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LOS ALAMOS SCIENTIFIC LABORATORY
of the
University of California
LOS ALAMOS • NEW MEXICO

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

UNITED STATES
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I. SUMMARY

Accelerator Structures

Drift Tube Structure -- 201.25 MHz

Continued study of the post-coupled drift tube structure has revealed no serious problems. It has been decided to use this structure in the drift tube linac. Final design has started on the drift tube tanks, and final layout of the tanks is complete.

Side-Coupled Structure -- 805 MHz

The Model K accelerator tank, with its bridge coupler and waveguide feed, has been run successfully at 900 kW and 6% duty factor (DF). This is three times the design power for Model K, and indicates that the structure will operate without sparking at well over the design gradients. At these power levels, there was some heating of the input window, but this has been remedied by a Ti coating. The present design of bridge coupler uses posts to balance the coupler. This application of the resonant $\pi/2$ -mode coupling principle was very successful in these tests.

The electron prototype accelerator (EPA) is installed except for one of the 12 sections, which had to be reworked because of leaks.

RF Power Sources

201.25 MHz

The system was operated throughout the quarter. A number of problems were encountered with the resonant cavity supplied by Continental Electronics for the 7835 final power amplifier. These problems have been met by remachining certain cavity parts which had manufacturing defects, and substituting a blocking condenser of improved design for the upper plate blocker. The 7835 modulator has been redesigned. A 7835 tube was destroyed by failure of the water system protective interlocks; this system has now been redesigned.

805 MHz

The klystron modulator was rebuilt and the new version has been satisfactory. During the last two quarters, the Litton 1.25-MW klystron has operated for about 250 h at substantial levels of

both peak and average power. The behavior of the klystron has been generally satisfactory.

A second 1.25-MW Amplitron was received from Raytheon; its rf envelope, although cleaner than that of the first Amplitron, was not satisfactory for use with the linac.

Proposals have been received from the respective vendors to build pre-production and production models of the tubes mentioned above. It has been decided that klystrons will be the design choice, and negotiations with the vendor will be initiated. However, a certain degree of compatibility between the two tube types is being designed into the rf system so that if crossed-field devices are further developed (at the vendor's expense) they could be included in the LAMPF system.

Accelerator Control and Instrumentation

Wiring and installation of controls for EPA are being continued. Operation of the mockup computer has been continued in a generally satisfactory way. The so-called "Resident System Programs," which organize the operation of the computer, have been augmented. A number of operational programs were put into service and performed well. A series of programs was checked out to turn on the Amplitron test stand.

Some problems were encountered with interface hardware, both at the computer and at the module location, and corrective steps were taken.

Injector System

Operation of developmental ion sources has continued, with encouraging results, especially as regards lifetime at high DF. The test stand was enlarged to accommodate work with a 200-keV accelerating column.

Experimental Area

A new design of the remote-handling system was worked out. It replaces the older system of cranes and manipulators and TV viewers which operated remotely within the target area shields and hot cells. The new system is designed

around a shielded vehicle which moves along the top of the target area shield. It is designed to service all target cells, part of the secondary beam channels, the target area process and mechanical equipment, and the beam stops. In turn, it would be serviced in a separate building.

Scheduling, Facilities Planning, and Construction

The LAMPF site preparation is 95% complete. Bids have been opened for \$2.9 million of additional construction, including the Lab-Office building and the Equipment Test Laboratory building. Totals were close to final estimates.

Design engineering is essentially complete for the second phase of utility work.

Final criteria are being developed for the injector and drift tube accelerator buildings.

Requests were issued by the AEC for proposals for supplying electric power to LAMPF. A proposal received from the Public Service Company of New Mexico jointly with the U.S. Bureau of Reclamation is being evaluated.

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II. ACCELERATOR STRUCTURES

Introduction

The Model K accelerator tank, with its bridge coupler, has been successfully run at high power (900 kW) and full (6%) duty factor (DF). The bridge cavity uses resonant post stabilization of its fields such as was described in the preceding quarterly report (LA-3772-MS) for the drift tube linac. No sparking, vacuum outgassing, or other problems were encountered in the operation of the tank, even though the power is more than three times the peak power required to drive Model K to design gradient. These results give added confidence in the bridge coupler concept, with resonant post tuners and waveguide feed into the bridge. A vacuum window heating problem was encountered but steps are being taken to resolve this.

Work on the Electron Prototype Accelerator (EPA) has been continued, with completion of all tank sections expected within two weeks. Installation is continuing and should be completed during the next quarter.

Studies have been continued of the resonant post coupler for the drift tube accelerator section of the linac. No deleterious effects in accelerating field quality have been detected in this system, and the decision has been made to use these couplers in the drift tube linac for LAMPF. Final design of this linac has started, with three prototype drift tubes under construction and final tank layout complete. Criteria for control wiring and rack layout are being generated, so that building design may be completed. A general approach to accelerator tank and beam line local controls is being developed which will be the guideline for the entire accelerator.

Side-Coupled Accelerator Studies

Model K

Measurements on the Model K accelerator tank with bridge cell indicated that the bridging cell could be analyzed as two nonresonantly coupled cells in the middle of the cavity chain. Power flow phase shift was observed across the bridging

cell and the relative amplitudes of the two tanks of Model K could be changed by perturbations in either tank.

In extending the principle used to stabilize the drift-tube accelerator, a post tuner was placed in the bridging cell, making the center tuner about 3-in. long. In this way, the two Model K tanks were effectively resonantly coupled. The slug was tuned to give zero power flow phase shift across the bridge coupler. This resulted in a symmetrical passband near the $\pi/2$ -mode and removed the tilt sensitivity. Experiments and theory indicated that an asymmetry in the tuner could be used to control the relative amplitudes of the field in the two tanks.

A $\frac{1}{4}$ -in. deep by $\frac{3}{8}$ -in. wide notch was cut in the tuner. This provided a $\pm 5\%$ variation of the tank amplitudes about their nominal value when the tuner was rotated in the tank to provide coupling asymmetry to the post. By rotating the tuner, the amplitude in each tank was equalized.

With the tuner in place and properly adjusted, Model K behaves in all respects as expected from calculations based on the coupled circuit model.

Power flow phase shift measurements indicated that the coupling cells connecting the two tanks to the bridging cell were about 20 MHz high in frequency. Before performing the experiments with the bridge coupler post tuner (above), these cells were tuned to the correct frequency. It was feared that the frequency error was too great for it to be practical to lower the coupling cell frequencies by squeezing the cells. Instead, a $\frac{1}{4}$ -in. diam slug with a spherical end was inserted through the coupling cell probe hole. The length of this was adjusted until the coupling cells were resonant at the correct frequency as determined by power flow phase shift measurements.

When properly adjusted, these slugs protruded slightly more than halfway across the coupling cell gap. No trouble with sparking has been experienced due to the tuning slugs, even though, when driving in the center, these cells have the greatest power flow field amplitude.

The coupling iris was enlarged until Model K VSWR was 1.2 to 1, overcoupled, with the G, E. waveguide window in place.

Model K, with the bridge coupler and resonant post tuner, has been run at high power for testing purposes and no fundamental problems have been encountered. Using the klystron power amplifier test stand, operation at greater than 900 kW at 6% DF for periods up to 30 min have been recorded. A multipactor discharge in the waveguide vacuum window region caused additional heating of the window and precluded operation for longer periods. Design power for Model K is less than 300 kW, and so the model is running at appreciably higher gradients than will be encountered in the final accelerator, transmitting full power. There are no problems with sparking or vacuum outgassing. The window problem is under study; but it has been encountered and solved at other accelerator installations. Consequently, it should not prove too difficult in this instance.

Electron Prototype Accelerator

Electrical Measurements

Tuning of all individual segments of EPA has been completed. Eight sections have been returned from brazing for final tuning and are now assembled or waiting to be assembled in the Iron House.

The EPA bridge couplers are resonantly coupled with post tuners in the same manner as the Model K bridge coupler except that three tuning slugs were required to remove the power flow phase shifts. A copper bar was brazed in the bottom of the center bridge coupler to compensate for detuning caused by the waveguide iris. Measurements on the seven sections plus two bridge couplers presently installed show no problems with field distribution.

In the bridge coupler, tuning was routine and followed the experience with Model K. All three tuning slugs were adjusted simultaneously to remove the power flow phase shift. On completion of the accelerator assembly, experiments will be performed to determine the validity of this procedure by observing the tank tilt sensitivity to end-cell tuning errors.

A preliminary measurement indicates that the existing iris will give a 5:1 VSWR, undercoupled, when the accelerator assembly is completed. The iris size will then be adjusted for near unity coupling. A preliminary Q measurement gives the EPA Q as 26,000, i.e., ~12% below the theoretical value, as expected.

Mechanical Engineering and Installation

Ninety-four brazing furnace heats have been run to date, using the LASL furnace facility; this is an average of slightly more than three heats per week since embarking upon the program. Ten of the 12 tank sections for EPA have been successfully furnace brazed and all such work should be completed after four more heats.

Installation of the EPA is being continued with seven tank sections and two bridge couplers presently mounted on the support structure. Six tank sections and a bridge coupler are shown in Fig. 1. All vacuum manifold welds and mechanical rf joint assemblies tested to date have been vacuum tight. One knife edge flange was nicked during assembly but with minor field repair the joint was assembled vacuum tight. This shows that it is possible to make field repairs to damaged flanges and obtain vacuum-tight joints without major rework.

All three bridge couplers have been assembly brazed vacuum tight at a vendor's facility. Two bridge couplers have been installed

Fig. 1. Six tank sections of the EPA in place.

Fig. 2. EPA center bridge coupler,

and the third is on hand ready for assembly. The center bridge coupler, which will feed rf power to the entire accelerator, is shown in Fig. 2. The oval shaped coupling iris hole in the bridge tank wall will be finish machined after the unit is installed on the accelerator. All tuning slugs for the bridge couplers have been modified with a longer slotted slug which makes the tuner act as a post coupler in the tank.

An alignment mount for one of the quadrupole doublets has been fabricated and is ready for installation.

Monitor loop probes are now being fabricated for all tanks in this accelerator system.

The injector section components were moved from the Iron House into the Electron Prototype Laboratory (EPL) Building. The electron gun and Model M are now installed and aligned on the support structure. To permit the electron gun vacuum pump to hang between the supporting I-beams, it was necessary to modify the gun housing slightly and build a new vacuum manifold.

Installation of the cooling system has begun. The pump, mix tank, and about half of the cooling tubes are in place. An additional stainless steel cooling system for collimators, tube forest, etc., has been designed and equipment is on order.

Alignment inspection fixtures are being fabricated for one quadrupole doublet magnet, and additional fixtures are being designed to align the doublet to the EPA beam line.

Fig. 3. Valve position vs time after initiating closing of solenoid valve.

The installation of the vacuum manifolds has proceeded along with tank installation. Leak checking has been made upon installation of each tank section. The only leaks found have been caused by copper gaskets which slipped during installation; these were changed to provide a tight system.

The ion pumps have been installed on the electron gun and Model M. These units will be evacuated using spare ion pump power supplies until the rack-mounted units can be energized.

The hardware necessary for coupling together the various components in the target area has been designed and drawings completed. The vacuum manifolding drawings are also complete. The cold trap, which will be Freon cooled, has been received.

The support stand for the spectrometer has been completed and an adjustable mount for the tube forest beam dump has been designed and fabrication drawings are nearing completion.

A high-speed actuator has been developed for a 2-in. CVC vacuum valve to provide a rapid vacuum closure and to prevent target cooling water being dumped into the accelerating system in the event of target burnout. A cushion has been provided to prevent valve damage from the fast closing forces. Tests were performed using a linear potentiometer and an oscilloscope for position and time measurements. Figure 3 shows that the valve port is covered in 30 msec and that the gate is sealed and locked 55 msec after the closing signal is initiated.

Proton Linac Final Design

Production Brazing Furnaces

Specifications for brazing furnaces and associated equipment have been written and fabrication problems discussed with five potential suppliers. Quotations for two furnaces, five bases, five retorts, and necessary control panels are due shortly.

Attachment of Cooling Tubes to the Waveguide Tank Sections

A rectangular copper tube, as used on EPA, has been selected to carry the cooling water along the waveguide tank sections. Cooling tubes have been attached with Devcon aluminum-filled epoxy for the modeling work; however, tests indicate that this epoxy is subject to radiation damage at the levels anticipated in LAMPF. Of the several tube attachment methods that have been considered, soft soldering the tubes to the tanks is the most attractive, because costs and temperatures involved are both lower than would be required for brazing.

An oven has been designed which will permit a tank section to be heated to about 600°F. With the tubes clamped in place over a layer of lead-tin solder, it is planned to solder all tubes on a section at one time. The oven design allows for rotation of the tank in the oven and has windows to observe the melting of the solder. To prevent oxidation on the inside of the tank, provisions will be made to circulate inert gas through the inside of the tank sections. These sections will be set on a carriage and rolled in and out of the oven to eliminate some crane handling.

Preliminary tests on lead-tin solders and various soldering fluxes have been carried out in a small oven. It appears from these tests that a good lead-tin solder joint can be obtained with oven soldering.

Drift Tube Accelerator Studies

Drift Tube and Quadrupole Magnet Design

The quadrupole coil winding forms have been developed for the first group of quadrupole magnets in Tank 1 and they include the rather difficult bend around the yoke. Detailed drawings

are complete for all four groups in the first tank.

All winding is accomplished without intermediate annealing; however, the completed coil is annealed on a stainless steel form in a hydrogen furnace. The annealing form serves to hold the winding shape during the firing cycle.

Several cements of both commercial and LASL origin are being evaluated for potting the quadrupole coil. Although several appear promising, many good and bad features are encountered. Test samples made up of a soft-iron rod wound with the coil covered with a glass sleeve were used to model the magnet geometry. The samples were potted, cured, and subjected to the 1600°F brazing cycle. The resulting assemblies were evaluated on the basis of bond strength, cracks, glass-sleeve embrittlement, and reaction during the heat. One cement that appears to meet most of the requirements was used to pot a new quadrupole magnet. This particular magnet has not yet been fired or undergone further tests. A commercial woven quartz sleeve is being evaluated that is much less susceptible to embrittlement than the glass sleeve. The quartz material represents a cost of only a few dollars more per coil over that of the glass.

Copper forgings have been made for the drift tube bodies of Tank 1. The first forgings were made in one pass at 1800°F and exhibited severe blistering when fired in hydrogen. Subsequent forgings were heated to 1450°F and forged in three passes. Blistering, while less severe, is still present and the forgings are being rough machined and refired for further blister studies prior to final machining.

The quadrupole magnet rejected due to an error in the pole tip shape was used to evaluate the coil potting process and for subsequent power tests. The magnet was designed to operate at 700 A and during tests was driven to 1000 A to collect data and update power dissipation and pressure drop equations used in the Engineering Parameter Subroutine of PARMILA. Preliminary field surveys were made to determine the gradient and quadrupole strength, and the results are given

below. Although the measurements cannot be considered precise, due to the pole tip error, they are at least approximately correct.

	Current (A)	Gradient (G/cm)	Quadrupole Strength (G)
Design	701	8335	21,800
Measured	700	7610	25,600

Measurements at the higher currents indicate that the iron is operating at high flux densities. The code QADFLX predicts flux densities of 16.5 kG/cm in the midsection of the pole. This particular quadrupole magnet represents the most severe saturation problem that will occur in the drift tube linac.

The prototype Tank 1 drift tube support was checked after assembly, and the hard and soft vacuum seal designs performed satisfactorily. Both of these seals could be made without affecting the drift tube alignment. Tear down and reassembly revealed lateral alignment deviations of up to ± 0.040 in. A modification of the clamping mechanism resulted in alignment reproducibility of ± 0.002 in. after numerous assemblies.

A ten-stem alignment model is being constructed to study the mutual alignment problems encountered in the first ten cells of Tank 1.

The first three Tank 1 drift tubes with their associated quadrupole magnets are being fabricated and will serve as pilot models to carry out the various phases of construction from the design through completion. The units will be used to evaluate design, fabrication, brazing, leak checking, magnet assembly, and the resulting magnetic field characteristics.

Four-Foot Power Model

A second water cooling system is being installed on the 4-ft power model. Two independent cooling circuits will now be available: one for the tank walls and one for the drift tubes, drift tube plates, tuning slug, etc. This system will more closely approximate the system planned for the 201-MHz sections of the final installation, making control system studies more applicable.

The drive mechanism of the tuning slug has been modified to include two motors coupled to-

gether to provide dual drive speeds. A linear potentiometer has been installed for position indication. An automatic cycling circuit has been incorporated so that life cycle tests can be made, and these will be started as soon as the cycle counter can be installed.

A post coupler has been designed to investigate breakdown problems at high rf power and will be installed in an existing monitor loop port. Fabrication of this item is scheduled for completion Nov. 1, 1967.

A second generation anode loop has been designed and is being fabricated. This new power loop is larger in diameter than the former and has vacuum O-ring grooves in the ceramic insulator rather than in the conductor. It is anticipated that these two changes will reduce arcing.

Drift Tube Linac Tank Engineering

A method for joining tank sections¹ has been evaluated. The welding was performed at LASL. It was concluded that very little difficulty should arise in making the weld joints inside the tank as proposed. The continuous copper welds were made by a craftsman positioned inside the tank. Final assembly welding of the tank sections can thus be made without rotating the tanks.

Design has therefore begun on the adjustable support mounts on the assumption that the tanks will not be rotated in assembly.

Copper-Clad Steel for Drift Tube Linac

Quotations for the copper-clad steel plates required for tank fabrication have been received and are being evaluated. This material will consist of 13 plates weighing $\sim 70,000$ lb total and will be $\sim \frac{5}{8}$ -in. steel backing plate with $\frac{1}{8}$ -in. OFHC copper cladding.

Computer Studies

Long Side-Coupled Cavity Chain with Multiple Drives

The various cavity chains associated with a rf drive cluster of the side-coupled linac can conceivably be coupled together to make a single cluster tank with multiple drives. Such a cavity

chain maintains at least partial accelerating fields throughout when one drive fails. In the latter case, the accelerating gradient along the cluster tank is no longer constant. It has been found that a large increase in power supplied to the remaining drives is necessary in order to maintain satisfactory beam dynamics under these conditions.

Recent studies indicate a modification of the above scheme would require a smaller power increase to the remaining drives when one drive failed. The modified scheme uses field tilt adjusters in the bridge coupling cavities to reduce greatly the variation in gradient along the cluster tank. (Flattening the cluster tank gradient in this way ameliorates the beam dynamics limitation and hence requires less power.) Experiments indicate the field in a bridge coupler unit may be tilted with a rotatable resonant post having an asymmetric tab or slot at the end.

Circuit analog and particle dynamics codes were used to calculate the performance of a cluster tank with 4.3% nearest neighbor coupling and with seven drives, one of which had failed. Under the modified scheme, the remaining drives needed to be increased by about 32% of the power normally supplied for tank losses. This is about half the additional power capability required by the unmodified scheme.

Additional equipment and changes to the side-coupled linac as presently envisioned that would be necessary to implement the modified coupled cluster scheme would include the following: (1) Special bridge couplers with expansion joints and vacuum isolation windows. (2) Remotely controlled bridge cavity field tilt adjusters. (3) Remotely controlled waveguide impedance match adjusters. (4) RF gates to prevent energy from leaking back into cluster building when faulty drive unit is disconnected. (5) Control system modifications. (6) Interlock system modifications. Careful study is being made of less expensive alternatives.

Bridge Coupler

The study has been continued of the effect of a TM_{011} resonance not far removed from the

desired TM_{010} resonance in a bridge cavity. Analysis and computer studies of the circuit analog for a full length tank, which included three bridge cavities, indicated that the presence of a nearby TM_{011} resonance can introduce an unwanted power dependent phase shift. This shift appears across bridge coupler units not containing the input drive port, and can be about 10° in the longest side-coupled linac tanks. Measurements made using Model K and its bridge coupler showed that the predicted phase shift did actually exist.

Experimentally and analytically it was found that the unwanted phase shift could be eliminated by means of a resonant post in the bridge cavity. The effect of the post is to introduce an additional mode into the mode spectrum of the bridge cavity. By tuning the post to resonance, the effects of the unwanted modes are made to cancel.

Theory of Sensitivity to Tuning Errors

Several extensions have been made to the tuning error analysis for the uniform multiply-coupled chain of resonators. Biperiodic multiply-coupled chains have now been included. The effect of a stopband has been determined. The theory for both full-cell and half-cell terminations to the chain has now been worked out. These extensions shed some light on the theoretical limit on field stability that may be achieved in the resonantly-coupled drift tube linac and the side-coupled linac with direct coupling.

When the stopband in the dispersion characteristic for a biperiodic structure is closed, the sensitivity of the fields in the accelerating cells to tuning errors is proportional to a ratio of even-order coupling terms (coupling between 2nd, 4th, etc., nearest neighbors) for the coupling cells to odd-order coupling terms (coupling between 1st, 3rd, etc., nearest neighbors). The sensitivity is proportional to the size of the stopband for moderate sizes of stopband. The results obtained for the chain terminated in full cells are very similar to those obtained for the chain terminated in half cells. The method of analysis and the results are described more fully in two technical memoranda.^{2,3}

LALA Computer Studies

Single cell test cavities are now being fabricated with a beam hole diameter of 1.25 in. for $\beta = 0.35, 0.45, 0.55$, and of 1.5 in. for $\beta = 0.55, 0.65$. Shunt impedance optimization curves for single-cell cavities with a beam hole diameter of 1.5 in. for $\beta = 0.725, 0.8$, and 0.85 are 60% complete. Single-cell test cavities are also to be fabricated for these three values of β . The purpose of this program is not only to compare the values of resonant frequencies, shunt impedances, Q's, etc., with values predicted by the LALA code, but also to examine the transverse mode characteristics of the cells.

The design curves for accelerating cells with a 1.5-in. beam hole for values of $\beta = 0.45$ through $\beta = 0.85$ are 60% complete. Design curves for accelerating cells with a 1.25-in. beam hole for values of $\beta = 0.35$ through $\beta = 0.55$ are about 15% complete.

Drift Tube Linac Temperature Control

An analysis of the temperature control system for the drift tube linac has been initiated. The first objective is to model the thermal behavior of the 4-ft, 201-MHz test cavity on an analog computer. After this has been done, various methods of closed loop control can be simulated and evaluated.

Instrumentation and Related Equipment

Beam Position Monitors

The logic circuitry required for multiplexing and computer control of the beam position monitors has been designed and is being built in modular form. Filtering of all signal leads in and out of each module and the main chassis is provided to minimize problems resulting from operation in a noisy environment.

All of the analog circuits required for the beam position monitor have been developed. Work is in progress to improve the designs to meet the desired accuracy and sensitivity specifications. No difficulties are anticipated.

Use of an Ozalid machine for making negatives from full-sized tape art work has facilitated

the development of a printed circuit mixer which has tuned lines printed on the circuit board. The new design prevents ground loops by inductively coupling all inputs to and outputs from the mixer except for the sampling pulse.

The principal analog circuits under development are: (a) the tuned mixer, (b) the gated clamp, and (c) the fast store-and-hold. The first two circuits are fundamental to the beam position monitor design. The third is required to make the position information compatible with the present computer interface equipment. All three circuits are performing satisfactorily, although some improvement is expected for each.

Rotating Coil Magnet Measuring Device

An instrument will be used to determine the harmonic content of the fields for all quadrupole magnets by means of a rotating coil of wire. Interchangeable coils will allow use of this apparatus with both quadrupole doublets and drift tube quadrupole magnets. The design of the device is complete and some of the components are presently on hand. A technique has been developed for the winding of coils using 0.005-in. diam magnet wire. Preliminary indications are that coils wound by this technique are satisfactory.

Positioning Fixture for Hall Effect Probe

A Hall effect probe is being designed primarily for use with the quadrupole doublet magnets; however, it will be possible to modify the device for use with drift tube quadrupole magnets. Design parameters for this tool have been established and preliminary design work has been completed. Investigation of materials and special components is currently in progress.

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III. RF POWER SOURCES

Introduction

A second 1.25-MW Amplitron was received; its rf output is cleaner than that of the first tube, but it is still not satisfactory for use in the accelerator. The klystron modulator was rebuilt and some 250 h of running time at significant peak powers and duty factors have been achieved on the 1.25-MW klystron test stand without failure of major components.

Proposals for the production of klystrons and Amplitrons have been received from the respective vendors. On the basis of experimental work, cost review, and the content of these proposals, it has been decided to use klystrons for the LAMPF 805-MHz rf power sources.

A modulator suitable for further testing of the 3-MW, 201.25-MHz rf system is now operational. The second 7835 polyurethane plate blocker failed in a manner similar to the first failure; a Teflon blocker is being tested.

A start has been made on standardization of control philosophy, hardware, and circuits for the accelerator rf sources.

Specifications are being prepared for the main dc power supplies for the accelerator and the Equipment Test Laboratory (ETL) Building.

A hybrid (tube-varactor) multiplier chain has been developed which is a substantial improvement over the earlier tube or solid-state devices. Measurements of phase stability and signal-to-noise ratio for the hybrid chain give quite satisfactory results.

RF Control Studies

Overall System Design

The central computer-operated control system planned for turning the Amplitron test stand on and off has been operated under program control. Checkout of the analog-to-digital signals through the Module Interface Unit (MIU) remains to be done, at which time sustained operation and computer-controlled experiments are contemplated.

The klystron test stand is being wired for computer control. This system will use extra channels in the existing computer interface equipment located in the Amplitron test stand.

Policies for standardization of control philosophy, hardware, and circuits were established in several areas. As a basic ground rule, each rf module will be capable of complete turn-on, operation, and turn-off at the local level, independent of the central system. This approach is believed necessary for maintenance reasons, and also to facilitate installation and initial turn-on.

The general situation with regard to system designs is as follows:

1. In order to insure maximum flexibility for future expansion of the role of the central computer, all local monitoring and control, both analog and digital, is to be compatible with the computer interface equipment.

2. Components, both large and small, will be designed on a modular, quick-disconnect basis as far as possible to minimize accelerator down time.

3. Local control will be centralized, with information designed to tell the operator what unit to replace on the basis of the most likely failures, with binary information preferred over analog.

4. Standards were issued on the following components: (a) relays (ac, dc, and dc-sensitive); (b) lamps (28-V and 6-V standard incandescent, 6-V subminiature); (c) contactors; and (d) chassis connectors.

5. Vendor information on the following typical items is being studied: (a) racks and associated hardware; (b) circuit breakers; (c) panel meters (including custom specials); (d) heavy-duty switches, etc.; and (e) terminal strips. (Decisions on the latter items should be completed within 2 months.)

Standard methods are being developed for preparing printed circuit card specifications.

A "universal monitoring circuit" is being designed with approximately the following specifications:

Input signals: ± 3 V dc, ± 3 V pulses
(minimum pulse width 5
 μ sec), 2.1 V rms at 60 cps.

Outputs: two separate relay contacts
rated at 2 A at 28 V dc, one lamp.

This circuit would be used in conjunction with a module status panel.

Frequency and Phase Reference Studies

Significant progress has been made in improved multiplier chains by the development of a hybrid version using tube drivers and varactor multipliers. As indicated in an earlier report, long chains of all solid-state multipliers become difficult to tune up and unpredictable in long periods of continuous operation because of the lack of interstage isolation. The transistor-varactor chain now under test for multiplication from a crystal frequency of 2.485 MHz to 805 MHz has 47 tuning adjustments in each chain, all of which are interdependent in varying degrees, making tuneup a tedious 3-4 h job. However, the high efficiency of varactors as multipliers makes them ideally suited to the present requirement and, where only one or two stages are involved, they are very stable, easy to tune, and quite tolerant of drive level and frequency changes.

Consequently, a hybrid version has been designed using two-stage varactor quadruplers and tube drivers. Two hybrid multipliers have been completed and tested for signal-to-noise ratios and phase stability with very good results. Representative charts of amplitude modulation due to noise are given in Fig. 4. The equipment is shown in a block diagram on the figures, as are power and voltage levels. The charts indicate signal-to-noise ratios better than 120 dB.

Phase stability is shown in Figs. 5 and 6, in which the all-tube multipliers and the hybrid multipliers are compared. The conditions for Fig. 5 were $\xi = 0.036$ V/deg for the tube multiplier and 0.039 V/deg for the hybrid. The HP310A wave analyzer bandwidth $\Delta f_{a\frac{1}{2}} = 108$ Hz. Background from measurement system with phase-bridge inputs shorted or autocorrelating input from one multiplier was less than 10μ V or 2×10^{-5} deg $\sqrt{\text{cps}}$. Sweep speed was 50 kilocycles/min. Diodes were HP423A with matched load resistor.

The conditions for Fig. 6 were the same as above, except that a HP302A wave analyzer with $\Delta f_{a\frac{1}{2}} = 3.5$ Hz was used and the sweep speed was 1000 cycles/min. Note also the expanded horizontal scale.

It is evident that the hybrid is substantially better below ~ 400 kHz and almost as good at the higher frequencies. The overall picture is definitely in favor of the hybrid multipliers. In addition to a better signal, the hybrid is a simpler device in that it uses only six tubes and seven varactors whereas the tube version uses 21 tubes and 19 diodes.

As part of the program of life testing these multipliers, the original tube multipliers were operated continuously for 6000 h each and then retested for phase stability and noise. Improvements in both respects are indicated in Fig. 6 in which the chart for phase stability taken in Oct. 1967, after 6000 h of operation (center of figure), is compared with one made under identical conditions in Feb. 1967 (top), after about 400 h of operation. The reliability of the signal quality over a long time period is well established by the improvement with aging. In addition, a good record of component reliability has been established. The first tube failure occurred after 6100 h of operation representing well over 250,000 tube-hours. This tube failure was primarily due to an overloaded screen-dropping resistor which changed value enough to cause screen dissipation to exceed specifications, eventually resulting in tube failure. A similar life test should be made on the hybrid multipliers before a final selection between the two types is made; hence, the two hybrids will be operated continuously for the next several months.

The 805-MHz drive line has been installed in the Mockup Building and the Electron Prototype Accelerator (EPA) Building. This is a $3\frac{1}{8}$ -in. rigid coaxial line running overhead from the large screen room in the Mockup Building through both buildings. This line will have couplers at strategic locations along its length to provide at least five 805-MHz outputs at ~ 7 W each.

The power amplifiers required between the frequency multipliers and the coaxial drive line are under construction and test. In order to get

Fig. 4. Hybrid multiplier amplitude modulation (upper curve: bandwidth 3000 cycles, sweep speed 50 kilocycles/min; lower curve: 3.5 cycles, 300 cycles/min).

Fig. 5. Phase fluctuation spectral density, $S_{\phi}(\omega)$, of hybrid and all-tube multiplier chains at 805-MHz output.

Fig. 6. Same as Fig. 5 but with different wave analyzer, bandwidth, and sweep speed (see text).

Fig. 7. 800-MHz low power amplifiers. Upper view: cathode end with air manifolds and outlet ports; lower view: anode cavity and air inlet ports.

Fig. 8. Amplifier integrator reset circuit.

couplers with acceptable directivity and VSWR, the coupling ratios must be kept above 14 dB. By taking into account this ratio, the power tapped off, and the power loss in the line itself, ~ 350 W is required at the input end of the mockup drive line. If three stages are used, this power gain can be realized with each stage operating conservatively. The first two stages have been completed. Tests indicate that a gain of 10 dB per stage is possible with optimum tuning and voltages, and that 8 or 9-dB gain can be maintained over long periods.

The amplifiers are shown in Fig. 7. The Machlett 8536 planar triode is used in a grounded grid configuration in both stages. The anode circuit is a coaxial cavity and the cathode drive circuit is a double-tuned matching network so that both the cathode and input line can be matched accurately. Cooling is somewhat unusual in that the cavity end plate and ground plane are drilled so that cooling air can be forced into the grid and cathode-mounting rings. Preliminary signal-to-noise measurements indicate no degradation of signal as a result of amplification; in fact, there seems to be some improvement as a result of filtering action by the high Q of the anode cavity. The third stage, which will use an 8226 coaxial tetrode, is almost complete. Phase coherence will be measured after all three stages are in operation.

RF Phase and Amplitude Control Studies

The phase and amplitude control devices for EPA have been built and partially bench-tested. These devices include motorized slow phase shift-

ers, which initially will be locally controlled; but, by simple modification, they can be converted to central computer control. The fast phase and amplitude control circuits are similar in design to those previously proven on both the Amplitron and klystron test stands.

The integrator circuits in the fast phase and amplitude control loops must be gated off between pulses to prevent runaway during the open-loop period between pulses. A new circuit using 2N3382 field effect transistors (FET's) was developed which seems to perform the function adequately. A circuit diagram of the integrator and gate is shown in Fig. 8.

The operation of the circuit is as follows: During the accelerator pulse the 10-V logic pulse is on, turning the parallel FET off (open circuit) and the series FET on ($\sim$ short circuit). This allows the circuit to operate as though the FET's were not present. Between pulses the parallel FET is on, effectively placing a low resistance across the integrator which discharges the integration capacitor and prevents the integration circuit from running away. Similarly, the series FET is turned off, effectively opening the input to the next stage so the discharging capacitor voltage does not appear at the controller output.

Feasibility studies are being performed on the application of nonlinear control circuitry to fast phase and amplitude control. A simplified model of the control loop has been programmed on the PACE analog computer at LASL. Experiments performed with this model are encouraging, showing significant improvements in correction times. Improvements of the model will be made using LASL's Hybrid Computer System, which allows the easy introduction of time delay and other refinements of the model. A physical model is being developed with the aid of the klystron test stand.

Logic and Protective Circuitry

A video pulse amplifier with one "saturated" output and one linearly controlled output was designed and constructed for use on modulator rf-interface units. This unit has been in operation for several weeks.

Fault-protection logic has been designed and constructed for use on the EPA 100-kW klystron amplifier. This logic is similar to other units except for the arc detector. Arcs will be detected as "loss of rf output" in the $3\frac{1}{8}$ -in. coaxial line. This has the advantage of requiring no sensitive solid-state light detector at the output rf window. False arc-detector triggering due to electrical noise should thus be eliminated. The circuit has the disadvantage of requiring rather complex logic.

The 1.25-MW klystron logic has been modified as follows: (1) Pulse position and width control on the high-voltage modulator and PIN diode modulator are now independent within the constraints of the logic, with no extra generators required. (2) A PIN diode modulator with amplitude adjustment is now internal to the logic. (3) A saturated amplifier was added to insure that operator error could not result in the destruction of the solid-state, high-voltage modulator driver. (4) A pulse-width trigger circuit was added to the klystron crowbar trip unit.

805-MHz Power Amplifiers

System Choice

The choice of the proper rf system for the waveguide portion of the accelerator has been a major problem since the beginning of this project. In all, three different systems have been studied--triodes, crossed-field amplifiers, and klystrons. In each case, the study has been carried to the point of operating a 1.25-MW peak (full-design specification) power tube into a resonant load. A study of this degree of completeness inevitably involves solution of essentially all the engineering problems associated with a particular system. Thus, a substantial understanding has been achieved of the difficulties of both the system and the tube for any of the three choices.

The triode system study was terminated in the summer of 1967. Experimental work has continued on both crossed-field amplifiers and klystrons; in addition firm proposals have been received from Litton(klystrons) and Raytheon (crossed-field amplifiers) covering the remaining

tube engineering and development work and the initial cost of tubes for the machine.

The conclusion reached is that the design choice at this time is the klystron. In summary, the major considerations are: (1) Considerably more development work is needed on crossed-field amplifiers before they will perform as well as klystrons. (2) The crossed-field amplifier system is more complicated than is the klystron system. (3) Equipment costs are essentially the same for either approach. (4) Tube costs are high in either case--so high, in fact, that the dominant operating cost is in tube replacement. Thus, the higher efficiency of the crossed-field amplifiers (which reduces power cost) is not a major consideration in any discussion of operating costs. The actual tube life is, of course, unknown at this time. Apparently Raytheon and Litton believe it will be about the same for either crossed-field amplifiers or klystrons. A report is being prepared which will discuss the system choice in detail.

A modest amount of flexibility will be maintained in the total system so that if some change in rf systems is indicated in the future due to advances in the state-of-the-art it can be made without undue expense. Some effort will be continued on the crossed-field amplifier studies for the next few months to permit an orderly completion of the experiments now in progress.

Amplitron Program

Test Results - 1.25-MW QKS1493 S/N 1:

Operation of Amplitron No. 1 into the resonant cavity was so marginal, in terms of spurious outputs, that operation was switched back to the resistive load for preliminary control experiments. The magnetic field was adjusted to permit operation at a lower voltage, ~ 42 kV, where the back-wall mode excitation was not excessive.

Under these conditions, linear-control loops using only integral compensation were for the first time closed on phase and amplitude simultaneously. Phase was controlled by the varactor phase shifter; amplitude by the hard-tube modulator with current sensing. Both loops were fairly slow,

with ~ 30-50 kHz correction bandwidth, limited by the compensation and rise-time of the modulator in the amplitude loop. Disturbances could be introduced into both loops separately or simultaneously without adverse effect.

Some operation was achieved with the driver klystron and the 1.25-MW Amplitron in parallel. The results were obscured by the spurious oscillations, but the gross behavior was similar to that with separate modulators and power supplies. It was possible to obtain 100 kW at the input of the Amplitron by applying 37 kV to the klystron driver. Approximately 450 h of operation have been accumulated with no sign of tube degradation.

Test Results - 1.25-MW QKS1493 S/N2:

The second 1.25-MW Amplitron was received and installed. Initial tests into a resistive load showed no oscillations at frequencies higher than 805 MHz, with a smear of noise ~ 50 dB down around 750 MHz. A Rieke diagram was constructed to determine the tube's characteristics with load VSWR's to 1.5:1 at all phases. There was no evidence of oscillations at frequencies higher than 805 MHz. However, strong oscillations over a 20-30 MHz band near 750 MHz were evidenced in several areas.

The overall operation into the cavity load was characterized by a very limited dynamic range where operation was essentially all at 805 MHz and reasonably satisfactory. Outside this range, the 750-MHz oscillation appeared with attendant noisy waveforms.

Adjustment of magnetic shunting bars on the outside of the stages did affect dynamic range, power out, spectrum, etc. One combination was found which produced a dynamic range of ~ 2.4 dB. Subsequently, a sensitive magnetic probe was used to map the field produced by the electromagnets at the 500-G level. It was found that the field was shifted considerably toward the solenoids and had asymmetries which showed a 10% tilt of the field in the central region of the interaction space. Field-shaping pieces of steel were mounted in positions which optimized the uniformity of the electromagnetic system; however, operation was not improved.

To provide a uniform field as the starting point for further investigation, a new magnetic system was designed. This involves use of the more symmetrical Raytheon pole pieces for the tube body itself, swinging both solenoids into diametrically opposite positions, and lowering the solenoids somewhat to give symmetry in the vertical plane. A field map of a model indicated improved symmetry of the field and considerably less tilt in the central interaction-space region. No tests have yet been performed on the tube since the new magnets were installed.

In summary, the change in geometry incorporated in the second tube to move the back-wall modes higher in frequency, hence out of the excitation range, appears to have been successful. The 750-MHz region oscillation is believed to be π -mode oscillation caused primarily by matching problems. Unfortunately, this oscillation results in very limited dynamic range and generally uncontrollable performance in a system with tolerances as tight as those of LAMPF.

Crossed-Field Amplifier Research

To obtain more reliable data on the resonant characteristics of the experimental anode structures, an accurate cold-probe model was constructed of aluminum. The simplest and easiest to construct anode--a periodic hole and slot array--was tested in two forms. One anode used eight resonators equally spaced around the structure and the other was unsymmetrical in that one resonator was omitted. The dispersion characteristics of both anodes were carefully measured using very small probes (electric and magnetic) protruding from the cathode (which could be rotated) into the interaction space. Several instruments were used to find the resonant modes--power meter, sampling oscilloscope, tuned detector-voltmeter--and each gave about the same results. The small size of the probes and the agreement between the electric and magnetic probes gave confidence that the fields measured were reasonably undisturbed by the presence of the probes.

Fig. 9. Electric field intensity at cathode of symmetrical cross-field amplifier.

The $\pi/4$ -, $\pi/2$ -, $3\pi/4$ -, and π -modes were isolated for the eight resonator system and in addition the double degeneracy of the $\pi/4$ -, $\pi/2$ -, and $3\pi/4$ -modes was detected. These degeneracies exist in the form of two resonances in which the fields have the same cell-to-cell phase-shift characteristics, but with the nodes and antinodes of the two sets of fields interchanged. The two fields are linearly independent solutions of the field equations at their resonant frequency. If the anode is precisely machined, these modes occur at the same frequency. As a result of dimensional errors, there is a frequency separation between them. This is shown in Fig. 9 for the eight-resonator $\pi/2$ -mode where it is seen that the node and antinode points are roughly interchanged and a frequency split exists. The same region of the dispersion curve is given in Fig. 10 for the seven-resonator system. In the sense that this system does not have cell-to-cell periodicity as defined by Floquet's Theorem, it is not possible to speak of Fig. 10 as a map of $\pi/2$ -modes, although there is a 2-cycle closure around the anode.

Fig. 10. Electric field intensity at cathode of unsymmetrical cross-field amplifier.

It is seen, however, that the 795.8-MHz resonance has a uniform field distribution and furthermore that a wide frequency separation (23.7 MHz) exists between it and the nearest "degenerate" mode. This frequency separation is probably due to the omission of the eighth resonator as well as to machining tolerances in the anode. Of all the modes measured in the seven-resonator anode, the 795.8-MHz mode has the most uniform shape. Because of this and because of the good frequency separation with the next nearest resonance, it has been decided to machine an anode out of copper for use in an experimental tube body and tentatively to operate in the 795.8-MHz mode. Because the frequency is very close to 805 MHz, no changes will be made in the existing design dimensions, but the copper anode will be machined to closer tolerances. The cold-probe cavity is now being re-worked to include slots and fittings for the attachment of WR-975 waveguide input and output sections. This will allow the determination of the degree of mismatch to be expected through measurements of VSWR at low powers.

Fig. 11. Simplified schematic of original modulator circuit.

The first stage of machining has been done on the vacuum vessel for the experimental crossed-field amplifier. Completion of the vessel is dependent upon successful brazing of four stainless steel inserts.

Fabrication of the vacuum manifold and ceramic-to-metal high-voltage terminal is complete. The old Amplitron stand is presently being modified to hold the vacuum pump and amplifier.

1.25-MW Klystron Program

Test Results: The klystron has been run in excess of 250 h on various experiments. Power has been provided to two separate resonant loads and performance was satisfactory in both cases. Both loads were run with the connecting waveguide length adjusted so that the detuned short position of the load coincided with that of the klystron. This places a voltage minimum at the klystron output gap and window positions during the load fill-time.

Measurements of tube efficiency were refined; this particular tube was found to have a conversion efficiency of 35%.

The modulator circuit and construction have undergone several evolutionary changes with the result that no further modulator tubes have been lost; there were only two circuit failures during the 250 h of operation.

Fig. 12. Simplified schematic of present modulator circuit.

In the preceding report, several failures were noted of the ML7248 switch tubes used to control the klystron modulating anode voltage. The original circuit is shown in simplified form in Fig. 11. Operation is as follows: When the klystron mod-anode is at cathode potential, no current flows. When the mod-anode is at body potential, full beam current flows. Between pulses tube VT-1 was conducting (at zero bias) and VT-2 was nonconducting. During the pulse a positive voltage at the dotted ends of the pulse transformer turned VT-2 on and VT-1 off. C_1 and C_2 represent the total tube and circuit capacitances between mod-anode and cathode and mod-anode and body respectively. During the pulse rise-time C_1 must be charged and the plate current of VT-1 is $i = C_1 dV_1/dt$. There is a small mod-anode interception current that must be carried by VT-1 during the pulse flat top. Similarly, during the pulse decay time, tube VT-1 must supply current to charge capacitor C_2 . Circuit failures were of several kinds; e.g., internal or external arcs from mod-anode to cathode or mod-anode to body or from cathode to body and in various portions of the modulator circuit. Several times VT-2 and R_1 were lost simultaneously, inferring cathode to mod-anode arcing. Also, R_1 (which was supposed to limit any harmful current flowing to the mod-anode) limited

the current through the protective fuse F_1 so that it did not clear the fault in time to prevent severe damage. During these arcs, energy was transformer-coupled back to the low-power stages of the transistor pulse driver, causing more damage.

The modulator was changed to the circuit shown in Fig. 12. Some power is consumed in R_2 but the simplification of circuit outweighs the decrease in efficiency. Furthermore, a crowbar circuit was added to protect against catastrophic circuit failure until the performance reliability of the circuit is ascertained.

There is an optimum value of R_2 for the circuit in Fig. 12. The pulse decay time is proportional to $R_2 C_1$ and so from this point of view R_2 should be small; however, during the pulse the power lost in R_2 is V^2/R_2 and thus a large value is indicated. The conversion efficiency is given by

$$\eta = \frac{P_o}{K + P_{in} \left(1 + \frac{a R_2 C_1}{\tau_{rf}} \right) + \frac{V^2}{R_2}}$$

where P_o = rf power output, P_{in} = beam power input, a = a constant that relates $R_2 C_1$ to decay time, τ_{rf} = rf pulse length, and V^2/R_2 = power dissipated in R_2 . Upon differentiating, it is found that η is a maximum at

$$R_2 = \sqrt{\frac{V^2 \tau_{rf}}{P_{in} a C}}$$

Consequently, R_2 is 46 k Ω for $\tau_{rf} = 500 \mu\text{sec}$ and $R_2 = 65 \text{ k}\Omega$ for $\tau_{rf} = 1000 \mu\text{sec}$. Efficiency is weakly dependent on R_2 . Presently 125 k Ω is used to limit modulator tube current.

The circuit changes shown gave much more room in the pulse transformer core window, permitting a reduction of the electric gradient in the pulse transformer to 50 V/mil.

The crowbar can be fired from sensing circuits on total current i_1 , mod-anode current i_2 , or modulator anode current i_3 . In the more than 250 h since these changes were made, the crowbar has fired twice, and both times excessive i_1 was the cause.

Litton has fabricated and partially tested a second model L-5120 tube. This tube was run for a short time (75 min) at 12% DF (150 kW average output) when the window failed and the tube went down to air. Examination of the window (AL-300) revealed an improper welding procedure. Some difficulty was experienced with discontinuities in the rf output of this tube of the same type as reported on the first tube. There seemed to be some indication that they could be corrected by proper adjustment of the magnetic field and the resonant frequency of the klystron cavities, but these measurements were not completed.

201,25-MHz Amplifier Program

During the past three months a new set of operation parameters has been determined for the totem-pole Intermediate Power Amplifier (IPA). These include the rf power output characteristics as a function of plate and screen voltages into a flat load, as well as a Rieke diagram for load VSWR up to 1.5:1. Tests were also run to determine the relative phase shift between input and output as the screen modulator was used to control input power. Through a 2 to 1 range of plate current, this phase shift was found to be $\sim 3^\circ$.

A 7835 tube was lost due to failure of the water-flow monitoring and interlocking systems. This system has been reworked using redundant flow meters and interlocks with dissimilar failure modes. The 7835 tube has been sent to RCA for inspection.

In the process of replacing the 7835 tube, many badly burned parts were found in the tube cavity and the output cavity body was found to be badly out of round. This piece was reworked at LASL, the burned parts with which it mated were cleaned up, and the finger stock replaced. The output cavity body was out of round due to a basic fault in the manufacturing process. A new design and manufacturing procedure have been formulated and a new part is presently being made.

After reassembling the 7835 cavity, operation was attempted utilizing a single 7482 modulator. The system was run for several hours at 3%

DF and 3 MW output; however, erratic modulator operation developed when the DF was increased to 6%. After 45 min at 6% DF and 3 MW output the upper blocker failed just as the previous polyurethane blocker had failed. The new Teflon blocker was inserted and the system reactivated. Through either erratic modulator operation or problems with the new blocker, it was impossible to operate at high power for any sustained length of time. Modulator gas bursts were noticed above the 26-kV supply voltage, as well as pulse instability.

A modulator was constructed using a pair of 7482 tubes. The 7835 system with the new modulator was run for several hours at 6% DF and 3 MW output. No apparent difficulties were encountered with the new Teflon blocker during high average power operation.

Final design of a 14-in. 200-MHz transmission line is complete, including 45° and 90° mitered elbows, and experimental sections of this transmission line are scheduled for shop fabrication. Evaluation of this line will be conducted using the existing 200-MHz power amplifier.

An Ohm-Weve type resistor bank has been purchased and installed, with minor terminal modifications, to replace the nichrome ribbon unit on the 7835 crowbar. This unit has been tested except for high DF operation and seems to perform satisfactorily.

The 7835 crowbar is undergoing a final evaluation prior to prototype design. All high-current connections and mechanical layouts have been redesigned. The solid-state trigger circuit is being simplified. The Krytron circuit has been modified (higher trigger input and lower keep-alive current) to increase usable lifetime. A 300-V supply and two relays have been completely eliminated.

The design for the 200-MHz water cabinet has been completed.

Floating Deck Modulator Development

Two 4CW100,000D modulators have been built and operated on the Amplitron load. Both units have performed well enough so that the next

model could be designed as a production prototype. The 4CW100,000D modulator, without modification, will be used in the 201-MHz system to modulate the anodes of the 4616 tetrodes.

Two versions of the 7835 modulator have been tested. The first used a 4CW100,000D modulator driving a single 7482 PV. The modulator operated reasonably well, but a single 7482 PV appeared to have insufficient grid and anode dissipation for this application. A second version has been built using two 7482 PV's. This unit is apparently satisfactory.

At the present time the primary modulator effort is being directed toward developing a prototype 7835 modulator using two 4CW250,000V's. It is felt, on the basis of experience with the 4CW100,000D and tests at Eimac, that this tube is superior to the 7482 for the required application; its use will result in a simpler and more reliable modulator.

High-Voltage Power Supplies

The study of high-voltage power supplies for the rf system has continued. Supplies were designed and tentative specifications written for the 200-MHz power amplifier, the 800-MHz power amplifier, and the ETL Building. The specifications covered the fused disconnect switch/vacuum breaker, voltage regulator, transformer, and rectifier stack.

A series of meetings was arranged with prospective vendors to discuss the tentative specifications and solicit their comments. These comments will be of help in preparing final specifications.

Specifications should be ready for the solicitation of bids sometime in November 1967 for the power supplies for the ETL Building. These supplies will be rated at 90 kV at 6 A with a tap for 60 kV at 6 A. DC output will be continuous over a 75% range.

EPA 100-kW RF Power Supply

Construction of the klystron 100-kW rf power supply for the low-energy end of the EPA is completed. It is undergoing testing into a dummy load.

IV. ACCELERATOR CONTROL AND INSTRUMENTATION

Introduction

The major efforts this quarter have been toward gaining operational experience with the computer control system, and the design and fabrication of the control system for the Electron Prototype Accelerator (EPA). The problems of maintaining a computer on-line in the operation of an accelerator received considerable attention. With the Amplitron test stand being operational most of the period, experience was gained in the use of the programs as they have been designed. Statistics were accumulated as to the reliability of the system. Weak spots in both the software and hardware were found and corrected. New programs were added to the system to improve its operation and prepare for the operation of the EPA.

Noise studies were made both within the interface units and in the transmission system between the computer and the test stand. A number of changes were found to be desirable and are to be incorporated in future designs.

The configuration of the LAMPF computer control system was established and the general control philosophy to be used in the design of the injector control and central control areas was also determined. These decisions will markedly influence the final design of the control system.

The design, fabrication, and installation of the control units for the EPA progressed very well. Both system designs and local control chassis designs are essentially complete. The computer control interface equipment has been fabricated and is undergoing bench checkout. About three-fourths of the various local control chassis have been fabricated or modified for installation and are in various stages of checkout and installation. The system wiring is well along; the control rack to machine area wiring is complete. Interchassis wiring and device hookup has started. This wiring is being guided by schedules which are prepared by a wiring and termination computer program.

Although the major emphasis has been as described above, numerous other areas have re-

ceived attention. These include water temperature control, water flow monitoring, the fast protect system, design of the injector control system, and studies of the application of various closed-circuit TV systems to both accelerator monitoring and experimental data acquisition problems.

Data Acquisition and Control System

Control Computer

The emphasis during the past quarter has been on gaining a better understanding of the problem of maintaining a computer which is operating on-line to an accelerator. The central processor of the present computer passed 4000 h with only one failure and that occurred early in the post-acceptance shakedown period. The other critical unit in the system is the disk because its failure forces the system off-line. One failure of the disk occurred when a transistor developed a temperature dependence which necessitated its replacement. All other units in the system have their functions duplicated so that a failure normally does not force a shutdown. Among these units, it was necessary to replace one transistor in the display scope plus two pairs of transistors and a clutch in the line printer. The auxiliary teletype had to be sent in for repairs but a spare was available to replace it. The console teletype required the standard maintenance plus cleaning of one set of contacts. The paper tape unit did not fail. In summary, the availability record for the computer system was encouraging because only one of the failures cited would have forced the computer off-line.

The accumulated experience and statistics are beginning to crystallize into a maintenance formula involving spare-parts storage preventive maintenance, and the use of redundant units, which should maximize the availability of the control computer at a level far better than any other critical system on the accelerator. However, this goal has by no means been achieved yet, and continued attention will be given to the problem. A step in this direction was taken when all of the diagnostic programs which came with the computer, along with those developed at LASL, were consolidated on the disk and made readily available to the people servicing the computer.

Fig. 13. Resident system programs and program package for prototype computer control system.

Programming

The core of the programming system, as illustrated in Fig. 13, is a package called the Resident System Programs. This package is resident in the computer's core memory as long as the computer is on-line to the accelerator. The next layer around the core includes Data Scan and the seven operational programs which service the accelerator operator's console. These programs were put into operation during the preceding quarter and all have performed well since then.

The resident package was augmented with the first versions of programs to handle the Power Off, Watchdog Timer, and Memory Parity interrupts. In each case, these programs dump the contents of memory on the disk for later printing and then restart the system. It is expected that these programs will evolve in the course of time into more sophisticated handling programs. The Scope Driver was modified to permit longer operator notes and a pointer was added to identify the most recent note. The operational program to deal with Analog Demands was elaborated to handle nonlinear command channels by means of an iteration process which makes use of calibration tables stored on the disk for each channel. Also, the Line-by-Line display was rewritten to

permit the addition of a generalized value-scaling feature.

Progress was made in the second layer of programs. The Vary and Time History programs are now operational. The former permits the operator to make a study on-line of the relation of any analog command channel to any analog data channel, whereas the latter allows the operator to get an on-line plot of the change of any analog data channel with time. Both programs still have awkward features as well as a few subtle difficulties but these will be solved in due course.

A number of new display programs are now available. The Channel Index program allows the operator to find the operator channel number for any data or command channel associated with the Amplitron test stand. The channels for the two EPA modules are being organized for addition to the program. The beam position and intensity display program for EPA has been tested with simulated data. Three graphs are presented to the operator, one each for x-displacement, y-displacement, and intensity. The scaling of the intensity graph can be chosen with the light pen. The data-scanning program which goes along with this display has been defined and work has started on it.

A series of programs to turn on the Amplitron test stand automatically were completed and tested. Out of this effort has come a generalized program for sequencing equipment. It can readily be adapted to the klystron test stand and to EPA. But, more important, the work has pointed the way to a rudimentary language in which sequencing and operating procedures can be written. This language is being defined in more detail and work will begin soon to implement it for the computer.

Computer Interface Unit (CIU)

Two modifications to the CIU were designed, installed, and checked out. The first was a RICE (Remote Information and Control Equipment) Parity Error Buffer (RPEB). All transmissions from the CIU to each RICE are validated in the RICE by checking parity. When the RICE detects an error, it alerts the CIU over a private cable.

The CIU in turn sets the bit in the RPEB dedicated to that RICE and generates an interrupt to the computer. In response to this interrupt, the computer can interrogate the RPEB to determine which RICE detected the error so that the appropriate retransmission can be made.

The second modification allows data-take instructions (DTK's) to be synchronized to the T_1 pulse which gates on the rf power amplifiers. Previously the computer received the T_1 pulse via a priority interrupt and initiated the DTK transmission. In the new scheme, the computer transmits the DTK to the CIU which forwards it to the selected RICE. Part of the DTK instruction is the delay between T_1 and the sample time. This delay is loaded in a counter in the CIU and the countdown is initiated by the T_1 pulse. On a count of zero, the data channel is sampled. With this new feature the computer can sample a data channel within 10 μ sec of a specified time.

Since going operational in May 1967, only one weak logic module has been replaced in the CIU (as the result of preventive maintenance) and no component failures have been experienced in about 2000 h of ON time.

Remote Information and Control Equipment (RICE)

The module data and control hardware has been operational in the Amplitron test stand for the past quarter. As a sequel to the noise tests performed earlier in a screen room, the following data were acquired with the equipment operating in the test stand with the Amplitron tube off: 4×10^7 binary data samples taken with no errors; 2.2×10^6 analog data samples taken and checked to $\pm 0.3\%$ accuracy with no errors, and 2.4×10^4 binary commands executed and verified with only one recoverable error during transmission. Two other tests were performed under conditions more closely resembling actual accelerator operation. In the first, the Amplitron test stand was sequenced on by the computer with only one error--a data transmission error detected by parity checking logic--recoverable error--which occurred when the crowbar fired. In the second test, the Amplitron was operating in its stable range and 5×10^5 binary data

samples were taken with only four errors (which were recoverable). Three were detected during arcing of the tube and the fourth coincided with a crowbar fault. These results are taken as an indication of continued improvement in the noise tolerance in the data system. However, there still are some troublesome areas. These are mainly in connection with voltage spikes induced in ground loops when the crowbar fires and generated by unsuppressed relay coils when they open. The former are being attacked by improving the grounding system and the latter by bypassing the coils.

Hardware reliability appears quite encouraging. The RICE and RICE Input/Output (RICE I/O) contain approximately 1500 logic elements and they have been operated very nearly continuously this past quarter with only one logic element failure. Unfortunately, the cable drivers have not exhibited the same reliability as there have been several failures, all attributable to a design flaw which will be corrected in future systems. For the moment, spare driver boards are kept on hand to facilitate quick repair of the equipment.

Two additional RICE systems have been constructed for EPA and a thorough bench check of each is nearing completion. A fourth RICE unit fabricated with diode-transistor logic for greater noise immunity is in the design stage. This system will operate with the ion source test stand.

Remote Information and Control Equipment Input/Output (RICE I/O)

The RICE I/O chassis which are to be used in the EPA were wired and checked for proper functional operation with the RICE. The RICE I/O units employ printed circuit cards designed and fabricated for this application. These chassis serve a larger number of channels than does the one in the Amplitron test stand. Each chassis can accommodate 52 analog data signals, 110 bits of binary data, 50 bits of binary command, and 30 pulse channels. Channel assignments for EPA are approaching these numbers. Fifty printed circuit cards containing ~ 1700 logic elements (multiple elements/logic package) perform the function of assimilating the data and

executing the commands. About 2000 wire terminations were required for each chassis.

Module Interface Unit (MIU)

The MIU for EPA is nearing completion. It consists of seven chassis: two each for analog command, analog data, and binary data functions and one for binary commands. The binary command chassis and the 15 printed circuit cards (each of which handles five binary commands) have been fabricated and are in the final stage of checkout; this consists of simulating a computer command to every channel and verifying that the command was executed.

There are 220 binary data channels in the EPA in addition to 75 "latch-back" channels which indicate to the computer that a command was completed. Assembly of the printed circuit cards is nearly complete and the two chassis to house these cards are expected shortly from an outside fabricator.

The analog command printed circuit cards which provide the logic and drive functions for the digital motors were found to be susceptible to damage if the shaft of the digital motor is turned physically. This action causes the motor to become a generator, sending voltages in excess of 30 V, peak-to-peak, back through the logic elements. A protection scheme based on diodes has been developed and the cards and chassis are being modified accordingly. This work will be completed shortly.

Two types of analog circuit boards are required to implement the analog data function. The first type is for those high-level measurements referenced to the control system ground that need neither amplification nor ground isolation. The second is for those channels that need either amplification or ground isolation, or both. Both types of boards are being assembled in-house on a time available basis. The analog data chassis are due shortly.

Approximately 70% of the interchassis cables between the control chassis and the MIU have been built and checked. All of the interchassis cables between the MIU and RICE I/O have been

fabricated and checked, except for the analog cables which are scheduled for delivery soon.

Video Control Unit (VCU)

The console VCU was installed and checked out for proper operation with the CIU and module VCU. Several video signals from the Amplitron and klystron were fed into the video system and selected by the computer.

Head Control System

The computer-controlled head control logic for the EPA electron gun was fabricated and partially checked out. This unit will interact with the computer through the RICE-CIU system and the high-voltage head in EPA. Signal and power switching logic have been incorporated into this chassis to enable the head to operate with the manual control chassis or under computer control.

Injector System

Preliminary work, in the way of identifying the control and instrumentation functions, has been started on the ion source test stand. In addition, the design of the RICE and the RICE I/O units for the test stand has been started. The ion source test stand is to be implemented as Module No. 4 of the computer mockup facility. The operation of this test stand will provide further opportunity to check out the computer control equipment and philosophy.

RF Module Control

805-MHz Modules

Considerable effort was required to modify the Amplitron test stand control and interlock systems during the Amplitron modulator change-out. A new control chassis was designed and built for the new modulator screen circuit.

Wiring between the Amplitron test stand and the klystron test stand has been completed and is ready for checkout. This will allow both test stands to be operated either locally or with the computer.

Accelerator Module Control

201.25-MHz Modules

Discussions have been carried on concerning the water temperature control system for the 4-ft drift tube model. These discussions have led to a preliminary design for the controller that will incorporate, in addition to closing the temperature loop, provisions for controlling the cooling water flow based on the rf phase bridge error. This preliminary design is to function only during steady-state operation of the rf into the tank; it will try to control only very small and low-frequency variations of the phase bridge error. Experiments will be designed that will determine more exactly the dynamic response of the system. This information should allow a better controller to be designed.

EPA Modules

The design of the control system, both local and computer, for the EPA has been completed. The local control is completely independent of the computer and, with but one or two exceptions, independent of the MIU and the RICE. The computer is given control of the various systems through the MIU-RICE by switching "mode" selector switches from local to computer. Complete instrumentation is provided for both control modes independent of the other. A number of technical notes have been written describing in detail the operation of some of the systems in EPA¹ and more will be prepared in the near future to complete the description.

The bulk of the fabrication of the required control chassis and printed circuit cards has been done by Eagle-Picher Co., Socorro, N.M. Some additional chassis and printed circuit cards have been fabricated at LASL. The actual fabrication is about 60-75% complete. The chassis and printed circuit card checkout is proceeding. Complete checkout of each chassis is being performed prior to installation in the EPA equipment racks.

Installation of the completed control chassis in the EPA equipment racks has been started. It is planned that a systematic checkout of each system be done immediately following installation. It is hoped in this way to provide operating systems

at the earliest possible dates. Installation is being planned to provide complete local control of the accelerator so that required experiments can be started. Installation and checkout of computer control will follow almost immediately.

Auxiliary Operational Systems

Timing System (EPA)

The timing requirements for EPA were modified to provide greater flexibility. Previous requirements did not include the ability to shift the beam and rf gates with respect to the 60-Hz zero crossing over a full half-cycle. There had been no provision made to shift the turn off of the beam and rf pulses with respect to each other. The turn on of the beam pulse could be delayed but not the turn off.

The present requirements are: (1) The delay between the 60-Hz zero crossing and the rf gate (phasing control) must be variable from near zero to ~ a half cycle. (2) The beam gate may be turned on at the beginning, during, or following the rf gate. (3) The duration of the beam gate and rf gate must be independently controllable.

The computer-controlled master pulser was modified to fit these requirements. This unit, located in the control room, uses counters, set by the computer except for the phasing delay, to control the intervals.

A second "manual (local) master pulser" has been designed. This unit will be located in the control racks near the EPA. The intervals are set by one-shot multivibrators which are controlled by a set of potentiometers and switches on the front panel. A "remote-local" switch is used to transfer from computer control to manual control of the timing.

The interfacing to the Fast Protect system (see below) is included in the local master pulser. This permits rapid cutoff of the beam gate if required. The system and equipment design has been completed and fabrication has been started.

Fast Protect System

"Fast Protect" refers to a hardware system which can very rapidly inhibit injection of

Fig. 14. Functional diagram of Fast Protect system.

beam into the linac in the event of an abnormality which may cause beam spill. Fast Protect is a composite of the systems previously referred to as the Fast Shutdown and RF Permissive systems. RF Permissive requires that a check signal be present from each module before the beam is injected. Should a fault occur, the beam will be inhibited for the remainder of that beam time. In addition, a computer interrupt is generated which results in a scan of fault words generated at the module. In this manner, the source of the trouble can be quickly located. Figure 14 is a functional diagram illustrating the relationships between the Fast Protect system, fault words, generation of the computer fault interrupt, and inhibition of the beam.

Duplication of all active elements in the Fast Protect system is done to assure fail-safe operation. Capability of checking the duplicated systems individually with the computer is provided. In this manner, a defective element in the duplicated system can be detected.

Operational Support Systems

Rad-Safe

The surplus Victoreen area monitoring system (described last quarter) was diverted to the drift tube test stand to provide area monitoring in accordance with new safety procedures. A second surplus Victoreen area-monitoring system was reconditioned and installed in the Electron Prototype Laboratory (EPL) racks. An eight-channel recording system was planned and the panel for this system was designed and installed. The rad-safe cables have been installed.

A variety of sensors is under evaluation

for use at the target end of the accelerator. Semi-rads and plastic scintillators will be employed for measuring the radiation time dependence.

TV Systems

Two television cable systems were installed between the EPL control racks and the accelerator area, making it possible to monitor accelerator operation visually in any two areas simultaneously.

Potential applications of TV systems for a wide variety of purposes along the accelerator are continually being sought and evaluated. During the past quarter, the limitations imposed by the basic properties of TV systems and particularly the camera tubes have been studied.

For data acquisition of transitory phenomena, all available vidicon camera tubes have been found to retain an image for too long a time for events which recur within 10 to 15 scans of the image. For readout of spark-chamber data, as being attempted at the University of Chicago, the camera tube should recover within three scans. The image-orthicon camera tube can be read out in one scan and also has greater sensitivity, but is much more costly and is more sensitive to stray magnetic fields.

The Plumbicon, manufactured by Phillips and under development by RCA, was found to read out in two to three scans. The present product by Phillips has less resolution and is larger than the vidicon.

It was learned that a new camera tube, having the physical dimensions and electrical requirements of a standard vidicon, has been developed at Bell Laboratories for "picture-phone." This tube has a photo surface which is comprised of a single crystal of silicon. Present versions have 2% of the image left after one scan and it is reported that the tube can be made faster. RCA is developing a commercial version but has not progressed far enough to supply prototype tubes.

No TV system employing a beam deflection camera tube (such as any of the above) can provide spatial accuracy better than 1% (more likely 2%). For this reason, the development of a mosaic of

Fig. 15. Proposed console for the Central Control Room.

solid-state photo sensors to replace the camera tube is being followed closely.

Centralized Control

Injector Control

The control philosophy of the Injector Control Room (ICR) has been changed somewhat in that there will be no computer in this area.² The ICR will contain only manual controls for the injector modules. These include local controls for the Cockcroft-Walton machine and a digital simulator for communication with the head control RICE units. For on-line operation, the injector modules will be controlled from the Central Control Room (CCR) so that any of the three injectors can be placed under control of the accelerator operator through the Central Control Computer (CCC). If it proves desirable to have a console in the ICR serviced by the computer, this will be added at a future date. The manual console is being designed with this possibility in mind.

Central Control

The entire facility will be controlled via a single computer system in the CCR. The console is designed to be serviced by the computer as a standard peripheral unit and consequently additional consoles can be easily added to the system. In particular, a computer-serviced console will be provided in the Experimental Control Room (ECR). This console will be connected to the CCC as a peripheral unit through special parallel-to-serial

interface units. The principal advantage of a computer-serviced console in ECR is that it provides the capability for switching control of the accelerator to ECR when the experimental program begins.

Operator-Machine Interface

The conceptual design of the control console was essentially completed. The console can be housed in three low-profile racks (Fig. 15). The console is centered around a highly versatile display scope and a Master Control Panel (MCP). The display scope is capable of displaying vectors and alphanumeric characters of varying intensities and sizes. The MCP contains a standard alphanumeric keyboard, a matrix of program-select buttons, and special demand switches and warning lights. In addition to the display scope and MCP, the console contains a video scope, a slew panel, a system fault panel, a system status panel, and a general display panel. Special purpose control consoles (e.g., in ECR) may contain a few additional special panels.

Miscellaneous

Channel Engineering

In performing the channel engineering function for EPA, it was necessary to schedule all of the wiring, from terminal boxes to the MIU, through the MIU to the RICE I/O and RICE, and on to the computer. Part of channel engineering is to provide channel numbers vs channel title records for the computer section. The channel engineering function and the resulting computer tabulations provide the coordination necessary to complete the hardware portions of the control and instrumentation of the EPA.

Wiring and Termination

Application of the "prototype" Wiring and Termination Designation System to the EPL/EPA facilities has been a useful experience. Adjustments and revisions, made to meet the immediate application problems, have been held to a minimum so as not to delay application to the EPL/EPA wiring. Other more extensive revisions which will facilitate the work of programmers, of personnel who write the wiring description, and of those who do the actual installation work have

been held in reserve. These revisions have now been worked out in detail and are being adapted to the system. A summary report for the convenience of users is in preparation.

The revisions do not require any change in the form of the basic data. As a consequence, the Wire and Termination Schedule (Rack Book) is still a part of the output. The number of input forms and the total number of cards required will be appreciably reduced.

Assuming a plant having one million wires, an average of three wires per cable, and an average of ten cables per route, the following comparisons can be made:

<u>Feature</u>	<u>Present System</u>	<u>Revised System</u>
Cards required (heading cards neglected)		
Wire	1,000,000	500,000
Cable List	333,000	50,000
Route List	33,000	
Total	1,366,000	550,000
Number of input forms	5	2
Path identification	None	Unique
Path trace		
Computer time/trace	~ 5 min	<< 60 sec
Availability	Only when that part of system is complete	Any time
Listing of each terminal	Twice plus number of jumpers	Once plus number of jumpers

Safety Systems

The master interlock system for EPA has been designed and final drawings are being made. Because of the complexity of the target area, a separate ready panel is being built and will be mounted directly above the master interlock panel. Maximum flexibility has been designed into the panels so that almost any future changes can be made at the chassis terminals without removing the chassis. The criteria for the design of the interlock logic were developed under close collaboration with the accelerator and target design groups.

Water Flow Indication

An inexpensive and reliable electronic circuit has been developed to indicate water flow

through a pipe. This circuit uses the water flow to cool a heated thermistor placed in the flow channel. Should the flow stop, the thermistor temperature rises and a relay is opened providing the indication. A similar circuit is used to provide a high temperature indication for any device on which the thermistor is mounted. The two circuits are packaged on one printed circuit card. A complete description of the circuits and their operation has been prepared for prospective users.³ The details of the mechanical installation of the transducers in various types of systems are still under development.

References

1. "EPA Focus Magnet Control Chassis-Operation Notes," MP-1-2906; "Instrumentation of the EPA Vacuum System," MP-1-2907; "EPA Steering Magnet Control Chassis SM03-SM06-Operation Notes," MP-1-2908; "EPA Steering Magnet Control Chassis SM01-SM02-Operation Notes," MP-1-2914.
2. "Plans for the LAMPF Control Computer System," MP-1-908.
3. "Electronics for Water Monitoring," MP-1-1601; "Calibration and Testing Procedure for the Water Flow Switch," MP-1-2909; "Troubleshooting Procedure for the Water Flow Switch," MP-1-2910.

V. ACCELERATOR PHYSICS

Introduction

Numerical calculations on single-particle motion were continued as a basis for setting tolerances on certain errors that adversely affect the transverse admittance of the side-coupled linac. Probability distributions for the transverse admittance were calculated for specified tolerances on one or more of the types of errors considered.

Calculations were made on the effects of third-order quadrupole lens aberrations in the waveguide linac. It is shown that, if only one transverse coordinate is considered, there can be a growth in transverse emittance. When both transverse coordinates are considered, and an appropriate region of input phase space taken, neither growth nor distortion of the phase space results from third-order aberrations.

Preliminary design of the Faraday cage for the high-intensity ion source injector power supply has been done on the basis of using prefabricated panel sections of galvanized steel. Contact with vendors of shielded enclosures indicates that the LASL design, with some modifications, is basically acceptable and that fabrication of the Faraday cage is a straightforward procedure.

Detailed mechanical layout for the Cockcroft-Walton power supply has been received; these drawings reflect the modifications recommended by LASL. According to the present schedule, all design drawings will be complete by Jan. 1, 1968, and the unit will be ready for initial acceptance tests at the factory in the latter part of May 1968.

Three of the five accelerating electrodes for the partial column have been fabricated but need to be polished. The remaining two electrodes should be ready for polishing within a week or two. The anode for the column has been fabricated and polished and is ready for assembly.

The ion source laboratory test stand has been enlarged to permit work with the 200-keV column. Ion source life tests continue, with encouraging results. Design has been started of optics for matching between the column and the injector beam transport system.

A magnetic testing system using rotating coils is almost complete. Magnetic gradient measurements have been carried out on two air-cooled quadrupole magnets to be used on the electron prototype accelerator (EPA).

Particle Dynamics Studies

Waveguide Linac

Numerical calculations were performed using LINAC as a basis for setting tolerances on certain errors that adversely affect the transverse admittance of the side-coupled linac. The types of errors considered were: (a) doublet axis displacement from linac axis, (b) quad axis displacement from doublet axis, (c) tilt of doublet axis with respect to linac axis, (d) tilt of quad axis with respect to doublet axis, (e) rotation of doublet about its axis, (f) rotation of quad about its axis, (g) doublet field strength errors, and (h) quad field strength errors.

Probability distributions for the transverse admittance were calculated for specified tolerances on one or more of these types of errors. Two such probability distributions are shown in Figs. 16 and 17, where the probability distribution P is plotted versus the transverse admittance E . The probability that the admittance will lie in the range $a \leq E \leq b$ is given by $P(b) - P(a)$. The effect of beam steering, which somewhat compensates for errors of the first four types mentioned above, is not included in these results.

The transverse admittance depends on the size of the beam hole in the accelerating tanks. For these calculations, the diameter of the beam hole was assumed to be 1.25 in. in the $\frac{1}{4}$ -MW driven tanks (the first 32 tanks) and 1.5 in. in the $\frac{1}{2}$ -MW driven tanks. With no errors, the admittance area is about 4.4π cm-mrad.

Although the transverse admittance could be significantly reduced by errors having the tolerances specified in Fig. 17, there is still a high probability that the side-coupled linac will accept the full beam emitted from the drift-tube linac. At the entrance to the side-coupled linac, the beam is expected to have an emittance area of about 1π cm-mrad.

Fig. 16. Probability distribution vs transverse admittance for indicated conditions.

Fig. 17. Probability distribution vs transverse admittance for indicated conditions.

Fig. 18. $(W_x + W_y)/\beta\gamma$ for selected particles at 800 MeV.

Fig. 19. Growth of xx' phase space for square input beam.

Numerical and theoretical calculations on the effects of third-order quadrupole lens aberrations were carried out for the waveguide linac. Numerical calculations (program TRACK) used quadrupole fields to third-order (as determined by Maxwell's equations) and first-order-only linac transformations. The theoretical calculation is an extension of previous work¹ and predicts that the total transverse emittance $W_x + W_y = \text{constant}$, where

$$\frac{W_x}{\beta\gamma} = \frac{x^2 + \left(\beta_x x' + \alpha_x x\right)^2}{\beta_x}$$

β_x, α_x = first-order transformation parameters.

Figure 18 shows W_x and W_y for several particles as calculated from TRACK. The sum remains constant although the ratio W_x/W_y varies by about a factor of 40. Another prediction is for the rate of growth/shrinkage of W_x or W_y as shown in Fig. 19. In this particular case the input phase space is such that $W_x(0) = W_y(0)$ and that each particle in xx' phase space is associated with all particles in yy' phase space. The data points are measured areas of phase plots from TRACK. The conclusion is that for an input phase space given by $W_x + W_y = W_0 = \text{constant}$, neither growth nor distortion of the phase space results from third-order quad aberrations. Figure 19 shows that in this linac design some particles approach $W_x = 0.7 W_0$, $W_y = 0.2 W_0$ and vice versa.

Beam Transport Optics

An analysis to third order of rectangular bending magnets was added to the program STEFFEN. Magnet measurement data consist of field values on a mesh in the magnet midplane which are fitted to the functions

$$B \equiv B_y(x=y=0) = B_0 \frac{1 + \cosh 2D/F}{\cosh 4z/F + \cosh 2D/F}$$

$$\frac{d^2 B_y}{dx^2}(x=y=0) = b_2 B \left(e^{-((z-G)/\lambda)^2} + e^{-((z+G)/\lambda)^2} \right)$$

by a least-squares program. Good but not exact agreement with the program TRANSPORT is obtained through second order for the limiting case $F \rightarrow 0$ and $b_2 = 0$. For the magnet analyzed significant differences were caused by the $d^2 B_y/dx^2$ term through all orders.

Electron Prototype Accelerator (EPA)

A target collimator for beam scraping on the EPA has been ordered from Research Magnetic Systems, Inc. This unit will be a modification of their standard design and will withstand full impingement of the EPA beam. The design of the rotating wheel beam scanner is complete and fabrication is now under way. This design will permit both x and y beam profiles to be displayed simultaneously on an oscilloscope presentation.

Injector Program

Cockcroft-Walton (C-W) Power Supply

Preliminary design of the Faraday cage for the high-intensity ion source injector power supply has been done on the basis of using pre-fabricated panel sections of galvanized steel. Contact with vendors of shielded enclosures indicates that this design, with some modifications, is basically acceptable and that fabrication of the Faraday cage is a straightforward procedure. Normal installation time is estimated at 250 man-days and material delivery is estimated at 3-4 months. Another slightly different approach to the Faraday cage installation would be the use of stainless steel panels backed by laminated wood. This approach was used by U.S. Steel Corp. in building a Faraday cage for their 1-MeV electron microscope power supply. The cost and practicality of such a cage will be investigated at LASL.

Detailed mechanical layout for the fabrication of the C-W power supply has been received from Haefely & Co. These drawings reflect the modifications to their earlier drawings which were recommended by LASL. Haefely & Co. also have sent their manufacturing schedule, indicating all design drawings will be complete by Jan. 1968, and that the unit will be ready for initial acceptance tests at the factory the latter part of May 1968.

Accelerating Column

Three of the five accelerating electrodes for the partial column have been fabricated but need to be polished. The remaining two electrodes should be ready for polishing within a week or two. The anode for the column has been fabricated and polished and is ready for assembly.

A number of adhesive materials have been tested for use on the ceramic-titanium ring column. These tests were made on small tensile samples, and in a group of eight probable adhesives only four appear to have reasonable tensile strength. The results are listed below.

<u>Commercial Name</u>	<u>Generic Type</u>	<u>Tensile Strength (psi)</u>
1. Vinylseal MA-28-14	Vinyl alcohol- acetate	4861
2. Clear Lexan	Polycarbonate	4278
3. Loctite 404	Cyanoacrylate	5094
4. Hysol 1C	Epoxy	3361

Considerable experience with the vinyl alcohol-acetate has been accumulated in fabricating and repairing the lens filter from electron model studies. Its use appears quite satisfactory only as long as the joint is kept under compression. The creep strength of the adhesive is rather poor. On the other hand, the polycarbonate has a creep strength which is better by an order of magnitude. Loctite adhesive has also been used on the present ion source test stand with some degree of success. The high-voltage extraction electrode and Faraday cup were assembled using this adhesive, and the assembly has held together satisfactorily without the joints being placed in compression. To test the polycarbonate further, two large 15-in. radius, 1-in. thick ceramic rings have been joined with a titanium spacer between. The joint appears to be very satisfactory. Vacuum, strength, and alignment tests have not been made to date.

Double-Drift Buncher

Over the past year or so, a very detailed understanding has been achieved of the theoretical approach to the double-drift buncher; consequently, activity in this area has been temporarily curtailed in favor of more pressing work. The double-drift buncher can now be designed when all the beam-transport characteristics up to the buncher have been established.

Some double-drift problems for CERN and RHEL have been continued; however, work on these programs consists of supplying these organizations with computer codes for their own analysis.

Ion Source Test Stand

Since the end of the last report period, activity has been directed toward making improvements in the facilities. The major improvements in the laboratory layout and furnishings in anticipation of going to 200 kV are: (1) The ion source

laboratory has been increased in area by a factor of one and one-half. (2) A substantial metal protective fence with a metal gate and interlocks has been installed to isolate the high-voltage area. (3) The 250-kV power supply has been moved to an additional room specially constructed outside of the Mockup Building. This provides additional space inside the high-voltage area for the 200-kV transport studies.

A second pump stand for outgassing cathodes has been put into operation. It has a 500 liter/sec vacuum pump and the associated equipment. Activated charcoal is being tried on this system as a substitute for liquid nitrogen trapping. So far no bad effects are observed on the outgassed cathodes.

The first cathode used on the ion source test stand failed to reactivate after being kept hot for 2157 h at normal operating temperature. This failure may have developed after having been exposed to dry nitrogen. The cathode had been pulsed for 188 h (7.8 days) at 6% DF (500 μ sec pulses at 120 pulses/sec). The experience in this case indicates that cathode life is not going to be a major problem. The second cathode had a heater-on lifetime of 670 h, i.e., about a month, which is not an unreasonable life since weekly replacement is practical. The second cathode failed at the weld where the nickel gauze filament is attached to the $\frac{1}{16}$ -in. diam nickel post which holds it in place and is also the heater current lead.

The "noise" which is associated with the pulsed proton beam current from the ion source is of considerable interest. Photographs of oscilloscope traces of the ion current show this "noise" amplitude to be in the neighborhood of 5% rms of the dc level. Reports from other laboratories indicate similar "noise" levels for duoplasmatrons with large expansion cups. A trace obtained on the present test stand shows this "noise" level very clearly (Fig. 20). The top trace is the current on the extractor and the lower trace is the current passing through the extractor aperture and incident on the Faraday cup. With little dc component of current on the extractor, conditions are such that use can be made of a spectrum analyzer on the extractor to investigate the

Fig. 20. Traces for electrode (upper) and Faraday cup (lower) currents. (Vertical scale: 10 mA/cm; horizontal scale: 20 μ sec/cm.)

dominant frequency components in the current pulse. This approach will be pursued.

Preliminary attempts to measure the frequency spectral distribution were made using wave analyzers on arc current pulses. A continuous spectrum was obtained which decreased in amplitude from the lower measuring limit of the apparatus (about 1 MHz) to near zero amplitude at the upper measuring limit (about 10 MHz). The spectrum turned out to be independent of the "noise" level on the arc pulse, and no discrete spectral lines were found in the indicated range. The interpretation of this result is that the spectral distribution is dominated by the fast rise and fall times of the pulse current. There is consequently some concern that if "noise" is to interfere with the fast control of the higher energy portion of the accelerator, then so might the Fourier component of the desired fast rise and fall times ($\sim 1 \mu$ sec).

Expanded sweep oscilloscope traces of the "noise" show that it is composed of two sinusoidal components; the larger is $\sim 5\%$ rms amplitude at ~ 3 MHz, whereas the smaller is $\sim 2\%$ rms amplitude at ~ 14 MHz.

In a primary attempt to raise the ion source current to the required 50 mA, the expansion cup dimensions were changed. The depth of the cup was reduced from 2.5 to 0.8 cm. It was believed that the acceptance angle of the cup aperture would thus be increased, allowing a greater plasma density to appear at the plasma surface. Improvements were noted in the current

Fig. 21. Effect of plasma "cooling" on the extraction area.

magnitude up to 40 mA for what are believed to be good emittance parameters (not yet measured). The Child-Langmuir law indicated that 50 mA should be obtained with the configuration, which is shown in Fig. 21A. The reason for not obtaining the expected value is probably that the area of the plasma surface at the cup aperture is not as large as the cup aperture due to "cooling" of the plasma near the cup surfaces. The difference in radius to account for the smaller current is only about 1 mm.

Another expansion cup configuration, shown in Fig. 21B, is being fabricated to study the effect of the "cooling" of the plasma. The plasma surface does not extend to the full diameter of the cup opening unless the edge of the cup is undercut. The cup being made will have a 1-mm undercut but this can easily be deepened if necessary.

The anode aperture has been accidentally enlarged in steps with both the first and second anode fixtures. These enlargements probably occurred when the pulser transistors failed and put the source on 100% DF; a calculation of the

Fig. 22. Expansion cup detail, with expanded view of anode aperture.

heat flow around the anode aperture strengthens this belief. In an effort to achieve a fail-safe situation, an investigation was made of possible alloys with both desirable magnetic and thermal conductivity properties, but none was found. However, it was concluded that a laminate of copper, for good thermal conductivity, and soft iron, for good magnetic shielding of the cup interior, had distinct advantages. Such a septum, shown by the expanded insert of Fig. 22, is now in the source.

The vacuum in the system operates in the region of 4×10^{-6} torr, insuring a hydrogen life of the ion pumping elements of at least 4000 h.

Beam Transport

Various means of matching the beam output characteristics from the accelerating column to the desired beam transport characteristics have been investigated. This was made necessary for two basic reasons. First, the exit aperture of the accelerating column acts as a diverging electrostatic lens, with a focal length given approximately by

$$\frac{1}{f} = \frac{V'}{4V},$$

Fig. 23. Compensating lens for exit region of an accelerating column.

where V' is the potential gradient in the column just prior to the aperture and V is the potential at the last electrode. For example, the 200-keV partial column has a focal length of $f = -4(200 \text{ keV}) / (25 \text{ keV/cm}) = -32 \text{ cm}$. Thus the virtual image of the beam lies deep inside the column near the ion source; by taking space charge into account, the waist at the focal point is 0.4-cm radius. This is to be compared with a minimum waist of 0.7-cm radius designed for the transport system.

Second, the design minimum waist for the transport system is based on space charge, length of transport system, number of periodic focusing lenses, and a 90° nondispersive bending system. For example, if the minimum waist of the transport system were to be reduced to 0.4 cm, as would be required by an unmatched accelerating column, the number of focusing lenses would approximately double, increasing the complexity of the beam transport system. Thus, it is necessary to match the exit lens of the column to the transport system.

There are three ways which have been considered as possible practical matching configurations: (a) an electrostatic correction lens at the end of the column; (b) a magnetic triplet focusing lens system; and (c) a magnetic quadruplex focusing lens system. The desired system is one which will give the proper match with the least aberration, and must be easy to adjust to matching conditions.

The first system (Fig. 23), an electrostatic correcting lens, is similar to an Einzel lens. In the figure, the V 's represent the various electrodes

Fig. 24. Beam profiles for nonsymmetric triplet lens system.

as well as their potentials; $Z = 0$ for the end of the column and $Z = a$ for the extension electrode V_4 . Space charge has been neglected as the length of the lens is so short that the response to space charge is negligible during the beam passage through the lens. Lens V_2 is normally the exit aperture. By adding another aperture, V_4 , at the desired exit potential (200 kV for the partial column, 750 kV for the full column) and allowing the V_2 potential to be greater than the exit potential, the focal length of the column can be increased to infinity (or even made + if desired) by the proper voltage combinations and spacings. The condition for proper matching is

$$\frac{V_4 - V_2}{a} \approx \frac{10(V_1 - V_2)}{d_{12}}.$$

That is, the potential gradient between V_4 and V_2 must be at least an order of magnitude greater than that between V_2 and V_1 . Unfortunately the column cannot support a potential gradient of this magnitude in the vacuum system. Because of this limitation, calculations of the aberrations have not progressed.

The second and third systems would use the strong focusing lenses in the original beam transport system to effect the desired phase space matching from the end of the accelerating column

Fig. 25. Beam profiles for quadruplet lens system.

to the input of the first bending magnet. The beam profiles calculated for the two possible geometries of lenses are shown in Figs. 24 and 25. These calculations were carried out using a modified form of the LASL computer program BEAMCAL² in which either two gradients and two lens spacings or four gradients could be varied to obtain specified values of the size and divergence of the beam at the entrance to the first bending magnet. It was assumed that the beam starts at a circular waist from a virtual source chosen so that, after drifting a distance equivalent to the end of the accelerating column, the beam has the required size and divergence.

The nonsymmetric triplet has the advantage that only two currents need be varied in tuning the beam; but the quadruplet system has four variable currents. However, the required lens spacings in the triplet system are determined by the beam parameters and matching requirements whereas a considerable variation in the spacing of the lenses is possible in the quadruplet system for matching a given beam. A similar quadruplet lens system has been employed at Argonne³ to match the proton beam from the linac to the ZGS. For the two systems presented in Figs. 24 and 25, the nonsymmetric triplet adds 0.25π cm-mrad, and the

quadruplet system adds 0.29π cm-mrad total effective emittance to the beam.

The two quadrupole lens focusing systems have been designed for use with the 200-kV test stand. Tests will be made of the proposed methods for producing a parallel beam at the entrance to the first bending magnet from the diverging beam that emerges from the accelerating column. Tuning and general performance will also be evaluated before a decision is made between the lens systems.

Magnet Testing Program

The design of a rotating coil system for carrying out harmonic analysis of quadrupole magnets has been completed and fabrication of the components is almost complete. The design of a general purpose test stand for carrying out magnetic measurements on quadrupole magnets has been started. The test stand will incorporate variable x-y-z motion for the test equipment carriage and will have provision for adjusting the angular orientation of the quadrupole magnet. The test stand will be used for gradient and alignment measurements on quadrupole lenses.

Mechanical inspection and preliminary gradient measurements have been carried out on the two air-cooled quadrupole magnets to be used on the EPA. Both doublets meet magnetic gradient specifications and detailed magnetic field information has been obtained for the two doublets. In the mechanical inspection, deviations in the position of the center of the pole-to-pole spacing from the quadrupole doublet axis as large as 0.003-in. were observed, as were deviations of the angle of the quadrupole lens axes to the doublet axis up to 1 mrad. A more detailed comparison of the two doublets will be made using multipole harmonic analysis.

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VI. EXPERIMENTAL AREA

Introduction

The review of user requirements is being continued in an effort to maximize the flexibility of the experimental area and to develop the most efficient and economical arrangement for construction and operation of the facilities.

General Remarks

Among important decisions is the establishment of the floor elevation of the experimental area at 60-in. below the main beam line. The experimental floor will be of thin construction, sufficient to transmit the anticipated loading to the tuff subgrade, but easily modified for any increased depth that may be required. Because of possible radiation leaks through service tunnels under the floor and beam channel and to allow for the floor space flexibility, it is now proposed that personnel access and utility services be provided at and above the floor level. Utility services and signal cables for experiments will be carried in shallow trenches easily accessible from the main floor. Shielding and load bearing for specific experimental setups can be provided by movable blocks in the trenches. Personnel access can be by walkways along the building walls served by stairs and service lifts on each side of the main beam shielding.

The support building is now planned as a two-story structure. Building services are at the third-floor level exposed or enclosed as directed by economy and performance, rather than being housed in a basement as previously planned. Personnel and service connections to the experimental area are provided at all three levels. The support building has been rotated 90° from the beam line to avoid the more expensive construction that would be required to retain the earth shielding of the beam channel and to eliminate possible interference with the last rf cluster building of the accelerator.

The development of a remote-maintenance (Merrimac) vehicle concept has permitted several important changes in the experimental area

design. The change room, warm-cell, and hot-cell systems are no longer needed in their original design. A shielded service cell will still be required near the target cells to handle the cooling and ventilation systems from the target areas. A second cell which can be located in another building will provide the capability for the repair and transfer of radioactive components.

The remote-maintenance vehicle permits a reduction of the inside height of the target cells by the amount previously required to accommodate in-cell handling equipment. The reduction provides considerable savings in shielding requirements, particularly in the present modular concept of the target cells.

The original single-target cell has been divided into three separate cells with one target per cell. The division will permit two secondary beam channels to emerge from each target cell with about 40 ft of space along the shielding wall between each channel. The space is considered sufficient to allow for typical experimental arrangements and space equivalent to a trailer for electrical and electronic equipment. Exterior to the primary shielding, space is available for many secondary beam channels. The shielding for each target cell has been calculated on the basis of a 10-MeV energy loss in the first target, a 50-MeV target in the second cell, and a full beam-stop target in the last cell. Each target cell will be maintained by the one proposed maintenance vehicle.

Calculations are presently under way to determine the deformations at the floor of the experimental area caused by the weight of the massive shielding of the target cells, the moving of the shield doors above the target cells, and the moving of the remote-maintenance vehicle above the cells. Deformations resulting from the weight of the Merrimac vehicle, estimated at 200 tons, vary from 2×10^{-3} in. immediately adjacent to the vehicle at the face of the shielding to 1.3×10^{-5} in. at the far end of the experimental floor.¹ These estimates of deformation are based on a subgrade of virgin tuff; estimates will also be made for broken, compacted tuff.

Shielding

Results from the LASL Monte Carlo Cascade Code can be summarized so that the production of cascade neutrons from the stopping of a line source of 800-MeV protons in a copper cylinder of infinite length can be described approximately by an expression of the form

$$\varphi(E) = e^{-K_1(E) \csc \theta} [A(E) e^{-K_2(E)(1 - \cos \theta)} + B(E)]$$

where θ is the angle of neutron emission with respect to the proton beam axis, E refers to the emitted neutron energy, and $\varphi(E)$ is the neutron flux at a particular energy (or energy interval) obtained from the corresponding angular dependent production term $A(E)$ and isotropic production term $B(E)$; the exponential term in $K_1(E)$ allows for the infinite cylinder absorption and the $K_2(E)$ term demonstrates the production angular dependence without absorption.

Computer least-squares fits are being made of the production data to this equation in an attempt to determine an analytical but probably empirical form of the energy dependence of $K_n(E)$, $A(E)$, and $B(E)$. Eventually, the results will be incorporated as the source term into a DTF-IV treatment of high-energy neutron transport.

In order to check earlier shielding estimates, a request was made of HASL (AEC, New York) to evaluate the LAMPF beam channel shielding at 800 MeV according to the method described by O'Brien and McLaughlin.² The results from an idealized geometry calculation indicate a dose rate in the service aisle above the beam line of 0.08 to 0.09 mrem/h, depending on the assumed hydrogen content of the surrounding media and for a beam spill of 2 nA/m. The earlier LASL calculation gave a result of 0.2 mrem/h. Neither calculation allowed for neutron leakage from ducts and access shafts. The results are at least consistent with the hoped for average dose rate of one-tenth tolerance or 0.25 mrem/h for personnel working in the service aisle.

Considerable effort has been expended to design a satisfactory arrangement of ducts and

conduits for the drift tube portion of LAMPF. As formulated, the present designs will cause no important shielding leakage.

Targets

Much of the targeting hardware for the Electron Prototype Accelerator (EPA) is on hand and the remainder is scheduled to be ready by Nov. 15. Some additional effort will be required to adapt the target equipment for attachment to other components of the beam line at the time of final assembly. No assembly is being attempted at present to avoid interference with the waveguide tank installation.

Originally, it was hoped that neutron shielding could be placed directly around the targets and beam stops of EPA. However, it now appears that the congestion of equipment at the end of EPA will prohibit such an installation, and that neutron shielding external to the Iron House may be required.

Remote Handling

In the 1964 LAMPF proposal, a single target cell was provided which was to contain all equipment necessary for the production and transport of the required secondary particle beams. Since the original proposal, the diversity of secondary beam requirements has increased, and the facilities have been redesigned to increase experimental flexibility and to make more efficient use of the accelerator. Basically, the redesign provides for two primary proton beam lines within a building area equivalent to the original experimental area.

The original single target cell was serviced by a totally enclosed remote manipulator which had TV monitoring only of its operation. A completely different concept of remote handling has been proposed, since concern exists about the reliability of manipulation equipment, the need for rescue equipment for manipulator retrieval, and the time required for blind manipulations where all activity must be monitored by TV. The new concept is based on the use of a shielded room that can be transported by a gantry crane. Duplication of

remote equipment is avoided and reliability is increased. The room has shielded viewing windows in its roof and manipulation equipment is mounted within it. The room would be driven along the top of the shielding and positioned straddling a target cell. The cell roof shielding would be rolled open, forming a vertical shaft up from the cell. The shielded room is lowered into this shaft until its exterior roof is flush with the top of the cell shielding. Personnel working on the room top can view directly the equipment beneath them within the cell, shaft, and the room itself. The appearance of the large ironclad room prompted the epithet "Merrimac" for this concept.

The use of the Merrimac allows the relocation to less valuable floor space of the hot cells and the air and water treatment cells. The elimination of manipulators from within the target cell allows the cell ceiling to be lowered by the distance (~ 5 ft) formerly reserved for a traversing manipulator carrying a load. The 5-ft shielding saving is reflected in lower floor loading, lower building height, and reduced shielding materials.

An additional building will be required to provide an area for Merrimac maintenance, a hot cell for target, magnet, etc., handling and maintenance, and a mockup area for checking out target cell equipment. It is believed that light metal building construction with minimal services will suffice.

The Merrimac shielded room will have the same inside floor area as the target cell, 10 ft wide by 15 ft long. The inside height of 5 ft is the minimum compatible with the size of manipulation equipment. This height requires the tipping of the electromechanical manipulator to a horizontal position for traveling. The side walls are laminated from three 6-in. thick slabs of boilerplate for a thickness of 18 in. and a building outside dimension of 13 x 18 ft. The flat roof is 30 in. thick and is filled with steel shot. Six lead glass viewing windows are mounted through the roof, and there is no floor. The room weighs ~ 200 tons. Mounted inside the room are a 5-ton cable hoist and an electromechanical manipulator of 150-lb capacity. The shot-filled roof will

provide mounting for transfer drawers and ball-and-tong type manipulators. Shielding is sufficient to allow 25 h/wk/man operation with a 4-kCi source within the building or 200 kCi along the beam line.

Many options are available in the design of the Merrimac gantry. The design presently favored is an all-hydraulic, rubber-tire mounted vehicle. The tires would be 37.5 - 51 size rated at 55 tons each at 3 mph and 80 psig pressure.

The heaviest shielding door over a target cell weighs ~ 1 kton. It is proposed to roll the doors open on hydraulically lowered rollers. Experiments will be run on the carrying capacity and quality of bearing plate required for rollers.

The Merrimac would service all cells, part of the secondary beam channel magnets, the air filter and water system cell, the beam stops, and any future areas containing high-level residual radioactivity.

Magnet Design

Quadrupoles

FORTTRAN codes have been written for computing the magnetic field characteristics of quadrupole magnets suitable for operation in the intense radiation environment that will exist within the target cell and its shield wall. For this application, single-turn magnets, which feature a minimum amount of insulation, are being considered. The codes developed thus far are: (a) for quadrupoles without iron, i.e., for the field produced by four bus bars of various shapes that are arranged symmetrically around the aperture center; the busses carry equal like and unlike currents for opposite (across the aperture center) or adjacent-located busses, respectively; and (b) for quadrupoles with iron, i.e., for the field produced by four rectangular bus bars and plane iron faces joining the busses at a 45° angle (Danby-type).

The code for ironless quadrupoles uses the field equation of an infinitely long current filament. By superposition of the fields of many filaments, the field is then computed for the various cross sections of the four busses. The

deviation from an ideal quadrupole field is then plotted over several radius vectors originating at the aperture center. A similar method was used by A. Septier.³

The code for the Danby-type magnet uses Laplace's equation in cylindrical coordinates for a field with quadrupole symmetry, i.e., for
$$\psi = \sum_{v=2}^{\infty} A_v r^v \sin v\phi; v = 2, 6, 10, \dots$$
 The boundary conditions are the scalar potentials of four conducting sheets placed symmetrically around the aperture, i.e., linearly varying scalar potential along the sheets and constant scalar potential along the iron pole faces.

A mechanical design study has been started for both the ironless and the Danby-type quadrupoles. A crude model has been made of wooden blocks. This will aid in the study of the connections between adjacent quadrupoles (for muon channels the connectors are 90° arcs in order that the interconnected quadrupoles form an alternating gradient channel).

Various insulating materials have been taken into consideration for these quadrupoles. Reactor cells and material test samples have been designed. Samples of the materials considered will be placed in the Omega West Reactor to be exposed, stress-tested, and compared with fast neutron doses of 10²⁰/cm².

Muon Channel Transport Code

The CERN 6008 B56/57 beam transport code for pions and muons has been modified at LASL for use on the CDC-6600 and tested on a problem which was computed concurrently at CERN by J. Franteau and at LASL, and for which complete agreement was obtained.

Some changes are being made in the LASL input/output routines in order to adapt the program to the peripheral computing facilities at LASL.

S. Ohnuma at Yale University also is writing a code, reportedly making use of two of J. Franteau's subroutines. These subroutines are the ones computing the overlap between two polygons approximating the beam emittance and beam acceptance in two-dimensional phase space.

The two independently derived programs (CERN-LASL and Yale) should provide adequate double-checking of results when muon channels are being designed.

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VII. LAMPF SCHEDULING AND FACILITY CONSTRUCTION

Introduction

Revisions in the IBM PERT Cost II scheduling of the LAMPF accelerator are in progress. Corrections became necessary in the instrumentation and control Work Breakdown Structures, the rf power subnet is being specialized, and corrections in logic are being considered for milestone summarization. None of these changes has affected the overall project completion date.

LAMPF site preparation is now 95% complete, and bids have been opened for about \$2,900,000 of additional construction which must await FY 68 funds. Design engineering is now essentially complete for the second phase of site utility work, but new and improved criteria are still being developed for the injector and drift tube accelerator buildings. A proposal for the supply of electric power to the facility is being evaluated for negotiation.

Accelerator scheduling

The application of PERT to LAMPF accelerator design and construction has been continued with several major revisions, none of which has produced a change in project completion date.

During the scheduling phase, numerous difficulties were encountered in CONT and KONT, the two subnets for LAMPF instrumentation and control systems. Eleven separate and unsuccessful computer runs were made in an effort to level manpower and to obtain a satisfactory schedule. It was concluded that a basic error had been committed early in the instrumentation and control portion of the Work Breakdown Structure. This segment of the structure was therefore corrected, and all associated network diagrams were reconstructed. Approximately 2250 data cards have now been replaced in the deck, and initial debugging has been completed.

As a consequence of the above revisions, the project Work Breakdown Structure has been increased from 52 to 55 8 x 24 in. sheets and the network diagrams have been increased from 47 to

52 36 x 54-in. drawings. The number of subnets has remained at seven and the input data deck still consists of ~ 7200 cards.

Difficulties were encountered in the summarization of milestone events. The problem was referred to three other organizations involved with PERT. Of these, IBM stated that the difficulty had never been encountered before, that it was a logic problem not a program deficiency, and that no help could be offered by the program author. The apparent solution has been submitted by Brookhaven National Laboratory, but verification has not yet been attempted. The completion of the Level I diagram, which consists solely of summarizing milestone events, is dependent upon the solution of this logic problem.

LAMPF Site and Building Activities

Site Roads, Grading, and Utility Work

Site preparation has progressed very well and very nearly on schedule (Fig. 26). The Equipment Test Laboratory (ETL) Building area is in the lower left corner and the experimental area is at the upper right. The Laboratory-Office Buildings and parking lot will occupy the large flat site just below the center of the picture, and the 115-kV substation will be located on the smaller plot to the left. Completion of the entire preparation package is now 95% out of a scheduled 98%. All paving work and essentially all grading and backfilling have been accomplished prior to the onset of winter weather. The remaining work in progress includes installation of road guard

Fig. 26. Aerial view of LAMPF site on Oct. 12, 1967.

rails, completion of drainage structures, and placement of the water line along the north side of the accelerator.

An additional 150,000 cu yds of excavation was made at the upper end of the Beam Channel, as seen in Fig. 26. The purpose of this modification was to accommodate the latest experimental facility layout. It was accomplished for the more favorable unit prices of the current site preparation contract.

Accelerator Building Design

Title II engineering for the Injector and 201.25-MHz accelerator buildings was not completed during this period as scheduled. The design modifications reported previously, concerned with Cockcroft-Walton enclosure interfaces and chilled water cooling systems, were accomplished but there developed interferences in the drift tube accelerator building that necessitated detailed review and redesign. The A-E was instructed to discontinue work in this area until new criteria could be developed. The primary problems were interferences between equipment space allotment in the Service Corridors, greater radiation leakage resulting from an increase in diameter of rf power coaxial conductors, and deterioration of radiation shielding integrity by the numerous electrical conduit runs required between Beam Channel and Equipment Aisle. The conceptual solution to these problems has now been achieved; primarily, it involves replacing the individual Service Corridors with one continuous Service Gallery that is located an additional 4 ft above the Beam Channel. Every effort is being made to get the detailed criteria on this new design to the A-E early in the next report period.

Equipment Test Laboratory Building

Title II plans and specifications for the ETL Building were issued to prospective bidders on Sep. 20 and bids were opened on Oct. 27, 1967. The apparent low bidder was J. R. Brennan Construction Co. of Santa Fe, N.M. The bid was \$718,700 as compared with the A-E estimate of \$886,000 and a budget allotment of \$700,000 for this portion of the facility. An award

of contract cannot be made until FY 68 funds become available; however, the bid included an award clause of 60 days from date of opening. The contract construction period will be 240 days.

Laboratory-Office Building

Design of the Laboratory-Office Building by W. C. Kruger & Associates was completed on schedule. Title II plans and specifications were reviewed on Aug. 25, issued to prospective bidders on Aug. 29, and opened on Sep. 28, 1967. J. R. Brennan Construction Co. of Santa Fe, N. M. was low bidder at \$1,306,700. The budget allotment for this structure was \$1,400,000 and the A-E estimate was \$1,417,593. Contract award must await receipt of FY 68 funds, but the bid included an award clause of 60 days from opening date. The contract construction period will be 450 days.

Utility Work

Title II plans and specification review was completed Oct. 18 for the second phase of site utility work. This package comprises the facility water storage tank, fire pumphouse, sewage lagoons, additions to the site water, sewage, and gas piping systems, and a small amount of the electric distribution. Estimated cost of the work is ~\$350,000. The advance notice has been distributed, but issuance of the bid documents awaits relaxation of the current government construction freeze.

Engineering design of the site 115-kV substation was completed on schedule by Uhl & Lopez Engineering, Inc. Authorization to proceed with Title II design was given on Aug. 1. On Sep. 20 Title II review was completed, and bid documents were issued on Sep. 25, 1967. The apparent low bidder, at the opening held on Oct. 26, was Gardner-Zemke & Beaty Electric of Albuquerque, N.M. The bid was \$906,000 compared with the A-E estimate of \$921,000 and a project budget allotment of \$800,000. This portion of the project is also dependent upon availability of FY 68 funds for contract award and is also covered by a 60-day award clause. The contract construction period will be 400 days.

On Aug. 9 approval was received from AEC Headquarters to issue a request for LAMPF electric power proposals. Albuquerque Operations Office issued the invitations on Sep. 15 with a proposal deadline of Oct. 16. The only positive response was a joint proposal by the New Mexico Public Service Company and the Bureau of Reclamation. This proposal for the supply of electric power and associated 115-kV distribution lines is currently being evaluated for negotiation.