the innovation for operating the drift tube sections of the linac in the $\pi/2$ mode. Conventionally, the Alvarez device operates in the 0 mode where the electric fields between accelerating gaps at any instant of time are all in phase. By insertion of radial posts into the vessel opposite each drift tube and by adjusting their depths of penetration so that they act as resonant elements at the same frequency as the main accelerator cells, the entire structure with its posts can be made to operate in the $\pi/2$ mode; the posts then act in an analogous fashion to the side-coupled cavities in the 805-MHz portion of the machine. With this innovation, the system displays the 0 mode field characteristic between gaps with the added advantage that the field distributions are less sensitive to frequency errors by a factor of 200 or more. The tank is also less sensitive to beam loading effects than is one of conventional design. The post couplers require very little additional rf power, are readily tunable, and have no mechanical interaction with the drift tubes.

Side-Coupled Structure--805 MHz

Fabrication and installation of the Electron Prototype Accelerator (EPA) has been continued during this period. Approximately one-fourth of the 100 cell $\beta = 1$ structure has been completed and is in place in its radiation enclosure ("Iron House"). Hydrogen furnace brazing of the resonant cells is being accomplished at LASL.

Model M, a 6-cell graded- β electron accelerator has been tested to demonstrate its usefulness as an injector for the EPA. An output beam of 1.1-MeV electrons at 20 mA peak current was obtained with a gun potential of 100 kV and rf drive power of 66 kW. Beam energy spread was approximately 10%. The device will be installed in the Iron House for use with the EPA at the appropriate time.

A bridge coupler was fabricated and installed to replace the center section of the 61-cell Model K tank described previously. The performance of the bridge under rf power drive appears to be satisfactory, but continued work is under way to match the feed waveguide to the tank load via this bridge configuration.

RF Power Sources

201.25 MHz

Greatly improved operational stability of the intermediate power amplifier prototype has been achieved. Radiofrequency leakage in the driver chain resulted in significant cross talk and instabilities followed by frequent crowbarring and erratic operations. Proper component relocation and shielding of the driver chain through the 4616 tubes have improved operations to the point where they have become routine. A suitably substantial 56-kW power supply was developed to permit 12% DF operation at the 200-kW level.

The upper plate blocking capacitor in the 7835 power amplifier failed after 1 h operation at 6% DF, 3 MW output, indicating a potential weakness which requires attention. Continental Electronics, the supplier, has developed a replacement, claimed to be improved, and it will be tested shortly. Meanwhile a substitute of old design is in situ, permitting continued study of performance of the system, but with operational periods being constrained by present hard-tube modulator emission limitations. An improved modulator for this service is under construction.

805-MHz

The most recent prototype Coaxitron received from RCA survived LASL test for only 47 h before failure. Its operation was erratic, even at low DF's. At time of failure, the input match began to fluctuate wildly and the tube pressure rose upon application of drive power. An older 3% DF tube was reinstalled to permit use of the test stand as an rf source for other purposes. It has been decided to discontinue further development of the Coaxitron as a final machine rf power source.

The Litton klystron test results are encouraging, with the power output having reached 1.25 MW at 6% DF. Efficiency of about 33% is calculated, with a gain of approximately 54 dB. Detailed studies of performance have been under way, considering particularly its performance sensitivity to load impedance variations with $VSWR \leq 1.5$. Generally stable operations were experienced.

The Raytheon Amplitron has been under power for some 200 h. Peak power of up to 1.4 MW was achieved using a resistive load; the efficiency was ~60%. Unwanted off-frequency oscillations observed when driving a resonant load were reduced by insertion of a LASL-developed ferrite isolator between Amplitron and cavity, and by use of a waveguide filter. Performance tests using resonant loads may thereby be continued.

Accelerator Control and Instrumentation

An encouraging success has been realized by the computer control group. The Amplitron test stand was carried through its turn-on sequence from the console by computer. The procedure entailed the integrated functioning of the computer and its programs, the operator console hardware, the Remote Information and Control Equipment and its associated input-output chassis, the Computer Interface Unit, and the Module Interface Unit.

The computer's operational reliability has been under close scrutiny for four months. Present indications are that its reliability is satisfactory.

Active planning and design were conducted in preparing the controls group for their responsibilities in computer control of the EPA.

Injector System

Preliminary plans for the construction of the prototype Cockcroft-Walton power supply to be used in the injector development program have been received from the Haefely Co. of Switzerland. Except for minor changes in some mechanical features, their proposal is deemed satisfactory.

An experimental ion source has been run almost continuously over the past $2\frac{1}{2}$ months at a cathode heater power of 70 W. The ion-source

proton current has been measured and checked calorimetrically, and ion current pulse shapes have been observed. Ion beams of from 20-40 mA at extraction voltages of from 20-35 kV possessed satisfactory emittance areas, i.e., 8π cm-mrad at 20 mA and 20 kV. The source was run at 6% DF with 500- μ sec pulses. Emittance measurements were conducted by replacing the Faraday cup with a collector system of slots and a quartz plate. Pressures as low as 10^{-8} torr have been obtained with a hot filament but with the hydrogen source removed.

Continued effort is reported in magnet engineering in the transport system.

Accelerator Physics

Numerical studies were continued of particle motion in various portions of the linac. Results include new tabulations of the basic parameters of the drift tube and waveguide portions, studies of the effects of quad magnet aberrations on the transverse motion, and buncher studies.

Experimental Area

The summer efforts to review and improve preliminary planning for the experimental area building configuration have been substantial and rewarding. This review is directed toward the establishment of an experimental area which is enhanced in flexibility in light of presently imagined experimental activities during early operational years of the facility, but with economy of construction in mind. A significant aspect of the planning involves questions about design of remote-handling apparatus. The intensity of effort in this program has been adjusted to assure a normal course of design effort through the usual phases from criteria development to contract drawings, which are to be prepared by early 1969.

A substantial portion of the mechanical and control systems for implementing the target developmental work is designed and in procurement. The initiation of the experimental program itself must await the attainment of a high-intensity electron beam from the EPA.

Programs suitable for pion and muon channel design have been obtained from CERN; they treat beam transmission parameters through a configuration of slits, quadrupoles, deflection magnets, and drift spaces. These programs are in the process of being applied to LAMPF objectives.

Project Scheduling and Facilities Planning

The preliminary program management network using IBM PERT Cost II for LAMPF accelerator construction scheduling has been developed to the 90% completion point. Network diagramming to Level III, where all group activities have been integrated, is essentially complete. The analysis has demonstrated the feasibility of obtaining a proton beam to Target Cell A by Dec. 31, 1971. The remaining effort to derive the initial schedule for departure into the machine construction era will entail reworking interface constraints between groups, shifting manpower to more critical enterprises, and making corrections necessary to take into account improved knowledge of the schedule for building and site construction. The input deck for this network now consists of 7200 cards describing milestone events, activities, manpower, event initiation, completion interfaces, and entry control. It is tentatively concluded that the choice of Level III is appropriate for a project of the complexity of LAMPF.

The site preparation work on Mesita de Los Alamos has progressed very well. The contract is slightly ahead of schedule, having passed the 72% completion point at the end of the report period. The water and gas lines are in place, and the access road is almost ready for use; the excavation work for the Injector Building, Beam Channel, and Experimental Area is in the final stages. Clearing of the areas for the Laboratory-Office Building and Equipment Test Laboratory Building (ETLB) has been completed.

Title II A-E design of the Injector and Alvarez accelerator buildings has been reactivated. Design had been held at the 85% completion point since last year to permit incorporation of any modifications deemed necessary in the interim before developing contract drawings.

Substantial effort was given to the Title I and Title II planning for the ETLB. Interim Title II drawings have been reviewed, with the expectation that these drawings will be ready for contractors' study by Sep. 1, 1967. The Laboratory-Office Building Title II design work by W. C. Kruger & Associates of Santa Fe is well advanced. It is expected that contract drawings for this facility will also be prepared by Sep. 1. The firm of Uhl & Lopez of Albuquerque was awarded the contract for the A-E design of the electrical substation during this period. The Title I review was conducted and well received. This firm is now actively engaged in the Title II preparation which is expected to be ready for contractors' study by the end of September. Title II design work is being continued on the site water and waste-disposal systems and is expected to be ready for issuance by the end of October.

Publications

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"Hard Tube Modulators for the Los Alamos Meson Facility," *Proc. Modulator Symposium*, Ft. Monmouth, N.J., May 1966. Army Electronics Command and Advisory Group on Electron Devices, 1967, p. 50.

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II. ACCELERATOR STRUCTURES

Introduction

A major achievement in the accelerator structures research is the development of a resonant coupling geometry for the drift tube accelerator section of the linac. The system consists of simple posts inserted in the side of the cavity which are made resonant with the same frequency as the main accelerator tank. Application of the coupled resonator model gives predictions of the performance which have been verified in extensive measurements. With these post couplers installed and tuned in a drift tube tank, an improvement of greater than a factor of 200 has been obtained in the sensitivity to tank tilt with end-cell frequency change. The tank is also much less sensitive to beam loading effects than the conventional drift tube tank.

Work on the Electron Prototype Accelerator (EPA) has continued, with about a quarter of the accelerator structure completed and installed in the Iron House. There were delays in receiving parts from outside vendors, but these problems seem to be solved now and rapid completion is anticipated. A prototype quadrupole magnet is undergoing test, and will be incorporated in EPA. All beam line equipment, such as scrapers, position monitors, steering coils, focusing solenoids, etc., are either on hand or are being fabricated.

The Model K bridge coupler has been installed and its electrical behavior is being investigated. Preliminary indications are that the bridge works properly in this configuration. Matching of the tank to the feed waveguide is under way.

Drift tube and quadrupole magnet design has been continued. A coil insulation and potting process using glass sleeving and refractory cement has been developed which appears very successful and will provide a highly radiation-resistant coil insulation and support structure capable of withstanding brazing temperatures. A low-energy dummy drift tube is being fabricated to investigate fabrication and brazing techniques.

Preliminary results with the nonresonant beam position monitor sensing the Model M electron beam indicate satisfactory performance.

Model K (61-cell, $\beta = 0.65$ side-coupled tank)

Testing

Observation of Model K coupling cavities during high-power runs has confirmed that the increase in VSWR with power, described in the preceding report, is indeed associated with the ceramic window and not with any breakdown or multipactoring in the coupling cavities. By carefully rounding the iris edges, the power at which this effect was noted was raised to > 600 kW at 3% DF, well beyond the design power for this particular tank.

Bridge Coupler

Model K bridge coupler has been successfully brazed vacuum tight and installed (Fig. 1) in the center section of the 61-cell Model K tank, replacing 12 cells. The mechanical rf joints were disassembled and reassembled satisfactorily and they were vacuum tight after installation. Reassembly was accomplished by using an original knife-edge mating with a new flange on the bridge coupler. The waveguide coupling iris (Fig. 2) is in the process of being machined in the side of the bridge coupler tank utilizing a magnetic base drill.

Radio-frequency measurements indicate that the relative amplitudes of the two tank halves can be varied over a $\pm 15\%$ range by adjusting the bridging cell tuning slugs. Some thought has been given the possibility of stabilizing the bridging cell with T-bar couplers in much the same manner as the Alvarez structure has been stabilized. The relative amplitudes of the fields in the two halves could then be controlled by the amount of asymmetry built into the coupler.

The coupling iris is being adjusted for a match to the waveguide in order that the model may be used as a load for rf amplifier tests. Thus far the VSWR has been reduced to ~ 1.2 .

Fig. 1. Model K bridge coupler.

The center section removed from Model K when the bridge coupler was installed is being used for verification of the coupled resonator model predictions. Specifically, measurements are being made of the sensitivity of the field tilt to end-cell perturbation vs stopband. This model will also be used to determine the bandwidth of some of the transverse modes which might cause beam deflection.

Model M (6-cell, graded- β electron accelerator)

The energy gain of Model M has been measured using a magnetic spectrometer. An output beam of 1.1 MeV at 20 mA peak current was obtained with an injection energy of 100 kV and rf excitation of 66 kW. The width of the energy spectrum was $\sim 10\%$. The variation of output energy with beam loading, rf drive power, and injection energy was reasonable.

The solenoid coils and mounting frame are on hand and a solenoid power supply is on order. These components will be installed when Model M is moved to the EPA complex.

Electron Prototype Accelerator (100-cell, side-coupled, $\beta = 1$)

Production tuning of the EPA segments is in progress, and the first three sections have been pretuned. Three of these have been returned from brazing and received a final tuning to minimize the fields in the coupling cells.

Fig. 2. Machining bridge coupler coupling iris.

The new tuning fixture has proved invaluable in the speedy tuning of the segments. A section of eight cells can be easily tuned in two days by one technician and one machinist. As experience in handling these segments is gained, the time for tuning a section might be reduced to one day.

Eighty feet of nonmagnetic support structure for the EPA has been installed in the Iron House area of the Electron Prototype Laboratory (EPL). The tank alignment mounts are on hand and will be installed simultaneously with an accelerator tank section. The interior of the EPA Iron House accelerator channel is shown in Fig. 3. Two of the twelve tank sections have been successfully brazed and installed along with their vacuum systems (Fig. 4) and the third tank section is being made ready for final assembly brazing. There have been some 50 brazing heats run to date; many are prebrazing heats of components, such as coupling cavities, stainless rings to segments, bridge coupler tanks, and others, which will be used throughout EPA. There has been some delay in the final assembly tank section brazing due to the inability of the outside vendor to deliver segments and clamshells on schedule. However, receipt of all segments and clamshells is expected to be complete by the latter part of August. A problem has been the appearance of blisters on copper surfaces during brazing operations on those parts forged at LASL from OFHC copper.

Fig. 3. EPA Iron House accelerator channel.

Blisters have occurred on only one of the segments so far, but $\sim 20\%$ of the clamshells are blistered to the extent that rejection is warranted. All of the vacuum manifolds and the four 600-liters/sec ion pumps have been received and tested.

Fabrication of three EPA bridge couplers is under way. All subassembly brazing of bridge coupler components to be performed at LASL is complete and the units are now ready for assembly brazing by an outside fabricator. A stainless steel waveguide flange has been designed for the bridge coupler to replace the original integral ceramic window design. The new flange will be more versatile by allowing various rf windows to be used in conjunction with metal vacuum seals, if desired. Nine bridge coupler tuning slug assemblies have been completed and are ready for mounting on the bridge tanks.

All cooling tubes for the EPA have been fabricated and are ready for installation. Supply and return headers are being made up and the pipe fittings required for installation are on order.

A prototype quadrupole doublet has been received and preliminary testing is under way. Investigation of the magnetic center of this doublet, using an alignment telescope and a vial of a colloidal suspension of ferrosferic oxide, indicates that the magnetic center can be located

Fig. 4. EPA tank sections.

within a few thousandths of an inch. Alignment mounts for two quadrupole doublets have been designed.

Beam line equipment (current monitors, beam position indicators, and scrapers) for EPA has been designed and tested with the Model M electron beam.

Drift Tube Accelerator Studies

Quadrupole Magnet Design

New quadrupole magnets for the drift tube section have been designed and detailed. Grouping was established by means of the criteria reported previously and the computer code QADFLX was used to optimize the pole and yoke geometry.

A quadrupole magnet of the first group in tank one (0.75 cm bore radius) was fabricated; however, an error in the grinding fixture cams, made on the tape-controlled mill, caused the pole tips to be out of tolerance. The errors have been corrected and another unit is being made. The rejected parts are being used in the coil insulation program.

Coil forms were designed and detailed for the new quadrupole magnet and the form for the first group of tank one was fabricated. Special tube benders were made to handle the conductor diameter and the special bend radius. Coils were wound with the new form in one operation without intermediate annealing. The completed

Fig. 5. Quadrupole magnet coil and potting form

Fig. 6. Porcelain-coated poles and glass-sleeve insulated coil.

coils were annealed in a hydrogen furnace, then dressed on the winding form, in preparation for installation of the woven glass insulation sleeving.

A new coil insulation and potting process which is being investigated appears to show promise. The technique consists of pulling a woven refractory glass sleeve (Markel No. 5) over the coil, inserting the porcelain coated poles (fired at 1900°F), and installing the yoke. The assembly is placed in a teflon potting form and filled with a refractory cement while on a vibrating table. The particular cement used was cured by baking at 212°F for 48 h. Several small cracks occurred during the curing cycle. The sequence of the operation is indicated in Figs. 5 and 6, and Fig. 7 shows the completed quadrupole magnet after having been subjected to a typical hydrogen brazing

Fig. 7. Cement-potted quadrupole magnet after hydrogen firing.

Fig. 8. Machining drift tube bodies.

cycle of 1460°F . The quadrupole magnet (an early design) was operated several hours at the design current of 1100 A. The power was switched on and off several times without further cement cracking from the resulting forces and thermal shocks. The magnet performed normally throughout the tests.

A reaction of the porcelain on the poles was noted at the pole-to-yoke junction after hydrogen firing. This has since been attributed to the contamination by glass beads used in the cleaning process after the curing cycle. Subsequent disassembly revealed no reaction between the sleeve, porcelain, or cement. The glass sleeve does embrittle after firing and the resulting cement is a light and rather friable material; however, it seems to provide adequate coil support. Other cements are being investigated.

Testing is under way on several "loss of cooling water safety circuits." The usual flow switch type circuits are being evaluated as well as temperature sensing circuits. A circuit has been developed that uses a thermistor to sense the quad magnet temperature. As the temperature reaches the set point, the thermistor circuit trips a relay to shut off the quad power supply. This circuit has been tested and appears to be reliable with many advantages over the flow switch type of circuit.

Drift Tube Design

A prototype low-energy drift tube has been designed and is being fabricated to evaluate each phase of construction from the forgings to the final brazed assembly. The machining technique (Fig. 8) uses a standard keycutter to form water passages in the drift tube that could significantly reduce machining costs. The drift tube halves are oriented to stagger the key slots forming the cooling water channel. The drift tube program is paralleling the magnet development program and although this model will not incorporate a magnet, material was retained within the body to simulate the magnet weight for future dynamic studies.

A proposed tank, one single-stem drift tube support mount, has been completed and is being evaluated. Some specific design features permit alignment checks prior to making the vacuum seal and after making the hard and soft vacuum seals; they also have leak-checking capabilities of the stem penetration prior to evacuating the tank. Alignment is not adjustable, as such, but is accomplished by precise location of the stem mounting plate. Axial and transverse displacements of $\pm \frac{1}{16}$ in. can be made, and vertical corrections are achieved by shimming under the plate. The unit has successfully undergone assembly and vacuum tests and is ready for alignment studies.

Drift Tube Tank Studies

Drift Tube Tank Resonant Couplers: A major development has taken place in the design of the drift tube linear accelerator. A method has been developed for resonantly coupling the drift tube accelerator, making it in many ways similar to the side-coupled accelerator tanks used in the high

frequency portion of LAMPF. In all aspects this system has performed as predicted by theory and gives exceptional stability to the field distributions in the accelerator tanks.

Proton linear accelerators of the Alvarez or drift tube type generally operate in the 0 or what is sometimes referred to as the 2π cavity mode, indicating a zero phase shift in the accelerating electric field from one accelerating gap to the next in the operating electromagnetic mode in the cavity.¹ It has long been recognized that this particular cavity mode, while producing the desired field distributions, is very susceptible to perturbations in electric field distributions due to mechanical deformations or beam loading. This is primarily due to the poor energy propagation characteristics of the chosen mode of operation.

Recently²⁻⁷ operation of high-energy accelerating cavity chains in a particularly suitable mode, known as the $\pi/2$ mode, has been demonstrated, and in this report, preliminary results will be given to demonstrate the feasibility of modifying the ordinary 0-mode drift tube accelerator mode into a cavity mode. The latter has all of the stability properties of the $\pi/2$ mode described in earlier reports, without appreciably altering the efficiency of the structure as a particle accelerator. This is done by introducing resonant couplers of a suitable geometry to the side of the cavity, which in effect are analogous to the side cavities in the side-coupled cavity chain described previously.³ The coupler configurations, which have proven suitable, range from a T-bar shaped device to a simple post mounted on the cavity wall. An alternative method of cavity stabilization has been described by BNL⁸ utilizing multiple stems for drift tube support. This may be analyzed as a $\pi/2$ -mode system in a manner analogous to that described below. Several advantages of the stabilization system described here over the multistem cavity geometry are apparent. The power dissipation on the coupling structures can be made quite small, so that a minimum change in efficiency is necessary to effect the cavity stabilization. The couplers have no mechanical interaction with the drift tubes and are readily tunable.

Classification of Coupled Resonator Modes:

A general chain of N coupled resonators has N possible modes of oscillation for any one set of individual resonator single cavity resonant field distributions. It may be shown that the chain of resonators does not need to be periodic (or even doubly periodic) for these modes to exist, and that so long as energy can couple from resonator to resonator the modes excited in adjacent cavities need not have similar spatial characteristics at all. These results are used to describe the synthesis of the $\pi/2$ -mode system.

Consider a chain of generalized resonators as shown below. If these cavities all resonate at the

same frequency, and there are an odd number of resonators, there will exist a resonant mode of the system with alternate cavities unexcited except for a small field to allow power transmission, and a phase shift in the fields driving the unexcited resonator of π radians, as follows:

Drive to R_n from R_{n-1} (A) = - drive to R_n from R_{n+1} (B)

Thus, for a chain of coupled resonators to be consistent with this description, the $\pi/2$ mode is that set of field distributions which provides equal but opposite drives to alternate unexcited cavities. By proper choice of cavity configuration the ordinary mode of the drift tube linac may be converted into this mode.

The Resonant Couplers: There is at least one family of resonant couplers that has the desired properties. The distinctive feature of this family is an inductive stem mounted normal to the outer wall of the linac cavity. The "T-bar" coupler represents one end of this family, where the inductive stem is short and capped with a plate to increase the capacity of the end of the stem to the cavity wall and drift tube. The "post" coupler represents the other end of the family, where the

inductive stem is long and the capacity of the resonant circuit is just the capacity of the end of the stem to the drift tube and cavity wall. Both of these resonant couplers are shown in Fig. 9. In either case, the resonance considered is the one where currents oscillate up and down the stem charging and discharging the end of the stem with respect to the cavity wall and drift tube.

The most favorable location for the couplers seems to be at the points on the outer wall of the linac cavity that are aligned with the centers of the drift tubes and oriented $\pm 90^\circ$ from the drift tube stems. If the latter are in the vertical plane, the couplers would be in the horizontal plane.

Furthermore, the nature of the coupling between adjacent resonant couplers is such that adjacent couplers must be located on opposite sides of the cavity as shown in Fig. 10.

The Linac Modes: Consider the drift-tube linac cavity as a chain of $2N + 1$ coupled resonators numbered from 0 to $2N$, where the even-numbered resonators correspond to the accelerating cavities and the odd-numbered resonators to the resonant couplers. In order to determine the field directions corresponding to a mode with a phase shift per cell of ϕ , it is necessary to introduce the concept of an additional phase shift of $\pm \pi$ associated with the geometry of the resonant coupling device. The 0 and π modes, as shown in Fig. 10 A and C, have electric and magnetic fields that alternate in direction in adjacent accelerating cells. In the case shown, the 0 mode has a lower frequency than the π mode, and by convention the field direction in the coupler is defined to correspond to this classification.

T-BAR COUPLER

POST COUPLER

Fig. 9. "T-bar" and "post" couplers.

The arrows near the couplers show the relative directions of the currents on the stems in each mode. In the $\pi/2$ mode, the fields have the same phase in all accelerating cavities, as seen in Fig. 10B. The drive to the resonant couplers is opposite from adjacent cells, and the couplers are unexcited. Hence the original drift tube mode has been transformed into the $\pi/2$ mode of the composite system.

A general dispersion relation and a set of eigenfunctions may be derived⁷ for this biperiodic chain of coupled resonators with nearest and next nearest neighbor coupling; they are

$$k_1^2 \cos^2 \varphi = \left(1 - \frac{\omega_1^2}{\omega^2} + k_2 \cos 2\varphi\right) \left(1 + \frac{\omega_2^2}{\omega^2} + k_3 \cos 2\varphi\right), \quad (1)$$

$$X_{2n} = A \cos 2n\varphi$$

$$X_{2n+1} = B \cos (2n+1)\varphi,$$

where ω_1 is the even cell frequency, ω_2 is the odd cell frequency, k_1 is the coupling between adjacent cells, k_2 is the coupling between adjacent even cells, and k_3 is the coupling between adjacent odd

Fig. 10. Coupling in a 0, $\pi/2$, and π modes.

cells. The ratio of the amplitudes of the eigenfunctions for even and odd cells is

$$\frac{A}{B} = \frac{-k_1 \cos \varphi}{1 - \frac{1}{\omega^2} + k_2 \cos 2\varphi} = \frac{1 - \frac{\omega_1^2}{\omega^2} + k_3 \cos 2\varphi}{-k_1 \cos \varphi}.$$

The basic features of the dispersion relation (Eq. 1) may be revealed by superimposing the curves obtained by equating each of the factors on the right side of the equation to zero. The curves resulting when the first factor is equated to zero

are shown in Fig. 11. The same curves apply to the second factor when ω_1 and k_2 are replaced by ω_2 and k_3 , respectively. An example of superposition of two such curves is shown in Fig. 12.

Fig. 11. Basic features of the dispersion relation.

Both factors are positive for ω above the curve, and negative for ω below the curve. It is obvious from the dispersion relation that product of the factors must be (1) zero for $\phi = \pi/2$, and (2) positive for all other values of ϕ . The first condition implies that points P and Q are solutions of the dispersion relation. The second condition requires that the solution of the dispersion relation be either above both curves or below both curves on Fig. 12, thereby excluding the possibility that the solution lies between the curves. Suppose that the solution lies below the two curves for ϕ between 0 and $\pi/2$, and above the two curves for ϕ between $\pi/2$ and π . The desired behavior is obtained when k_2 and k_3 have opposite sign and k_1 is as large as possible.

The perturbation analysis for the case described here (large k_2 and k_3) has not been done explicitly. However, there are strong indications that even with large k_2 and k_3 , the behavior of the $\pi/2$ mode will be much the same as that obtained for $\pi/2$ mode operation without direct couplings. That is, if the stopband Q-P is closed, the field amplitudes and phases are independent of frequency errors in the individual cells to first order. If in fact this is true, the stability of the electromagnetic fields in the Alvarez accelerator may be enhanced orders of magnitude by the simple expedient of

Fig. 12. Solutions of the dispersion relation

placing small resonant couplers in the walls of the cavity.

Determining Biperiodic Alvarez Parameters from Single-Cell Measurements: The test cavity consists of two identical half-cells approximating the Alvarez tank for the desired energy with the appropriate drift tube suspended from a single stem. This cavity will have two modes, ignoring the resonance associated with the stem (which should be quite low in frequency); a cell frequency ω_1 and a coupling constant k_2 may then be calculated by the relations

$$\frac{2}{\omega_1^2} = \frac{1}{\omega_0^2} + \frac{1}{\omega_\pi^2}; \quad |k_2| = \left| 1 - \left(\frac{\omega_1}{\omega_0} \right)^2 \right|,$$

where ω_0 means either the 0 or π mode frequency.

After inserting a coupling device in the cavity (at 90° from the drift tube stem) the resulting three modes are measured.

The "zero" mode of the original system is now the $\pi/2$ mode for the new system. In practice, the presence of a metallic object (the tuner) in the cavity perturbs the operating mode. This perturbation is considered to be the result of a change in the Alvarez cell frequency ω_1 , whereas k_2 is assumed to be unaffected. A new ω_1 is then

calculated, using another result from the coupled resonator model, namely

$$\omega_1 = \omega_{\pi/2} \sqrt{1 + |k_2|}$$

The coupler frequency ω_2 and its coupling to the tank k_1 are calculated from the experimental data using the following relations derived from the coupled resonator theory:

$$\frac{1}{\omega_2^2} = \frac{1}{\omega_o^2} + \frac{1}{\omega_{\pi}^2} - (1 - |k_2|) \frac{1}{\omega_1^2}$$

$$k_1^2 = \left(1 - \left(\frac{\omega_2}{\omega_o}\right)^2\right) \left(1 - |k_2| - \left(\frac{\omega_1}{\omega_o}\right)^2\right)$$

Experimental values of k_1 and ω_2 for various size stems are displayed in Figs. 13 and 14 as determined from mode spectra measurements and the foregoing relations. A 2 x 6 in. plate was used on the end of the T-bar coupler in all cases. Figure 15 shows the coupling of the tuner to the accelerating cell for the closed stopband condition as a function of stem diameter. A plot of the stem length required for a closed stopband vs stem diameter is given in Fig. 16.

Fig. 13. Plot of k_1 vs stem length for various stem diameters.

Fig. 14. Plot of tuner frequency vs stem length.

Fig. 15. Plot of k_1 vs stem diameter.

Fig. 16. Plot of stem length vs stem diameter.

Experimental Results on the 10-cell Model

The 10-cell model consists of an 8-ft long piece of 24-in. diam aluminum pipe loaded with nine full drift tubes and two half drift tubes. The model resonates at 505 MHz, and the cell geometry is scaled from a 92-MeV linac geometry.

The bead perturbation technique was used to measure the electric field distributions in this model fitted with (a) T-bar couplers, (b) post couplers and (c) no couplers. The absolute field distributions are not too significant for, as in the side-coupled cavity case, crude manufacture of couplers introduces coupling constant errors which cause nonflat fields in the tuned-up case. However, the stability of the existing fields to programmed errors in the end cells is meaningful.

For this purpose, a tank "tilt" is defined as the difference between the electric fields in the end cells divided by the average of the fields of the end cells. The field stability is then quoted as the percentage change in tank tilt when the resonant frequency of one end cell is raised a certain amount and the resonant frequency of the other end cell is lowered by the same amount. An "improvement factor" is also defined for the field stability as the percentage change in tank tilt for the nonresonantly coupled structure divided by the change in tank tilt for the resonantly coupled structure.

The coupled resonator theory would predict the improvement in stability to be inversely proportional to the stopband. With care in adjusting the individual couplers, very great stability may be expected. In fact, experiments have shown that the field tilts reverse for a fixed perturbation when the resonant frequencies of the couplers go from below to above the frequency required to close the stopband in the mode spectrum.

The first and only attempt at tuning the T-bar couplers in the 10-cell model produced an improvement in field stability of a factor of five. That is, with the couplers installed, the tank tilt changed 5% for end-cell perturbations of ± 1 MHz. Without the resonant couplers, the tank tilt changed 27% for the same end-cell frequency perturbations. The Q of the tank with the couplers was 17,200 as compared to 21,000 for the same tank without the couplers.

Fig. 17. Partial mode spectrum and tilt sensitivity of 10-cell model.

Following successful operation of the T-bar couplers, 0.794-in. diam post couplers were installed in the 10-cell model. An improvement in field stability of about a factor of ten was achieved, and the Q of the structure was 17,400. Figure 17 shows a portion of the mode spectrum and the tilt sensitivity of this structure. From the tilt data it is concluded that the resonant frequencies of the post couplers are too high, since the direction of tilt is opposite to that for the nonresonantly coupled structure. For this reason the operating mode is shown as part of the lower passband in the mode spectrum.

The 10-cell model was then fitted with $\frac{3}{8}$ -in. diam post couplers. An improvement in field stability of a factor of seven was realized, and the Q of the configuration was 18,900. For this particular setting of the posts, the resonant frequencies of the posts were lower than required to close the stopband in the mode spectrum, and the direction of tilt was the same as that without the posts.

Experimental Results on the 35-cell Model

The 35-cell model consists of a 24-ft long piece of 14-in. diam aluminum pipe loaded with 34 full drift tubes and two half drift tubes. Unlike the 10-cell model, each cell in this model is of a different length. The cells at one end correspond to an energy of 40 MeV and those at the other end to 100 MeV.

A drift tube tank is defined as "flat" when the average axial electric field E_0 in each cell is the same. Since the electric field at the center of the gap E_c is more readily available than E_0 from the bead perturbation measurements, it is of interest to know the ratio E_c/E_0 . The MESSYMESH calculations indicate that this ratio is 2.9 for the 40-MeV geometry, and 1.8 for the 100-MeV geometry. For a "flat" field distribution in the 35-cell model, E_c at the 40-MeV end is expected to be 1.61 times as large as at the 100-MeV end. This factor of 1.61 is included in the calculation of the tilt of the 35-cell model so that a "flat" tank gives a zero tilt.

The axial electric fields in the end cells were mapped by pulling the $\frac{3}{8}$ -in. diam brass bead through the tank slowly. Numerical integrations were performed on these field profiles to obtain E_0 . The end cells of the tank were moved until the values of E_0 in the cells were very nearly equal. At this point, the E_c 's in the end cells were measured, and a ratio of E_c in the low- β cell (40 MeV) to E_c in the high- β cell (100 MeV) was obtained. The measured value of this ratio was 1.57, which compares well with the calculated value of 1.61. The positions of the end cells at this time were measured with a micrometer and recorded. These micrometer settings were used as the "initial conditions" for subsequent tilt measurements on post tuners.

The resonant frequency of the tank changes as a $\frac{3}{8}$ -in. diam metallic bead is pulled along its axis. The frequency variation is proportional to the square of the electric field at the position of the bead. Figures 18 through 25 are graphs of the resonant frequency of the tank vs bead position. In all of these figures the low-energy end (40 MeV) is on the left and the high-energy end (100 MeV) on the right.

Figure 18 shows the field distribution in a "flat" tank where the drift tubes are supported by four stems. The field distribution in the same tank after all but one supporting stem were removed from the drift tubes is given in Fig. 19. The tank is no longer flat as indicated by the fact that E_c at 40 MeV is 1.94 times E_c at 100 MeV giving a tilt of -18.6%.

One-inch diam post couplers were then installed, and set so that the distance from the end of the post to the drift tube body was 1.05 in. Figure 20 shows the field distributions in this configuration to have a tilt of 19%. The resonant frequency of the left end-cell was raised 3.5 MHz and that of the right end-cell was lowered 3.5 MHz. The resulting field distribution is seen in Fig. 21 to have an end-to-end tilt of 40.6%, a change of 21.6% for the 3.5-MHz perturbation. This represents considerable stability end-to-end, but the fields are seen to be high on both ends and low in the center.

Since the cells of this tank are of different lengths, it is reasonable that the post couplers be adjusted differently in order to achieve high field stability in all parts of the tank. The fact that the fields in the left end-cell of Fig. 21 increased, indicate that resonant posts in that end are too high in frequency. Since the fields in the right end-cell increased also, it appears that the resonant posts in that end are too low in frequency. The spacings of the posts were adjusted to vary from 0.90 in. at the 40-MeV end to 1.21 in. at the 100-MeV end. Figure 22 shows the field distribution for this variable spacing of the post couplers to have a tilt of 12.6% for the end cell in the initial condition. The end cells were again perturbed by ± 3.5 MHz and the resulting field distribution is seen in Fig. 23 to have a tilt of 22.2%. The tilt sensitivity of the 35-cell model without resonant couplers is 85% tilt per MHz perturbation. The resonantly coupled configurations described above represent an improvement in stability by a factor of 32.

The shape of the field distributions did not change appreciably during the last perturbation, indicating that the couplers were nearly correct, but slightly low, in frequency throughout the tank. The spacing of the couplers was increased by 0.020 in. and the resulting field distributions for the unperturbed and perturbed end-cells are given in Figs. 24 and 25. The tilt of the tank changed only 4% for the 3.5-MHz perturbation, giving an improvement in field stability by a factor of 75. The Q of the tank in this configuration

Fig. 18. Four $\frac{3}{4}$ -in. diam stems. End cells in initial condition. Tilt 0%.

Fig. 22. One $\frac{3}{4}$ -in. diam stem. Post couplers, variable spacing. End cells in initial condition. Tilt 12.6%.

Fig. 19. One $\frac{3}{4}$ -in. diam stem. End cells in initial condition. Tilt -18.6%.

Fig. 23. Stem and post couplers as in Fig. 22. Δf 's of end cells as in Fig. 21. Tilt 22.2%.

Fig. 20. One $\frac{3}{4}$ -in. diam stem. Post couplers, uniform spacing. End cells in initial condition. Tilt 19.0%.

Fig. 24. One $\frac{3}{4}$ -in. diam stem. Post couplers, spacing increased by 0.020 in. End cells in initial condition. Tilt 14.4%.

Fig. 21. Stem and post couplers as in Fig. 20. Δf (left end-cell) + 3.5 MHz; Δf (right end-cell) -3.5 MHz. Tilt 40.6%.

Fig. 25. Stem and post couplers as in Fig. 24. Δf 's of end cells as in Fig. 21. Tilt 18.4%.

In Figs. 18 through 25, the x axis is the axial position of the $\frac{3}{4}$ -in. diam brass bead and the y axis is the resonant frequency.

Fig. 26. Partial mode spectrum and tilt sensitivity of 35-cell model.

was 20,180. Figure 26 shows the mode spectrum and the tilt sensitivity of this configuration. With continued fine adjustment of the post couplers, an improvement factor of 200 was achieved.

Computer Studies

Long Side-Coupled Cavity Chain with Multiple Drives

With coupling between driven sections, a cavity chain maintains at least partial accelerating fields throughout when one drive fails. A preliminary calculation was made for 12 driven sections, all coupled together into one tank, with the second drive out. The results indicated that the beam dynamics would be good enough to permit operation of the linac if powers supplied by the remaining 11 drives were increased by appropriate amounts. It was estimated that the required power increases would range between 8 and 25%. These figures are probably conservative; more exact estimates of the required increases may be less than this. Further study is being made of this and alternative methods of possible operation with one drive unit out.

Bridge Coupler

The long cavity in a bridge coupler may have resonances other than the desired TM_{010} resonance near the operating frequency. For example, any one of the resonances TM_{011} , TM_{012} , TE_{112} , or TE_{113} can be close to the TM_{010} for

Fig. 27. Coupled resonator models for simulating bridge coupler mode spectra.

certain ratios of the length to diameter of the long cavity. In particular, the presence of the TM_{011} resonance may affect the performance of the unit, since this field configuration also couples to adjacent cells.

Circuit analogs for the tanks with bridge couplers are being used to investigate the effect of a nearby TM_{011} resonance. Mode spectra were measured for the Model K bridge coupler assembly alone. This assembly includes adjoining half main cells. The circuits (a) and (b) in Fig. 27 were then used to try to simulate the observed behavior. A parameter fitting computer code was able to make model (a) exhibit mode spectra close to the observed spectra. Model (b) did not give as good a fit as model (a).

Calculations have been initiated to determine the effect of an extra resonance on the sensitivity to tuning errors for a full length tank containing bridge couplers.

Drift Tube Linac

In at least some respects, the drift tube linac behaves like a chain of simple resonators with multiple coupling. (Multiple coupling implies that coupling between second, third, etc., nearest neighbors is important, as well as coupling between adjacent resonators.) A way has been found to extend the first-order tuning error analysis from the case of the simply coupled chain to the case of the uniform multiply coupled chain. This analysis is being pursued as a step toward finding the theoretical limit on field stability that may be achieved in the resonantly coupled drift tube linac and in the side-coupled cavity linac with direct coupling.

Instrumentation and Related Equipment

Beam Position Monitor

The beam position monitor has been tested with the electron beam from the Model M test stand. Experiments indicate that the sensitivity of the loops is about as expected and the device has position dependent outputs. The mixers were not accurately matched, so no attempt was made to determine beam position quantitatively. Problems with interactions between the four mixers require that the mixer be redesigned for better isolation of each unit. Changes will also be made in the mixer design, eliminating the possibility of ground loops, to make it compatible with the accelerator control system.

The EPA requires seven position monitors. It is planned to provide three sets of three monitors with multiplexing so that beam position may be determined in three places simultaneously during each beam pulse.

Alignment

A 1.3 mW helium-neon tooling laser with an electronic centering detector has been received and is now being used to align the EPA tank sections. The tooling laser is mounted on a modified transit base and the centering detector is mounted in a special holder inserted in the bore of an EPA tank section. A striding target holder will be used for alignment checks of the

EPA after assembly of all tanks is complete. Experience to date indicates that with this apparatus it is possible to align the EPA system to ± 0.005 in. within a 100-ft length.

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III. RF POWER SOURCES

Introduction

Substantial progress has been made towards the choice of the 805-MHz power amplifier for the accelerator. A Coaxitron was run successfully at 1.25-MW power output and 6% DF for 100 h at RCA but failed after less than 50-h operation at LASL; this failure, combined with previous experience with this type of tube, led to the conclusion that the Coaxitron should be abandoned without further development. The Amplitron runs satisfactorily into a resistive load with power outputs as high as 1.4 MW and efficiency of 60%; operation into a resonant load is possible if an appropriate combination of isolators and filters is placed in the system. The present Amplitron has operated some 200 h at significant peak-power levels and duty factors without any sign of distress. On the whole, the outlook for the Amplitron is promising. Similarly, all the tests performed on the klystron give encouraging results. The klystron performance is relatively insensitive to load VSWR ≤ 1.5 . Power output of 1.25 MW (6% DF) is obtained with an efficiency of $\sim 33\%$ and gain of 54 dB. More detailed tests on the performance of the klystron are under way.

The 201.25-MHz Intermediate Power Amplifier (IPA) has been rebuilt in order to reduce the rf leakage problems; it now is much easier to make meaningful measurements using this equipment. A blocker failed in the 7835 power amplifier while operating at 3-MW power output and 6% DF; improved versions are being designed by Continental Electronics.

Work is being continued on the development of a suitable rf multiplier chain for frequency control of the accelerator.

A new Amplitron modulator has been assembled and is being tested. Construction of a new 7835 modulator has been started.

RF Control Studies

Overall System Design

Nearly all of the binary command and data points which the computer will control or monitor in automatic operation of the Amplitron test stand have been successfully exercised by the computer. The necessary equipment for commanding high-voltage, raise-lower, and other digital-to-analog operations has been installed and is being checked. Signal lines and conditioning amplifiers are being installed to allow the computer to sample data, such as Amplitron current, during the pulse.

Frequency and Phase Control Studies

The merits of step-recovery diodes as multipliers have been thoroughly investigated. Two complete multiplier chains were designed, built, and tested for stability and signal purity. These started with a 2.483-MHz crystal which was multiplied 81 times in two stages to obtain 201.125 MHz, followed by a quadrupler to derive 805 MHz. On the surface, this chain appears simple in that only two stages, each multiplying by 9, are needed to reach 201.250 MHz, but actually 17 tuning adjustments are involved. Since there is very little isolation between different sections, all tuning adjustments are somewhat interdependent. Also, the diode bias, which determines its capacity and, therefore, the tuning adjustments of associated circuitry, is substantially determined by drive. This in turn is determined by power supply voltages and tuning of preceding stages, thus making the entire chain very critical of adjustments, power-supply regulation, and signal level from the crystal-oscillator source. Because of the high order of multiplication employed, adjacent sidebands are very close to the desired harmonic and very small adjustment errors or component drift cause the multipliers to shift to an adjacent order of multiplication. When this occurs, succeeding stages quit completely.

Furthermore, since adjacent harmonics are very close to the desired signal in these high-order multipliers, sideband filters become quite complex. As would be expected, lower orders of multiplication, such as in the 201.250-MHz to 805-MHz stage, result in much better stability; but, in lower orders of multiplication, varactors are at least as stable, are far more efficient, and operate at a power level at least an order higher. As a result of the above studies, the transistor/step-recovery diode multiplier chain will not be pursued further. Because tubes will provide better interstage isolation, a tube/step-recovery diode version will be investigated to provide design information in case a need for a very simple, compact multiplier should arise.

Since a common problem with all solid-state multipliers and amplifiers is the lack of isolation between input and output, a vacuum tube-varactor multiplier chain has been investigated, and results are promising. The unit starts with penta-grid tube operating in the triode section as a crystal oscillator at 6.289 kHz and as an electron-coupled doubler in the pentode section with output at 12.578 kHz. This is followed by a 4-W beam power amplifier which drives two cascaded varactor doublers which deliver about 1 W at 50.312 MHz. At this point, the power level is boosted with another beam power amplifier to 3 W which drives cascaded varactor doublers to 201.250 MHz with about 0.75 W output. Such an arrangement is very stable, tunes up without serious interaction between stages, and is not sensitive to power-supply variations. Spurious signal components at the output of the last varactor are at least 45 dB down except for 301.875 MHz and 402.250 MHz which are 25 and 35 dB down respectively. The nearest significant spurious component is 12.570 removed from the 201.250 MHz and 45 dB down. It is, therefore, reasonable to expect that successive amplifiers will reduce all spurious components to 60 or 70 dB below the desired signal.

Logic and Protective Circuitry

A second arc detector, with associated delay and level-sensing circuitry, has been constructed, tested, and installed on the Amplitron

test stand. This unit is essentially identical to the unit already installed on the 1-MW klystron test stand.

The Amplitron logic circuitry has been modified so that the logic gates are insensitive to noise "spikes." The same change has also been made on the 200-MHz totem-pole logic.

New logic has been constructed and tested to allow safe operation when the Amplitron and klystron driver stage is pulsed from the same hard-tube modulator. This logic will allow cathode voltage to be applied to the Amplitron for a short preset period (1-20 μ sec) during which time low rf drive (from the klystron) is permitted. If drive is low at any time after this initial period, the logic will inhibit the modulator within 1 μ sec. Identical logic will be constructed for the 200-MHz stand so that the 4616 can be pulsed by the 7835 modulator.

The Amplitron crowbar-trigger circuitry has been modified to raise the noise immunity level from 5 to 20 V, by the adoption of hybrid (vacuum-tube/transistor) circuitry. These changes have drastically reduced false crowbar firings, and have made operation possible in the upper- and lower-mode areas without crowbar trips.

805-MHz Power Amplifiers

Coaxitron Program

A new Coaxitron was successfully operated at RCA for 100 h with a peak-power output of ~ 1.25 MW, DF of 6%, and pulse length of 670 μ sec; the efficiency was 40%. The tube was delivered to LASL where it operated erratically even at low DF. After 47 h of operation, the input match began to fluctuate wildly and tube pressure rose whenever drive was applied. This tube has been returned to RCA. The older 3% Coaxitron was reinstalled in the test stand and has been used for some testing of accelerator sections.

Following this tube failure, the decision was made to abandon the Coaxitron as a possible power source for the accelerator. The existing

tube will be used for testing of rf components but no further development of the Coaxitron system is contemplated.

Amplitron Program

Test Results: A substantial amount of time was spent determining in detail the operating characteristics of the 1.25-MW Amplitron. In the work described below, the Amplitron was driven by a 100-kW klystron operating from its own supply. Because of insertion loss in the input isolator between the klystron driver and the Amplitron, a maximum of about 70-kW peak drive was available at the Amplitron input. The two stages of the Amplitron were run with paralleled cathodes by the interim 4CX100,000D modulator operating as a switch. Each stage had its own electromagnet to permit investigation of different magnetic fields and balance between the stages.

Initial operation was into a resistive water load. Preliminary experiments with external shaping of the magnetic field by modifying pole-piece shapes and adding bars around the circumference of the individual stages showed that increased efficiency and gain could be obtained. The spectrum of the rf output under these conditions was reasonably good--one spike was present at 1140 MHz, about 30 dB down from the carrier. As with previous tubes, the spike could be reduced at the expense of efficiency and gain. Over 1.4 MW of peak power was obtained with 70-kW drive, 47.3 kV, 47.3 A of total current, and 60% efficiency. Figures 28, 29, and 30 are representative of operation into the resistive water load.

In general, one of the best tests of a high-power amplifier has been to drive steady-state reactive loads at several VSWR's and all phases to construct a Rieke diagram as outlined in previous progress reports. The results for the first 1.25-MW Amplitron indicated that severe oscillations occurred over a large area of the Smith chart. Investigation with a spectrum analyzer and cavity wavemeter showed the major oscillations occurred at about 750, 960, and 1140

MHz, with the particular load tuning determining the predominating frequency.

The 750-MHz oscillation is believed to be due to a resonance condition set up by mismatches in the connection between stages which can be remedied in the next tube. The 960- and 1140-MHz frequencies are part of a family of back-wall modes. The next tube will have a different geometry in the back-wall region designed to move the modes higher in frequency so that their excitation is less likely. Cold tests at Raytheon have indicated that these frequencies can be raised by 150 MHz or more.

The oscillations generate large amounts of noise power which modulates the 805-MHz output, current, and voltage waveforms. The geometry of the back-wall modes allows good coupling out of the tube through the cathode leads, thus explaining many of the problems which occurred in the modulator.

Operation into a resonant cavity load verified the performance predicted by the Rieke diagram; the oscillations were so severe that meaningful operation was not possible. However, two measures were taken which did allow high-power operation into a cavity load. Both involved external loading of the offending frequencies.

A ferrite isolator for use between the output of the Amplitron and the cavity was designed and built at LASL with design goals of 3-dB isolation and the capability of withstanding 1 MW in the forward direction. The finished isolator gives about 5 dB of isolation at 750 MHz and 4 dB at 805 MHz, tapering off at higher frequencies. Insertion loss at 805 MHz is about 0.7 dB. Its use in the system reduced the 750-MHz oscillation considerably.

To provide some loading for the higher frequency oscillations, a waveguide filter was constructed as a joint effort with Raytheon. This filter is positioned near the resonant load. It operates by allowing only those frequencies around 805 MHz to go to the resonant load, passing all

Fig. 28. Amplitron voltage, gain, and efficiency as function of current.

Fig. 29. Amplitron total rf power output as function of current (I), and voltage (V).

Fig. 30. Change in 805-MHz phase shift from Amplitron input to output as function of current.

other frequencies to a resistive load. (Loading at the higher frequencies can also be done with an output isolator designed to give isolation at both 805 MHz and the higher frequencies.)

With these two elements in the system, it was possible to drive the cavity well above its 250-kW design power; over 1 MW was obtained from the Amplitron, with about 850 kW entering the cavity. Subsequent operation into the cavity or the resistive load at power levels between 0.7 and 1.0 MW and DF's up to 6% has accumulated 200 h of pulse time with no apparent mechanical problems in the tube.

Preliminary control experiments were started, but the quality of operation into the cavity is still marginal. Efforts are currently being made to obtain more drive power in the hope that better synchronization might further reduce the spurious oscillations.

In summary, although the first 1.25-MW Amplitron is not satisfactory in some areas, in others, such as the capability for high-power operation, it appears quite successful. Furthermore, the experience gained with this tube and the resulting modifications planned for the second tube to be delivered in August, make reduction of the spurious oscillations appear quite feasible. On the whole, there is an optimistic outlook for this tube.

Crossed-Field Amplifier (CFA) Research:

The study of the operation of CFA's has progressed sufficiently so that it is appropriate to begin some laboratory work on actual tube structures. The philosophy of this experimental study is to emphasize work leading to a better understanding of the performance of CFA. To this end, the equipment is being designed so that a variety of slow-wave structures and cathodes can be tested without construction of a separate sealed-off device for each test. The tube vacuum chamber is in four sections--the tub and cover of OFHC copper, the ceramic standoff support for the cathode (designed for 50 kV), and the pump outlet. The tub and cover have been cast and are ready for machining. The cathode and pump outlet are

designed but not yet fabricated. The vacuum chamber is 9.75-in. inside height which will allow direct connection to the WR-975 waveguide through a variety of matching schemes. Vacuum windows will be the ceramic waveguide windows presently used for testing of accelerator sections.

Cold-test models have been designed for three different wideband anode structures and two narrow structures. The wideband structures are of the strapped-vane, ladder-line, and interdigital-line types. The narrow-band structures are of the hole-and-slot and rising-sun types. A model of the hole-and-slot structure has been finished; the others are being fabricated.

Cold tests of the hole-and-slot anode look promising. The dispersion curve has been obtained and the group and phase velocities have been determined in the π -mode region. The phase velocity corresponds quite well with the expected range of electric and magnetic fields in full-scale operation. To understand this structure better and to facilitate more accurate bead-pull experiments, another cold-probe model is being designed with a rotating electric probe in the interaction space.

The magnetic circuit has been designed. To obtain 2000 G, the 11.75-in. air gap requires about a 50,000 A-turn solenoid.

1.25-MW Klystron Program

The second Litton tube, Type L-5120, arrived at LASL at the end of June, and it has been undergoing a series of performance tests since. Figures 31-34 show representative steady-state characteristics; a definition of the drive saturation was made arbitrarily for Fig. 31, and used in Figs. 32 and 34.

The tube delivers satisfactorily the rated 1.25 MW at 6% DF. Load impedance has been varied by means of an E-H tuner to map the entire Smith chart within a circle having a radius corresponding to a VSWR of 1.5:1 and performance is everywhere satisfactory except at three points where the rf output is slightly modulated at a 10-MHz rate. Drive level can be adjusted to eliminate this spurious response. The power

delivered to the resistive part of the load within the 1.5:1 area changes by only a few percent, the amount due to the load reflection.

Efficiency (rf power output/beam power input) is somewhere between 31 and 34%. Steps are being taken to refine this measurement. RF power gain is ~ 54 dB.

One phenomenon was observed which is so far unexplained. As either drive or beam voltage is adjusted, there are two levels where rf power output does not vary continuously, but "jumps" about 5% in magnitude.

A series of detailed performance tests is now in progress. One of the most interesting and significant will be to operate the tube into a resonant load as it would be run on the accelerator.

201.25-MHz Power Amplifier Program

A refurbishing of the Intermediate Power Amplifier (IPA) has been completed. This work was necessary because rf leakage from the various stages produced a great deal of cross-talk in the instrumentation and instability in the logic circuits, causing random crowbaring and generally erratic operation. The rf components have now been relocated and shielded, and signal-carrying cables from the rf chain to the instrumentation have been rerouted, shortened, and physically separated from other cables carrying heavy currents. Operational stability has greatly improved as a result of these modifications. Operation of the chain up through the 4616 tubes is no longer a frustrating experience, but has become routine.

A 28-kV, 2-A power supply was built to permit operating the 200-MHz IPA at a 12% DF at 200-kW output. Although the operation of this unit is generally satisfactory, the resistor band mounted in series with the output to allow for crowbar operation was found to be marginal and is being enlarged.

A linear modulator has been designed, constructed, and bench-tested for use in modulating the 4616 screen grid on the totem-pole

Fig. 31. Klystron rf power output as function of rf drive at different cathode voltages.

Fig. 32. Klystron rf power output as function of cathode voltage at different drive levels.

Fig. 33. Change in 805-MHz phase shift from klystron input to output as function of cathode voltage at different drive levels.

Fig. 34. Change in 805-MHz phase shift through the klystron as function of rf drive at different cathode voltages.

amplifier. The specifications are:

Input drive: 0 to +10 V

Output: 0 to 1800 V (into 667- Ω load)

Duty Factor: 0 to 12%

Droop on 1-msec pulse out (667- Ω load): 2.5%

Bandwidth (667- Ω load): 400 kHz

Bandwidth (667- Ω paralleled with 0.035 μ F): 280 kHz

Worst deviation from linearity: 8%

Calculated dynamic output impedance (for small signals): 33 Ω

The modulator has a solid-state input section for interfacing the servo or logic signals to a 3-400Z triode voltage amplifier. Power amplification is accomplished with a 4CX1500B tetrode cathode-follower output stage. The unit has been tested in the 200-MHz test stand and has performed satisfactorily in both the saturated and unsaturated modes. An unregulated 3000-V, 0.5-A dc supply was also constructed for use with this modulator, which is equipped with a peak-reading voltmeter at the output.

During a heat run on the 7835 power amplifier, the upper plate blocker failed; this occurred after ~ 1 h of operation at 6% DF, 3-MW output. It would appear that the outer conductor of the blocker failed in hoop stress due to the differential expansion of the insulating plastic and the metallic outer cylinder. Since the outer cylinder was fabricated from sprayed aluminum, its tensile properties were considerably degraded as compared to normal aluminum. Continental Electronics, the fabricator, has since developed an improved blocker employing an extruded and machined outer conductor. This unit will be tested shortly. At the moment, the 7835 amplifier is being operated with a blocker identical to that which failed. Its operation to date has been satisfactory, but it has not been possible to subject it to any prolonged periods of operation at the 6% DF. This has been occasioned by hard-tube modulator problems; the Machlett 8618's employed in the modulator lose emission when pushed to the 6% DF. Operation of the 7835 amplifier at design power (3 MW) at 6% DF can now be maintained for only about 30 min before the modulator begins to exhibit emission limit.

The general subject of transferring large average-power levels through coaxial transmission lines has been given some attention. The 50- Ω transmission line now employed has a nominal outer conductor diameter of 9 in. Assuming an ambient environmental temperature of 100°F and imposing a limiting inner conductor temperature of 212°F, the line is rated at ~ 200 kW average power. LAMPF, however, requires transferring 360 kW of average power. A number of mechanisms can be employed to increase the average-power rating of a coaxial line. These include increasing the line size, pressurizing the line, filling the line with a gas having a higher heat-transfer coefficient than the air normally employed, and treating the conductor surfaces for greater heat emissivity.

Floating Deck Modulator Development

A new 4CW100,000D modulator has been constructed and is now undergoing electrical tests. Preliminary results indicate that it will operate satisfactorily. This new modulator is intended for use with an Amplitron and uses direct rf drive with no drive amplifiers on the floating deck. Another identical unit is in an advanced stage of construction and will be finished shortly. This unit is intended for further modulator experiments.

The new 7835 modulator is under construction and electrical tests will begin in August. The first version will use one 7482PV as the output tube with a 4CW100,000D modulator as a driver.

After some effort, a 4CW100,000D was installed in the Amplitron modulator and it has run well for ~ 200 h. Because of the high gain on the floating deck, numerous instabilities were found which had to be eliminated.

EIMAC has built a special rectifier diode for use in the rf interface unit by modifying one of their microwave triodes. The units are Y490's and function in a bridge demodulator on the floating deck. They supply 3 A peak, at 2000 V PIV, and 30 MHz.

The design of a 30-MHz rf interface between the pulse source and modulators was completed

and an experimental version built for testing. The equipment started with a 10-MHz crystal oscillator and tripler in a single triode-pentode stage to generate the reference frequency. This was followed by a low-level ($\frac{1}{4}$ W) keyer stage driving a 3-W beam power output stage to complete the exciter. Pulse keying was accomplished in the keyer stage by controlling its screen voltage by means of a clamp tube driven with a 30-V negative pulse. In the off condition, the keyer-tube screen operated at -25 V and in on condition was driven up to +175 V. With this screen excursion, the exciter output was zero in the off condition and saturated in the on condition with pulse rise and fall time less than 0.5 μ sec. Power stages consisted of a 2E26 followed by a 4CX250B driving a 4CX1500B 1.25-kW cw or 2.5-kW peak. A problem was encountered in the power stages in that decay time in tuned circuits prolonged the fall time of the pulse. This was corrected by introducing inverse feedback in each stage as needed.

Isolator Development

High-power isolators are of interest for possible use with any of the 805-MHz amplifiers being considered if the isolators can be obtained at a low enough cost. In an effort to understand the operation and economics of these devices better, a modest experimental program has been started. Thus far, this has resulted in a full height waveguide isolator with 4 dB of isolation and 0.7 dB of insertion loss at 805 MHz. The material used was a nickel ferrite supplied by Trans Tech. The magnetic bias field is generated by permanent bar magnets which are standard stock items. At present, the bias field is too low, which results in the rather high insertion loss. Better pole-tip shaping would undoubtedly increase the bias field; models of different pole-tip shapes are being constructed.

IV. ACCELERATOR CONTROL AND INSTRUMENTATION

Introduction

The development of the computer control system passed a milestone when the Amplitron test stand was stepped through its turn-on sequence from the operator's console. This exercise brought into play all the components which make up the control system--the computer and its programs, the operator console hardware, and the CIU-RICE-MIU complex (see below). It emphasized the very large effort required to get a system of this type operational because all the components cited above had to work together smoothly before even the simplest operator request could be serviced. The work required to automate the turn-on and operate the test stand is much smaller by comparison.

The computer system has been operational for 4 months and indications are that its reliability will be adequate. The resident systems programs and the basic operational programs for the Mockup Facility are essentially complete. Satisfactory progress has been made toward an array of general applications programs.

Implicit in the successful turn-on of the Amplitron test stand is the fact that checkout and integration of the Computer Interface Unit (CIU), the Remote Information and Control Equipment (RICE), its associated input/output chassis (RICE I/O), and the Module Interface Unit (MIU) were completed along with the modification of all control circuits in the test stand for local or remote control by the computer.

Among the special instrumentation and control packages developed were a high-temperature alarm to be used on magnets, a water flow monitor, and a flow switch, all based on the use of thermistors. Other circuits were developed to aid in solving the temperature control problem in the 4-ft Alvarez tank.

Summaries were compiled of the various devices and systems to be controlled or monitored in the Electron Prototype Accelerator (EPA).

Schematics were originated for their associated electrical systems. Channel lists for the data and command channels were tabulated.

Work has been continued on various operational support systems. A surplus radiation area monitor as well as several pieces of surplus TV monitoring equipment were reconditioned for use in the Electron Prototype Laboratory (EPL).

Design of the Injector Control Room was initiated. The changes being proposed to earlier preliminary designs reflect the experience gained so far in the Mockup Program.

Experimental work began on two components essential to the automation of beam emittance measurements. Results to date indicate that the proposed scheme will work.

Data Acquisition and Control System

Control Computer

Recently, the failure rate of peripheral units in the control computer system has averaged about one unit per week. Fortunately, there is sufficient redundancy in the system so that it is not always necessary to take the computer off-line in the event of a failure. Thus, if the accelerator were shut down for routine maintenance for two shifts a week, it would be possible to service the peripheral unit during such intervals. However, it is hoped that the failure rate can be reduced still further. Since the computer has been in operation only about 3 months, additional time will be required to accumulate sufficient statistics to permit a meaningful evaluation of the reliability problem.

Programming

The resident systems programs for the Mockup Facility were completed and debugged. It includes the Executive program plus Driver and Interrupt programs for each peripheral device. The basic package of operational programs was also completed and debugged. This includes programs which implement the seven functions on the operator's console--Status Display, Video Signal Selection, Program Selection, Display Selection, Analog Demand, Binary Command, and

Slewing--plus Data Scan, which monitors each data channel in the facility and checks it against preset tolerances. These two programming packages were used to turn on the Amplitron test stand through the operator's console. A program to do the first portion of the turn-on automatically was also demonstrated.

A number of displays were completed for the Scope Display. It is now possible to display the Time-of-Day Clock, any eight consecutive words in the computer's memory, and three different data channel lists. Moreover, a Line-by-Line display program was completed which permits an operator to compose dynamically, and store for later recall, lists of any data channel in the facility.

Work is nearing completion on a Vary program which will permit an operator to perform parametric studies on-line of any two analog data channels of the accelerator and have the results plotted on the Display Scope. A Time History program was also started which will allow an operator to observe any data channel as a function of time via a graph on the scope.

A diagnostic program to facilitate the study of noise problems in the CIU and RICE was written and used in the tests described later.

The programming effort was greatly facilitated by completion of three utility programs--Skooter, LDMD, and LDDL. Skooter takes care of bringing in all software packages from the disk. It gets its name from its ability to move itself about in core to avoid being overlaid by the program coming in from the disk. LDMD and LDDL make it easy for the programmer to use the disk and to debug his programs.

Computer Interface Unit

The dynamic checkout of the CIU with the computer and RICE was completed. This checkout includes the five RICE instructions (Command, Data Take, Data Collect, Video, and RICE Reset), the three CIU priority interrupts, and operation of the Command Busy Buffer and Cycle Counting Clock. The reliability of the CIU promises to be satisfactory. To date there have been no component failures in 1000 h of operation.

Remote Information and Control Equipment

Integration of the RICE with the CIU and computer was essentially completed. The main concern in implementing the RICE system was the noise environment in which it was necessary to operate. This problem was investigated in a test in which the CIU-RICE system was exercised by the computer with the RICE in a shielded room. In this test, 3×10^7 binary data bits were transferred with no error. In addition, approximately 1.5×10^6 analog data conversions were made and transferred into the computer with no error. This is to be compared to about 10^5 data transfers per hour that the control system is expected to make in operating the accelerator. In the case of commands, a sequence of 2.4×10^4 binary commands and binary data takes was run before the system detected its first recoverable error. This compares favorably with a figure of 1000 commands per hour for routine operation of the facility.

Upon installation in the Amplitron test stand, it was found that the RICE and the transmission system definitely were susceptible to the noise environment found there. Investigation showed this was principally due to the ac power line supplying the control system power. An rf filter and isolation transformer virtually eliminated the noise. In addition, it was necessary to suppress the relay coils in the local control circuitry in order to prevent noise entering the system when these relays were opened. The only remaining source of errors is the firing of the crowbar. This fault usually generates one or two recoverable errors but that kind of error rate is easily tolerable.

Two more RICE units are being wired for the EPA. Both units are nearing completion. Checkout of one unit is $\sim 80\%$ complete. These units will be identical to the one in the Amplitron test stand with the exception that more channels will be implemented in each case.

Module Interface Unit

The MIU for the Amplitron test stand was completed. Seventy-one binary data channels, four pulse command channels, five analog data

channels, and 31 binary command channels were installed. Very few troubles were encountered in making this system operational beyond those normally expected in interwiring chassis. Some filtering of inputs was necessary to eliminate marginal threshold levels.

The experience gained to date with the Amplitron MIU has indicated several changes to be made in the EPA MIU. The layout of the card cages has been changed to a conventional chassis-type system. The grounding of the entire MIU-RICE-RICE I/O system and the associated local control circuitry has been revamped principally to include signal returns with all transmitted signals.

The MIU contains five types of printed circuit boards--two types for the analog command and one each for analog data, binary data, and binary command. All these boards, with the exception of the binary command, were redesigned for the EPA and are currently being fabricated.

Remote Information and Control Equipment Input/Output

The RICE I/O chassis installed in the Amplitron test stand was wired to the analog and binary command and data channels in the MIU. Analog current and voltage data were read from magnet power supplies and the IVR position was read from a potentiometer. Binary command and data channels to and from various control relays and other test stand circuitry were exercised.

Wiring lists for two more RICE I/O chassis to be used for the EPA were prepared. These chassis have higher channel capacities than their counterpart in the Amplitron test stand: 52 analog inputs, 30 analog outputs, 110 binary input bits, and 50 binary command bits. Four new printed circuit boards were designed which will simplify the wiring and improve the logic fan out. These chassis are being wired.

Video Control Unit

One module Video Control Unit (VCU) was installed in the Amplitron test stand and checked for compatibility with the RICE. Its successful

operation makes it possible to select test video signals through the computer for viewing on the operator's console.

The console VCU was bench-tested and installed in the control console. Interface wiring with the CIU was done but functional checkout with the CIU is still pending.

A third module VCU was built for EPA which is functionally identical with the first two units but is built using general purpose printed circuit card logic boards. This unit was functionally bench-tested but awaits two power supplies to complete the chassis.

RF Module Control

805-MHz Modules

All control circuits in the Amplitron test stand were modified so that the test stand can be operated locally or by the computer. All data and command channels in the test stand appear to be operating satisfactorily.

Accelerator Module Control

201.25-MHz Modules

The 4-ft model has been instrumented so that temperature vs time can be recorded at various places on the tank. This will permit determination of the time constants which are involved in the temperature control loops. Sensing the temperature of the copper lining of the tank gives a signal whose rate of change is a very sensitive indicator of changes of power input to the tank. It is thought that this signal can be used to position a cooling water valve to produce an equal but opposite rate of change of cooling water temperature, thereby preserving the physical dimensions of the tank.

A basic flow-switch circuit has been designed for use in the Alvarez section of the machine. This circuit employs a 5-k Ω disk thermistor which is mounted on the current-carrying magnet winding and solid-state circuitry to activate an exceptionally reliable mercury relay. An experimental version of this circuit has been used in an Alvarez magnet test setup for several days and has operated satisfactorily.

805-MHz Modules

Stepping motor controls for steering and focus magnets for EPA have been designed. Motors are on hand and printed circuit boards have been ordered.

Electron Prototype Accelerator

The design of the electrical systems for EPA has been initiated. This effort required the defining and listing of the various pieces of equipment to be controlled or monitored. Once the lists were complete, schematics of the electrical systems were started. At present, schematics have been originated for the vacuum, water, target position, and steering magnet system and final versions of these schematics are being drawn. In addition, various chassis wiring schematics have been originated and are being drawn.

Components for the various chassis were ordered and have been received. Fabrication will start once the electrical drawings are complete. A significant amount of design and drafting remains to be done in this area in addition to the fabrication that is required.

Hardware channels for the EPA have been allocated. The following numbers of channels are expected: 177 binary data, 68 binary command, 41 analog command, and 86 analog data. These channels will be divided into two modules in the EPA for servicing by two independent RICE units. Assignment of operator identification numbers to hardware channels is in process.

Wiring lists for wires between the EPL Iron House and the associated control racks have been generated and will be used for pulling and terminating cables. This work has been started.

A water flow indicator circuit using a 5 k Ω glass-bead thermistor, similar to the one for the Alvarez magnets, has been designed for use in EPA. This circuit is binary and indicates whether there is a flow or not in the line in which the thermistor is installed. The indicator will operate properly over a 20 $^{\circ}$ F variation in the water temperature and has a switching time of ~ 1 sec. Printed circuit cards are now being laid

out for this circuit. A chassis layout for the Flow Indicator Panel will be made soon.

The electronic design of the water flow monitor circuit (flow rate, temperature, and flow switch) for use in EPA has been completed. The circuit must still be checked in the experimental setup using 5 k Ω bead thermistor probes. Equations relating voltage to flow rate and to temperature may then be written for the unipolar analog channels to make the monitor compatible with the computer.

Auxiliary Operational Systems

Master Pulser No. 1 was modified to improve the computer interface characteristics. Subsequent checkout of this device with the computer indicates that the modifications are satisfactory.

Operational Support Systems

Communications

Wiring lists were prepared for the interphone system in EPL. An additional amplifier system was planned so that selected channel conversations can be heard in the Central Control Room (CCR) without the use of headsets. For public address, three speakers are to be located within the Iron House in EPL and fed from the old PA line. Line-matching transformers are to be included to reduce line loss. An additional speaker will be located at the control racks in EPL and possibly another, if needed, near the IPA. The latter two speakers will be fed from a separate circuit controlled in CCR.

Radiation Safety Systems

A surplus Victoreen area monitoring system has been reconditioned and is ready to be installed. Three chambers located on the walls of the Iron House in EPL will be read by this system.

For machine monitoring, a small ion chamber will be located near each "beam scraper" along the accelerator. Their output will read, and record if desired, at the EPL control racks.

Two "rover" carts carrying a tissue-equivalent gamma detector, a Shonka-type neutron detector, and an alarm system will be used, one inside and one outside the Iron House.

The rad-safe cable system for EPA has been laid out.

TV System

Two surplus Kintel monitor and control systems have been procured. One of these has been reconditioned for use in the EPL control racks. A radiation-hardened Kintel system was also obtained. This system will be modified to work with the Kintel monitor and control systems. A Vicon Insul-8 TV system was obtained and has been reconditioned for installation in CCR. Cable components not in stock for these systems have been ordered. The TV cable system was designed.

A pan and tilt system and controls were ordered for use with the Vicon TV system.

Centralized Control

Injector Control

Design of the Injector Control Room (ICR) rack and panel layout has been started. Changes in design suggested by experience in the Mockup control room are being evaluated and will be incorporated when deemed superior to the preliminary design. Included in these possible changes are the following: (1) Duality of the on-line and off-line control consoles to the extent that the off-line console can be used for on-line control in the event of a serious breakdown of the on-line console. (2) Isolation of interarea grounds in the termination cabinets in the basement below ICR so that the ICR ground will be independent of ground noise in other areas. (3) Replacement of the teletype and multiple rotary switch inputs of the control consoles with a central keyboard input and digital displays.

Operator-Machine Interface

The dynamic checkout of all chassis associated with the operator's console in the

Mockup control room has been completed. The cross-talk and noise problems which had been observed in the status and VF panels were eliminated and no known problems exist at this time. However, experience to date has indicated several changes in portions of this system would be desirable, e.g., changing the status indications from many individual channels to a few summarized displays, utilization of the display scope for fault indications rather than the status panel, etc. These changes are being evaluated for use in the ICR.

Miscellaneous

Beam Profile Analyzers

Scintillator Plate - TV System: A line selector system was developed for separate display of the beam intensity profile. This was found to work with either a standard TV-scanning system or a random interlace-scanning system. For the latter, however, enough jitter existed that spatial resolution was somewhat reduced and the line selected tended to jitter between adjacent lines. The spatial resolution for the standard scanning system was found to be compatible with the rated bandpass of the system; the system tuning (alignment) thus appears to be satisfactory.

The TV-system sensitivity was found to be much less than had been expected. The equivalent ASA rating for the first Vidicon employed was 1200, indicating a sensitivity one-third that of the fast Polaroid "3000" film used to record pictures of the same scene. Experimentally, their sensitivities appear to differ by a much larger factor. The optics, geometry, and timing conditions are being checked in detail for an explanation.

Beam-Scanner System: Several timing systems for a beam scanner were considered in light of the following two design criteria: (1) When beam analysis is desired, the sampling probes must be on beam axis at the time the beam pulse is passing. (2) When a beam analysis is not desired, the passage of the sampling probe must be timed so as to miss the beam pulse.

Cable requirements were determined and a schematic drawn for the electrical system.

Gamma-Ray Pinhole Camera

Construction of a gamma-ray pinhole camera was completed. The first results from the 4-ft Alvarez accelerator tank were underexposed but sufficiently distinct to indicate a dominant source of x rays at one end of the center drift tube. Two faint sources at either side were tentatively traced to internal steel supporting structures; these probably scattered the primary radiation. More exposures will be made when the rf system is operating in a more stable manner.

Wiring and Terminations

A computer program to process wiring and termination information has now been programmed and is being "debugged". Every effort is being made to get the program and data cards ready in time to be of use in EPL.

V. ACCELERATOR PHYSICS

Introduction

A six-day operating life test of the duoplasmatron ion source, at 6% DF, was completed successfully, and measurements were made of the emittance. It appears that the new emittance measuring system will be very useful.

Numerical studies of particle motion in various portions of the linac were continued. Results include new tabulations of the basic parameters of the drift tube and waveguide portions, studies of the effects of quad magnet aberrations on the transverse motion, and buncher studies.

Drift Tube Linac Design and Layout

The final geometrical dimensions of the drift tube linac have been determined; the salient features are given in the accompanying table. The entire design procedure has received a critical review and a comparison was made of LASL¹ and BNL² design formulations; the agreement was excellent. The final LASL design was based on 150 new MESSYMESH runs, most of which were obtained from MURA.

Particle Dynamics Studies

Waveguide Linac

A numerical study of the effects of aberrations in the quadrupole lens in the waveguide linac has been initiated using the LASL computer program STEFFEN. In this application the predominant lens aberrations are of the third order. The presence of these aberrations may result in an increase in beam size and divergence of the beam envelope over the predictions of a first-order theory; hence, their effect should be assessed in the design of the linac.

Electron Prototype Accelerator

The design of the tungsten rotating wire-scanning wheels for beam profile monitoring on the Electron Prototype Accelerator (EPA) is partially completed and fabrication has begun.

Fig. 35. Multipole spectrum for a prototype Alvarez quadrupole magnet.

This device will provide integral beam profile information of the electron beam in two orthogonal directions.

A multipole field analysis has been carried out on one of the prototype Alvarez quadrupole magnets at the magnet testing laboratory at SLAC using their rotating coil system. The multipole spectrum in the central region of the magnet is presented in Fig. 35; only part of the fringe field contribution is contained in this spectrum. Moreover, because of difficulties encountered in aligning the rotating coil, the spectrum should be considered as an upper limit of the harmonic content in the magnet. It is anticipated, however, that the total harmonic content, including all the fringe field contribution, will not differ significantly from the spectrum in Fig. 35.

The harmonics corresponding to four-fold symmetry terms (6th, 10th, 14th) imply a maximum deviation from the quadrupole magnetic field (2nd harmonic) of $< 0.5\%$ at the radius measured (0.85 bore aperture). The octupole harmonics (4th and 12th) observed are believed to be due to an

DRIFT TUBE LINAC PARAMETERS

Cell No.	Tank 1	Tank 2		Tank 3	Tank 4
	1 to 31	32 to 59	60 to 97	98 to 135	136 to 165
Energy in (MeV)	0.75	5.39		41.33	72.72
Energy out (MeV)	5.39	41.33		72.72	100.00
Δ energy (MeV)	4.64	35.94		31.39	27.28
Tank length (cm)	326.0	1968.8		1875.0	1792.0
Tank diameter (cm)	94.0	90.0		88.0	88.0
D. T. diameter (cm)	18.0	16.0		16.0	16.0
D. T. corner radius (cm)	2.0	4.0		4.0	4.0
Bore radius (cm)	0.75	1.0	1.5	1.5	1.5
Bore corner radius (cm)	0.5	1.0		1.0	1.0
G/L	0.21-0.27	0.16-0.32		0.30-0.37	0.37-0.41
Number of cells	31	66		38	30
Number of quads	32	29	38	20	16
Quad gradient (kG/cm)	8.34-2.36	2.44-1.89	1.01-0.87	0.90-0.84	0.84-0.83
Quad length (cm)	2.62-7.88	7.88	16.29	16.29	16.29
E_0 (MV/m)	1.60-2.30	2.40		2.40	2.40
ϕ_s (deg)	-26°	-26°		-26°	-26°
Power (MW)	0.304	2.697		2.745	2.674
Intertank space (cm)	15.90	85.62		110.95	--

Total length including intertank spaces = 61.74 m (202.5 ft).

angular misalignment of the rotating coil and not to harmonic content in the magnet. The magnet will be inspected, however, for octupole distortion. The small amplitudes of the sextupole (3rd harmonic) and other odd harmonics is indicative of the precision of construction of the magnet. Although the present measurements are only preliminary and incomplete, they do indicate that the harmonic content of this design is comparable to that observed in other quadrupole magnets. A similar rotating coil system is now being engineered for use in testing the quadrupole magnets for LAMPF. Further studies will also be made to determine the integrated harmonic content including all the fringe field contributions and to determine whether pole-tip shaping can be used to reduce harmonic content.

Injector Program

Cockcroft-Walton (C-W) Power Supply

The grounding system for the LAMPF injector complex requires an isolated Faraday cage enclosure for each C-W power supply. The unusual nature of these enclosures relative to standard building construction practices makes it desirable to design and fabricate the cages as integral parts of the accelerator. Preliminary design work has been done to the extent that the associated injector building requirements have been established.

Preliminary plans for the construction of the C-W power supply have been received from Haefely & Co. Except for minor changes in the mechanical design, the plans are satisfactory.

Accelerating Column

The fabrication of the accelerating electrodes for the partial accelerating column is proceeding. The completion of all the electrodes is expected by the end of Sep. 1967. The outer high-pressure jacket has been received and will be tested at 50 psi of water pressure.

The results of the metal-to-ceramic brazing studies have been unsatisfactory. Although the technique developed at LASL, which consists of a single-step process of wetting and brazing using either Ag-27.3Cu-2.5Zr alloy or Ag-26.5Cu-5Ti alloy, has proved to be satisfactory on small test samples, the tests using a 5-in. diam ring configuration have failed. In the ring tests, the hoop stresses developed in cooling the brazed joint were not relieved by the brazing agent as expected. Although the seal appeared satisfactory upon visual inspection and was vacuum-tight, the entire assembly ruptured violently when the sealed joint was gently rapped. It is now evident that extrapolating the process to large ring diameters of 15 in., as required by the partial column, will not be satisfactory.

For the partial column, an alternate solution to the metal-to-ceramic sealing problem has been adopted to assure testing of the column in the near future. Vinyl acetate, or another adhesive that can be cured near room temperature, will be used to seal the ceramic-to-metal joints. The poor creep resistance of these adhesives will be compensated for by placing the ceramic-titanium inner column under several hundred pounds of compression by using the bellows on the downstream end of the column. Under these conditions, the vinyl acetate joints should be adequate for the partial column.

The search for a stronger joint for the full accelerating column will be continued; the effort will be directed in the three general fields of brazing, soft solder, and adhesives.

Double-Drift Buncher

The Many Rings Averaged (MRA) computer program has been modified to handle a beam with a finite transverse emittance and to account for

higher order corrections to the accelerating potential due to the aperture opening of the buncher cavity. The longitudinal impulse that a particle receives is proportional to the modified Bessel function $I_0(2\pi r/\beta\lambda\gamma)$. This means that a particle which passes through the second buncher cavity (operated at 402.5 MHz) at a radius of 1.0 cm receives approximately twice the energy change of an axial particle. A similar correction has been applied to the radial impulse.

The results of these modifications indicate that, for optimum bunching within a phase spread of $\pm 30^\circ$, assuming a 25-mA beam current, a 2π cm-mrad transverse phase space area, and an effective voltage of 20 kV on the first cavity. However, bunching occurs at a distance of ~ 180 cm from the first cavity, which is perhaps not long enough to contain the necessary diagnostic equipment. By halving the buncher voltages, the bunching distance is approximately doubled, but the proportion of particles bunched within a phase spread of $\pm 30^\circ$ is decreased to $\sim 75\%$.

Double-drift problems for CERN and RHEL are being continued. These double-drift bunchers have the frequency of the second cavity equal to the frequency of the first cavity.

Ion Source Test Stand

The ion source has been on the test stand with the cathode hot almost continuously over the past $2\frac{1}{2}$ months. Ion currents from 20-40 mA, at extraction voltages of 20-35 kV, and with good emittance areas (i.e., $\sim 8\pi$ cm-mrad at 20 mA and 20 kV) have been obtained. The source was run at 6% DF with 500- μ sec pulses.

A six-day system reliability and component life test was run. The arc current was 9 A and the ion-source magnet current was 2 A. There was no noticeable deterioration of system components--a good indication that no major problems are associated with the 6% DF. High voltage was not applied during the life test; however, it is expected that the addition of 20-35 kV extraction voltage for long periods of time will create no new problems.

The cathode was kept hot at the normal operating cathode heating power of 28 A at 2.5 V

and with the vacuum pump either under high vacuum or operating with a hydrogen pressure no greater than 2×10^{-5} torr gauge. The accumulated heater current time for this first cathode is now 1887 h. The system has been brought up to atmospheric pressure on dry nitrogen some six times. On two occasions the filament was removed from the source and temporarily stored in dry nitrogen (a suggestion obtained from CERN). Several times, after reinstallation of the cathode, arc pulsing had to be initiated by discharging a 3700- μ F capacitor, charged to 200 V, between the ion-source anode and cathode. Once activated, the source operated in a normal manner.

The ion-source proton current was measured and then checked calorimetrically using a water-cooled Faraday cup with a magnetic field electron trap. Use of a high DF simplifies the requirements for a calorimetric check of the ion current since the average power in the ion beam is large. The ion current pulse shape was observed on a cathode-ray oscilloscope. A typical example of the current pulse is given in Fig. 36. The high-frequency current oscillation during the pulse may be a characteristic of a large ion source expansion cup with a flat plasma extraction surface. The Faraday cup arrangement is shown in Fig. 37. The open end of the copper cup is at the left. Two small permanent magnets with soft iron pole pieces provide a magnetic field for the electron trap. Ceramic stubs insulate the cup from the magnets which are separately grounded. Soft silver solder is used for the joints and to attach the copper cooling tubes. The cooling-water flow was ~ 2 cm³/sec and the in-and-out temperature difference was measured by means of a pair of thermojunctions and a galvanometer. For example, the temperature difference was 8.5°C for a 10-mA, 20-kV beam.

For emittance measurements, the Faraday cup was replaced by a system of slots and a quartz plate. The slots are formed between edges of hexagonal copper bars which are silver soldered to a heavy water-cooled copper frame. The luminescent emittance pattern on the quartz plate is

viewed through a glass window with a cathetometer telescope. The portions of the photographic image caused by light from the arc were separated from the image caused by the blue luminescent light by taking two photographs-- one with and one without extraction voltage applied. A pair of pictures to give an emittance pattern is shown in Fig. 38; only the four slit images are used to determine the pattern. The emittance diagram is given in Fig. 39; the simple emittance area is $\sim 8\pi$ cm-mrad. Up to 700 W/cm² of instantaneous beam power has failed to erode significantly the slotted emittance plate. The quartz plate used as a scintillator showed definite darkening, although this apparently did not affect the scintillation efficiency.

The palladium-leak system for supplying hydrogen to the arc chamber has been used most of the time with manual rather than automatic control. It has been found necessary to use a purging flow of hydrogen over the palladium leak comparable to that through the leak. With this purging flow, the leak rate is constant for long periods of time if the palladium temperature is kept constant. Without the purging flow, the leak rate at a given temperature begins to deteriorate rapidly after ~ 8 h. Impurities probably accumulate in the region of the palladium surface without the purging flow. When the leak rate deteriorates, as is the case without purging, the hydrogen flow finally drops to only a few percent of its initial value, and the normal range of heater-current adjustment is exhausted.

The circuit diagram for the transistorized arc-pulsing circuit is shown in Fig. 40. The circuit used Motorola PNP transistors MP 1612B which are rated at 20 A at 100 V; there are three transistors in parallel on the output. The circuit was intended for tests below 100 V but has run practically continuously for a period of 5 days with 155 V applied across the transistors. The transistors failed, however, after application of 170 V. Rise and fall time of the circuit working into a dummy load at 10 A is better than 1 μ sec with excellent square voltage and current pulse shapes. The rise-and-fall time of the ion pulse obtained using this circuit to pulse the arc is about 5 μ sec. This can be seen from Fig. 36.

Fig. 36. Ion-current pulse; peak current ~ 22 mA, pulse length $500 \mu\text{sec}$, extraction voltage 20 kV, DF 6%. (For corresponding emittance pattern see Fig. 38.)

Fig. 37. Faraday cup with water cooling tube and magnet to trap secondary electrons.

Fig. 39. Emittance plot from pattern of Fig. 38.

Fig. 38. Emittance pattern for a 22-mA, 20-kV beam (Image with light from arc superposed at left; part of image from arc alone at right.)

Fig. 40. Transistorized arc-pulsing circuit.

An attempt will be made to get the required ion current with 150 V applied to this circuit. A protective device, such as a fuse, circuit breaker, or crowbar, must be developed to protect the ion source from an effective 100% DF if any of the output transistors should fail. Such a failure would short the full-power supply voltage continuously across the arc. It is believed that a transistor failure was responsible for the sudden enlargement of the anode hole from 1.5 to 2.0 mm diam on June 8, 1967.

A Varian large-cell 1000-liter/sec ion pump now keeps the vacuum pressure in the system in the low 10^{-8} torr range with the hydrogen turned off but with the filament hot. The only problems associated with the ion pump are related to the abnormally large size of the anode hole. On two occasions the aperture was enlarged by accidentally applying the full voltage to the arc. On the second of these occasions, the hydrogen feed rate increased from 3 cm³ atm/min for the 1.5-mm

diam hole to a 5 cm³ atm/min for the 2-mm hole, with a 200-µ gauge pressure of hydrogen in the arc chamber. An argon activation technique has been used to restore the pumping speed to handle the high hydrogen feed rates, especially after the system has been opened. A new 1-mm diam aperture will be installed soon, and this will reduce the hydrogen flow rate to a more manageable level, ~1.3 cm³ atm/min. The pump has been in use with hydrogen feed rates of 3 cm³ atm/min for 264 h and 5 cm³ atm/min for 107 h. A total of 72 liter atm or 6.4 g of hydrogen has been absorbed by the pump. Since titanium absorbs hydrogen in the ratio of 1.76 H to 1 Ti, ~1.5% of complete saturation of titanium is realized. In a previous test on an ULTEK pump the pump life corresponded to ~10% of saturation.

Beam Transport

Considerable effort was directed toward magnet engineering of the transport system. Each quadrupole triplet, of which there are four, requires

a field linearity of 0.3% over a beam diam of 1 in. for the outside quadrupoles and of 2 in. for the center quadrupole. This criterion appears to be easily attainable in commercial units. As presently designed, the triplets each dissipate only 100 W; consequently, water cooling is not necessary.

For the bending magnets, a field uniformity of 0.05% is required. Power is estimated at ~ 500 W, which will require water cooling. Although the "picture frame" type of magnet can be designed theoretically to give a uniform field, the uniformity depends on precise placement of the coil winding. With this type of magnet, it is difficult to design more than one entrance or exit port. Thus, a bending magnet of either the "H" or "C" frame type is preferable. Preliminary design studies have been made for the "C" frame magnet. Such magnets can be obtained commercially to fit design specifications.

An attempt was made to analyze the ion-source emittance pattern displayed on a quartz scintillating crystal using a Motorola S1110A camera with an RCA 7262-A vidicon. Further use of this camera was abandoned because of its random-interlace scanning system, which made a scope display of a single-scan line very difficult. However, other slightly more sophisticated TV camera scanning systems show promise of overcoming these difficulties.

References

1. D. A. Swenson, "Generation of Geometrical Dimensions for Drift Tube Linacs," MP-3/DAS-1, June 29, 1967.
2. A. Carne and P. M. Lapostolle, "Design Equations in an Alvarez-type Proton Linear Accelerator," Proc. of the 1966 Linear Accelerator Conf., LA-3609, p. 201.

VI. EXPERIMENTAL AREA

Introduction

A major review has been initiated of the experimental area layout and requirements. This review, which will continue for another 6 months, is oriented toward the fulfillment of user requirements and exploring ways of maximizing the flexibility of the experimental area while retaining economy of construction and maintenance. The most significant design change considered thus far involves the remote-handling system for the various target cells. A new concept in remote handling is being developed which is aimed at greater flexibility, reliability, and compatibility with possible future expansion of the experimental facilities.

Shielding

Some modification of the existing DTF-IV neutron transport codes is necessary in order to treat the transport of neutrons generated by the interactions of 800-MeV protons. The existing codes cannot handle the degree of anisotropy associated with the high-energy neutron transport. In particular, the version of DTF-IV which is capable of handling a line source in cylindrical geometry requires that the neutrons from a given line source element be emitted isotropically. The simplest line source model derived from a single scattering treatment of the data generated by the cascade code for a uniform beam loss in the linac structure requires that the emitted neutrons have both an isotropic component and a component which is exponential in $\cos \theta$, where θ is the angle of emission with respect to the primary proton beam direction. Below an emitted neutron energy of 50 MeV the isotropic component is dominant, but above 300 MeV it may be neglected entirely.

A general meeting is to be held at Oak Ridge in August to discuss, in part, the anisotropy problem in high-energy neutron transport. A decision on the manner by which to best modify the DTF codes will be postponed until after the Oak Ridge meeting.

An internal report, MP-6/DRFC/MJJ-1, has been written to discuss the problem of radiation transmission through ducts and voids. Following are the major conclusions cited in the report:

1) Secondary beam lines can be constructed economically for which the transport of neutrons from the respective beam line target is the same as the transport through the target cell shield as a whole.

2) The majority of neutrons transported by the secondary beam line are produced by the interaction of primary and secondary charged particles in the beam line itself.

3) The greatest potential neutron hazard in a correctly designed beam line will arise from the eventual interaction of the charged particles transported by the beam line.

Targets

The main target design effort has been directed toward the target-testing station of the Experimental Prototype Accelerator (EPA). Most of the mechanical and control systems have been designed and the components are in the procurement stage. The experimental work associated with target design has involved the development of brazing and coating techniques for graphite elements. The adequacy of the techniques will not be fully evaluated until a high-intensity electron beam is available from EPA.

Beam Transport Systems for Pions and Muons

The FORTRAN/FAB code, CERN 6008 B56/57 has been obtained from CERN.¹ It is a chain program written for the IBM-7090. The program computes from a set of cyclotron beam data, i. e., from a "Michaelis plot," the transmission coefficients through a chain consisting of (a) beam envelope defining slits, (b) quadrupole magnets, (c) deflection magnets with field index n , and (d) drift spaces, which the user defines by three-dimensional matrix parameters. The computations are carried out in the vertical and horizontal plane, i. e., the muons from pion decay are projected into those planes. The user has the option of carrying out the computation of pion or muon spectra as well as many other computations such as Coulomb scattering in a target.

Unfortunately, the program, when used at LASL, exceeded the core size of LASL's 7094

systems. Alternatives for remedying this situation were either to rewrite the chain links of immediate interest so that they would fit into the memory or to adapt the code for the CDC 6600. It was decided to do the latter. (An offer was also made of a CERN 6600 code written in "CERN FORTRAN," which differs from FORTRAN II and IV; it is said to have some advantages over the latter, but the LASL compiler will not accept it.)

The use of a pion focusing horn as a first magnetic beam element surrounding the target is being evaluated. To that end, a CERN code (no code name, written by C. Iselin) has been obtained for pion trajectories. The code produces very detailed trajectory information. Since there is the need to convert the horn output data into numbers that may be used as input to the pion-muon channel program just mentioned, the code is being converted to one that can readily be evaluated in terms of "Michaelis plot" data, and which can be plotted on film.

The pion-muon decay kinematics were studied in order to understand some of its implication on the design of a muon channel.² It is of interest to note that the quantity $\int B dl$ required to straighten out the muon trajectories to ones parallel to that of the parent pion varies only 7% over the momentum range 50-600 MeV/c of parent pions.

A design study is being undertaken concerning inorganic quadrupole magnets for use in the target cell and in the shield walls. Four conductors placed in various fashions around the beam to form an alternating gradient beam channel are being considered as quadrupole elements.

In order to evaluate the cost of magnets, a COMA program has been obtained from LRL.³

Reference

1. A. Citron, J. Fronteau, and J. Hornsby, CERN 62-36 and 63-30.
2. H. F. Vogel, Internal Report MP-4/HFV-1.
3. H. P. Hernandez, R. W. Schwarz, and R. Yourd, Proc. of the Internat. Symp. on Magnet Technology, Stanford University, 1965, p. 196.

VII. PROJECT SCHEDULING AND FACILITIES PLANNING

Introduction

The IBM PERT Cost II scheduling of the LAMPF accelerator has progressed to 90% completion. Derivations of Work Breakdown Structures and Network Diagramming to Level III are essentially complete. Network analysis has demonstrated the feasibility of obtaining a proton beam to target cell A by Dec. 31, 1971.

The Electron Prototype Laboratory (EPL) has been accepted for beneficial occupancy, and accelerator R&D activities are already in progress therein.

Site and building activities for LAMPF are as advanced as funding has dictated. Site preparation work is 72% complete. Title II engineering has been resumed for the Injector and 201.25-MHz accelerator buildings. The Equipment Test Laboratory Building (ETLB) has been given top priority and is now only about 2 weeks from Title II design completion. Designs of the Laboratory-Office Building, of the site electrical substation, and of the second phase of site water and sewage systems have also progressed to the Title II state.

LAMPF Scheduling Activities

The application of PERT to LAMPF accelerator design and construction is now ~ 90% complete. The major changes normally encountered in the derivation of an integrated project Work Breakdown Structure have been accomplished. The revised WBS consists of fifty-two 18 x 24 in. sheets detailed to Levels III and IV in the conventional repetitive format associated with large projects.

The Network Diagramming for accelerator design and construction is ~ 95% complete. All subnets have been developed down through Level III of the Work Breakdown Structure and hence the diagram shows milestone events to that degree of detail. This diagram comprises forty-seven 36 x 54 in. drawings which depict the following seven subnets:

<u>Computer Code Name</u>	<u>Subnet Subject</u>
INJK	Injection Systems
RFPS	RF Power Systems
CONT	First Subnet for Instrumentation and Control Systems
KONT	Second Subnet for Instrumentation and Control Systems
201S	201-MHz Accelerator Structures
805S	805-MHz Accelerator Structures
BMAR	Beam Areas

The input data deck now contains about 7200 cards, compared with the 2500 estimated originally. These cards describe activities, milestone events, manpower, event initiation, completion, and interfaces, and entry control.

Since Oct. 26, 1966, 105 computer runs (an average of 3 runs per week) have been required to coordinate all of the subnets into a self-consistent set. At present the number of project events exceeds the Level I summarization capabilities of the computer, and manual plotting must be employed. To date PERT network analysis has demonstrated the feasibility, with no funding constraints, of obtaining a proton beam to target cell A by Dec. 31, 1971.

Facility Activities for the R&D Program

The facility activity for the R&D program has progressed to such a sufficiently complete status that the individual technical groups can proceed with direction of the completion and modification work. For example, the EPL was essentially completed and accepted for beneficial occupancy; development activities are already in progress therein as described elsewhere in this report.

LAMPF Site and Building Activities

Site Roads, Grading, and Utility Work

Site preparation work has progressed very well and is slightly ahead of schedule at 72% completion. The asphalt concrete binder course is being laid on the access road; the water and gas supply lines are in place; and work is in progress on the associated drainage, relief, and valve pits. Site grading is very near completion, including three modifications effected since the beginning of the

project. The first of these was lowering of the Beam Channel by 4-ft, as reported previously. Second, after excavation of the Beam Channel to the planned vertical wall profile, it was determined that for future construction work in the channel a possibly hazardous condition existed because of fractures in some of the upper layers of tuff. To alleviate this condition it was decided to cut a 1-in-4 slope on a portion of the walls. This entailed ~ 12,000 yards of additional excavation which is now nearly complete. The third earthwork modification was the addition of ETLB and Laboratory-Office Building sites. Plans for these two facilities had progressed to the point that the required grading was well defined and could therefore be obtained under this contract at considerable savings in time and money. The clearing of these two areas has now been completed.

Accelerator Building Design

Title II engineering of the Injector and 201.25-MHz accelerator buildings was reactivated and completion is scheduled for the middle of the next report period. During the time that work on these buildings was held in abeyance, two major changes in criteria were involved which must now be incorporated into the design.

During specification negotiations for the 750-kV Cockcroft-Walton power supply to be used in the R&D program, it was ascertained that complete electrical isolation from building structures is necessary for Faraday cages around the LAMPF injectors. This new requirement resulted in a rather extensive modification to design interfaces and structural detail.

The second area of criteria changes involved the process water cooling systems. To take advantage of potential cost savings as well as to expedite design and construction, it was decided that the Injector and 201.25-MHz accelerator cooling system should be separated from other cooling facilities. Furthermore, consideration of operating parameters, maintenance conditions, alignment features, and relative costs led to the conclusion that the process water for all accelerator tank cooling should be chilled to 55°F. These

changes are currently being incorporated into the design by the A-E.

Equipment Test Laboratory Building

Since its initial function is to provide some of the required space for accelerator component assembly and testing, the so-called ETLB has been given priority consideration. During this period the criteria were prepared, approved, and transmitted to the A-E. Title I drawings were received and reviewed, and an interim Title II review has just been completed. A site for the building, approximately 1400 ft west of the Laboratory-Office facility, has been selected; clearing and grading have been initiated.

Laboratory-Office Building

Completed Title I documents for the Laboratory-Office Building were received from the A-E on May 1, 1967 as scheduled. The cost estimate for this portion of the project was \$1,345,000, which is \$80,000 less than budgeted at the outset of the design contract. The design concept was reviewed, and on May 17, 1967 comments were transmitted along with the notice to proceed with engineering design. An interim Title II design review was held on June 9, 1967 with every evidence that this portion of the facility is progressing on schedule.

Utility Work

As previously reported, Giffels & Rossetti had been instructed to proceed with Title II plans and specifications for the second phase of the site water and sewage systems. An interim set of plans was received at the beginning of June. A comprehensive review of these designs led to the conclusion that both cost and serviceability could be served better by consideration of alternative approaches. As a consequence, the A-E was directed to relocate the water storage system some 1200 ft to the west, so that domestic usage could be provided from the tank by gravity, and to change the sewage disposal system to a lagoon design, the success and economy of which have already been demonstrated in the community. Design completion for these

portions of the project is estimated to be August 30, 1967.

A contract with Uhl & Lopez of Albuquerque, N.M., for design of the site electric substation was successfully negotiated and became effective on May 24, 1967. An interim Title I design review was held on June 23, and the completed Title I documents were reviewed on July 27, 1967. Comments have been forwarded and the basic design has been approved so that the completed Title II engineering is expected within 60 days for this part of the project.