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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 April 30, 1967

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I. SUMMARY

Injector System

The injector for the LAMPF will comprise a 750-keV Cockcroft-Walton power supply, high-gradient column, buncher, and ancillary beam transport system. Agreement has been reached with the Haefely Co. of Switzerland on the design specifications for a prototype power supply including stabilizers and controls. The delivery time is ~ 14 months after the order is placed.

Accelerator Structures

Alvarez

Power tests on the 4-ft tank have been continued. Detailed comparisons have been made of heat removal from various sections of this tank with calculations based on the MESSY-MESH code. The agreement between theory and experiment is good. However, the tests revealed that, in a number of places, the temperature distributions will have to be smoothed out, and this will be done in the final design.

Design work has continued on tank No. 1. Because of the small size of the drift tubes and the low velocity of protons in this tank, the requirements for the quadrupole design are very severe. It has recently been shown that the beam aperture in the first tank can be decreased; this eases the problem of quadrupole design.

Starting with tank No. 2, it may be advantageous to utilize multistem drift tube support in order to achieve increased field stability, but at a cost of decreased shunt impedance. Theoretical and experimental studies are being pursued in order to arrive at a decision within the next few months.

805-MHz

Model K, a shaped, 61-cell, $\beta = 0.65$ side-coupled tank, has been tuned successfully. The measured Q is $\sim 25,000$ and the shunt impedance is $\sim 38 \text{ M}\Omega/\text{m}$, as anticipated. The

tank has been power-tested to design level, with some indication of arcing at the coupling iris; this defect should be easily corrected.

Final tests were made on Model L, a 5-cell, $\beta = 1$ electron accelerator. The measured electron energy vs rf input power is in accord with calculations. This accelerator was run at 20-mA peak power, 3-MeV energy gain, and 3% duty factor (DF).

Model M, a 6-cell, graded-velocity electron accelerator, which will be used as an injector for the electron prototype accelerator (EPA), has been run at 20-mA peak current, 1-MeV output energy, and 6% DF.

Calculations and fabrication on the 100-cell, side-coupled $\beta = 1$ accelerator, i.e., the EPA, have been continued in parallel. The calculations are designed to predict beam profile, phase acceptance of the accelerator, and the beam loss as a function of Model M operating characteristics. Machining of the cavities is being continued, and some brazing has been started.

RF Power Sources

201.25-MHz

The 7835 power amplifier has been operated at peak powers in excess of 3 MW at 6% DF, but for only short periods of time because of difficulties with modulator tubes. Machlett Laboratories is working to correct difficulties with the 8618 magnetically focused triode. A tetrode, the 4CW100,000D, is also being evaluated for modulator service. Despite the difficulties mentioned above, closed-loop amplitude control was demonstrated on the 7835 power amplifier system.

805-MHz

Serious difficulties are still being experienced with the Coaxitron under development by RCA. It is not clear that one of these will be available for evaluation by the time a tube choice will have to be made.

Litton Industries assembled the first 1.25-MW klystron. However, the tube would not go to full power and the efficiency was very low. A number of defects were revealed and the tube is now being redesigned.

A more encouraging picture is presented by the Amplitron program. The first 1.25-MW tube has been delivered and it has been operated at the 1-MW, 6% DF level with gain ≥ 11 dB and efficiency $\sim 50\%$. Measurements of output spectrum are reasonably satisfactory and the tube looks promising.

The first phase of a computational program to study, by analog computer, the performance of crossed-field microwave tubes has been completed.

Accelerator Control and Instrumentation

Work is being continued on the problems of radio-frequency and phase control. Two transistor/varactor multiplier chains have been completed. They use a 2,483-MHz crystal oscillator reference and varactor triplers and doublers to achieve 201,250 and 805,000 MHz. Tests of these multiplier chains will commence immediately. Also under development is a transistor/step-recovery diode multiplier chain. A vacuum tube multiplier chain built earlier is undergoing extensive tests.

Delivery, installation, and acceptance-testing of the entire SEL-810A computer system were completed. Bugs in the system are being eliminated and good progress has been made toward developing programs and testing components of computer interface equipment already developed.

A serious problem with cross-talk was revealed during dynamic checkout of the Computer Interface Unit (CIU) and the Driver-Terminator (D/T) chassis. The problem was surmounted but only at the cost of rewiring all interchassis connections in the control room, and rebuilding the D/T chassis. Installation of

prototype equipment for the control console has been completed.

Work is under way to provide computer control of the Amplitron test stand. However, it is going slowly because it is done on a non-interference basis.

An inexpensive temperature control system designed to control cavity water temperature to 0.1°F has been constructed and is awaiting test under actual operating conditions.

Control and instrumentation design for the EPA has been initiated. Manual and computer control will be incorporated in the final system.

Basic requirements have been established for the radiation monitoring and safety system for EPA, and radiation monitoring instruments are on order.

A design study was completed on a system for automating the measurement of beam profile with presentation of data to be on the digital display scope in the control room.

Accelerator Physics

Minor changes in the design of the linac were studied. These include a "tilt" in the accelerating gradient in the first Alvarez tank, small changes in the focus magnet strengths, and a decrease in the radial aperture in the waveguide tanks between 100 and 200 MeV. The overall effect of these changes is to produce a somewhat smoother variation in the fields as seen by the particles, and to place the radial aperture stop for the waveguide linac at the 100-MeV point. The length of the accelerator is essentially unchanged, and the number of 805-MHz rf power stations is reduced from 45 to 44.

The LASL-designed duoplasmatron ion source was placed in operation, and measurements of its characteristics were started.

Project Scheduling and Facilities Planning

Progress on the preliminary program management network and work breakdown schedules has been good during the past quarter. It is now anticipated that the first complete computer run can be made by June 1. Then will follow a detailed study of the results, personnel leveling, and organizational changes--all designed to accomplish facility construction as economically as possible with a minimum of personnel and on schedule. A reasonably realistic construction schedule through level III should be available by the end of the summer.

The building to house the EPA is 65% complete.

The initial phase of foundation studies, involving seismic measurements, experimental soil load-bearing investigations, and analytical calculations, has been completed. The results are very satisfactory. Geologically, the mesa on which the accelerator is to be situated is very stable. Loads of up to 8 t/ft² produce negligible creep. Furthermore, deformations up to above loading agree well with theoretical predictions based on the Young's modulus of the tuff.

The initial site preparation contract is now 16% complete. No unexpected difficulties have been encountered.

Criteria have been developed for design of the electrical substation and bid proposals have been solicited for design of this unit.

Title I engineering for the Laboratory-Office building is now being reviewed by LASL.

From the standpoint of economy of construction and efficiency of utilization, it has been decided to consolidate all the accelerator construction and maintenance space into a single building to be constructed as soon as funds become available. Criteria development for this building is proceeding.

Title II design has been initiated for a second phase of the site's water and waste disposal systems.

II. ACCELERATOR STRUCTURES

Introduction

Model K, the 61-cell, side-coupled optimized shunt impedance tank, has been run at field gradients greater than the design values for LAMPF. An anomalous change in VSWR at high power, probably associated with the coupling iris, is being investigated. Other than this effect, the accelerator tank behaved as expected. The bridge coupler, which will replace the center section of the tank, has been tuned and is now being brazed.

Model L, a 5-cell, $\beta = 1$ electron accelerator has been run at ~ 3 MeV, 3% DF, and 20-mA peak power for extended periods of time. Studies have been terminated on this model.

Model M, a 6-cell, graded- β electron accelerator, has been installed in the 100-ft long "iron house" shielded room in place of Model L. Operation at ~ 1 -MeV output energy, 30-mA peak, 6% DF was terminated after ~ 15 min when the inadvertently focused beam burned through the water-cooled Faraday cup. Work is being continued on this accelerator.

The design and fabrication of the Electron Prototype Accelerator (EPA) is well under way. Beam dynamics calculations are complete for the system, and indicate that quite reasonable energy spreads and beam diameters can be expected from the system being built. The computer code LALA has been used to optimize the cavity shape for EPA. Although significant gains in shunt impedance can be realized by reducing the bore hole, the decision to keep the beam aperture at 1.5 in. has been made after all factors were considered.

All of the copper forgings for the EPA have been procured, and machining is in progress at a vendor's plant. The support and alignment

rails are being fabricated and will be installed in the iron house within the next month. All major components of the vacuum system have been ordered. The design of the cooling system is finished and major components have been ordered.

The power tests on the 4-ft Alvarez accelerator tank were continued during the last quarter. Detailed comparisons have been made of the heat removed from various portions of the model with the theoretical heat loading derived from MESSYMESH calculations; agreement is excellent. Some potential trouble spots have turned up in the temperature distributions, and they will be corrected in the final Alvarez design.

A change in beam aperture diameter has considerably eased the quadrupole design problem in the first Alvarez tank. Redesign of these magnets is in progress. Drift tube design for the first Alvarez tank is also in progress.

Studies to evaluate the multistern drift tube support scheme are under way and preliminary measurements indicate a substantial increase in field stability is achievable, at a cost in system shunt impedance. Theoretical studies of the system behavior, using the coupled resonator model, and extensive experimental investigation of the effects of variable cell length are under way.

A nonresonant beam position monitor is under development. Prototype units will be evaluated on the EPA as they are developed.

805-MHz Accelerator Studies

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

Testing: Tuning of Model K has been completed. A mode spectrum measurement indicates a stop-band of only 18 kHz. The measured field flatness is $\pm 2\%$ of nominal, exclusive of the driven cell which is 8% low. The measured Q is 24,700, yielding a shunt

impedance of $38.1 \text{ M}\Omega/\text{m}$. The coupling iris has been enlarged to give a coupling factor of 1.25, overcoupled.

Radiofrequency power tests have been conducted at 375 kW peak, 3% DF. The only problem was an increase of input VSWR from 1.25 to ~ 1.7 as the power was increased. Disassembly of the integral iris-ceramic window showed evidence of arcing at the coupling iris which might account for this increase. The edges of the coupling iris have been carefully rounded and the ceramic window reassembled in preparation for further power tests. Viewing windows have been installed to verify the presence or absence of arcing in these tests.

Bridge Coupler: Parts for the bridge coupler assembly, which will replace the center section of Model K, have been received. The end cells, which terminate the two halves of Model K, were pretuned to 805 MHz. The coupling cells were then tuned, applying the results of the coupled circuit theory to the mode spectrum of the bridging assembly. A means of determining approximate values for all the bridging cell parameters (end cell-to-coupling cell, and coupling cell-to-bridging cell coupling constants) has been developed from the coupled circuit theory. A computer program to determine these parameters is being written.

The electric field on the axis of the bridging cell, as determined by perturbation techniques, is one fourth the electric field on the axis of the accelerating cells. The magnetic field at the wall of the bridging cell has been calculated (and verified by measurement) to be about one third the magnetic field on the wall of an accelerating cell; this shows that it is feasible to couple the waveguide to the bridging cell with an iris of reasonable dimensions.

Preliminary calculations indicate that the stored energy in the bridging cell is 0.75 - 1.0 times the stored energy in an accelerating cell.

This indicates a reduction in shunt impedance of $\sim 2\%$ for the modified Model K, since the fields in the bridging cell are not available for acceleration of the beam.

All subassemblies have been brazed together and are ready for the final assembly braze after minor machining is completed.

Combined tuning range of the three bridge coupler tuning slugs was found to be 1.09 MHz. This measurement was made with the complete assembly clamped together in the final assembly brazing configuration.

The Model K bridge coupler alignment mounts have been fabricated and are ready to be installed.

Model L (5-cell, $\beta = 1$ electron accelerator)

A new measurement has been made of the peak beam energy out of Model L at several rf power levels. The injection energy was 100 keV and the intensity was kept low enough that beam loading effects were small. The results are shown in Fig. 1, along with the revised calculation of energy vs power. This is a better measurement than the one reported earlier because of the higher beam intensity permitted by the pulsed gun and the iron house shielding. In addition, the spectrometer used was a great improvement over the magnet of the earlier measurements.

Fig. 1. Maximum beam energy vs rf power in Model L.

Some glass slide packs were browned by exposure to the beam. The range was consistent with the energy given by the spectrometer, and the spot size was ~ 1 -cm diam.

Model L has been run with 20-mA peak accelerated current at ~ 3 MeV and 3% DF.

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

Model M was installed in the iron house in place of Model L. It was placed close to the gun, with only a solenoid and steering magnet pair between. This is the way its installation is planned as the pre-accelerator for EPA. Model M was run with 20-mA peak accelerated current and 6% DF. The rf power level corresponded to slightly more than 1 MeV output energy. The run lasted about 15 min at full intensity, and terminated when the inadvertently focused beam burned through the water-cooled Faraday cup. Examination of the melted plate suggested a beam hot spot ~ 5 -mm diam; the behavior of the current collected for various solenoid settings suggested there was also a low-intensity, large-diameter halo.

The first of four solenoid magnets for axial focusing of the beam in Model M has been received and tested. It was found that water cooling will be required; otherwise, the solenoids performed as expected. These solenoids will be installed on Model M when this tank is moved to the Electron Prototype Laboratory (EPL) building to become part of the EPA injector.

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

Dynamics: Methods of calculating the radial motion of accelerated particles have been developed in connection with the construction and proposed operation of Model M and the EPA. A computer code (designated FARM, For Accelerator Radial Motion studies) is used to calculate trajectories for particles at relativistic velocities in circularly symmetric geometries under the

assumptions that space charge and beam loading effects may be neglected. The fields are specified by reading in values of the longitudinal electric field component on the axis. (This is the sort of field data that can be obtained experimentally from a bead-pull measurement.) On the CDC 6600 computer, over 100 particles can be traced through 15 cells in one minute. A brief description of the FARM code has been given in a technical memorandum.¹

Some tentative conclusions from analyzing the proposed Model M-EPA configuration are given below. The term "initial phase" refers to the time in the rf cycle that the particles enter the first cell of Model M. A particle with an initial phase of 90° enters this first cell just as the accelerating component of the electric field goes from negative to positive, and hence will experience a near-maximum accelerating field at the center of the cell.

Most electrons with initial phases in the range -30° to $+90^\circ$ are likely to be accelerated through the Model M-EPA combination and emerge with energies in the range 21 to 25 MeV, if proper focusing coils are used. A number of electrons with initial phases greater than 90° (electrons entering late) emerge from Model M near the axis, but are likely to be lost radially in EPA. Those in the 90° to 100° initial phase range are likely to gain several MeV in energy before being lost.

A number of electrons in the initial phase range -60° to -30° (electrons entering early) can penetrate through Model M and emerge somewhere in the whole radial range of the exit beam hole. If allowed to continue, most of these electrons will be lost radially in EPA. Those in the -50° to -30° phase range are likely to have several MeV of energy when they are finally lost. An aperture to scrape some of these electrons off the beam before they reach EPA might work as well or better near the exit of Model M than near the entrance of EPA.

The profile of the beam in Model M and EPA is expected to be somewhat triangular. That is, the number of particles per unit cross-sectional area is likely to come to a sharp peak at the center of the beam. (Some recent measurements with Model M do not conflict with this view.) At its edges, the density distribution will probably have a smooth tail, more like the normal distribution.

Cavity Optimization: The effects of dimensional changes in the cavity for the EPA were investigated (see Figs. 2, 3, and 4). A change of the beam hole radius from 1.9 cm to 0.9 cm gave a gain in shunt impedance of 21%. Changing the drift tube angle from 30° to 7.5° , which gave the maximum shunt impedance, furnished a gain of only 4%. Variation of the radius at the nose of the drift tube from the standard 0.4 cm to 0.1 cm increased the shunt impedance only 2.9%. Decreasing the radius of the nose of the drift tube also increases the probability of sparking across the drift tubes. Since the shunt impedance gains in altering the drift tube angle and the drift tube radius were small for this value of β , the drift tube angle was left at 30° , and the drift tube radius remained at 0.4 cm.

The present curve representing shunt impedance vs the outer radius of the cavity for the $\beta = 1$ configuration shows that the cavity with no coupling slots has a maximum shunt impedance when $R_{\max}$ is 14.4 cm. Adding a side-coupling cell to the cavity is qualitatively the same as making an outward perturbation in the cavity. Since this perturbation is in a region where the electric field is relatively intense, the resonant frequency is decreased. Consequently, it is useful to design the cavity such that the outer radius is somewhat less than the radius that exhibits the maximum shunt impedance. The $R_{\max}$ for the EPA cavities is 13.2 cm which is 8.33% smaller than the $R_{\max}$ giving the maximum shunt impedance. The philosophy is that with the addition of the side-coupled cavity, the shunt impedance of the chain will be maximized.

Fig. 2. Shunt impedance vs bore hole diameter in EPA cavity.

Fig. 4. Shunt impedance vs radius at end of nose cone in EPA cavity.

Fig. 3. Shunt impedance vs Q angle of nose cone in EPA cavity.

Tuning: Two segments and coupling cells for the EPA have been tuned to determine the initial dimensions for the half-gap of the remaining EPA segments.

A tracer lathe, with associated tools, has been placed in the tuning area along with a tuning fixture designed to facilitate handling of the segments. An air-conditioning unit is being installed to insure a constant temperature environment for the tuning process. Seven machined forgings are being tuned.

Fabrication: All clamshell and segment forgings for the 100-cell EPA have been fabricated at LASL; the forgings were produced by the 5000-ton Lake Erie press. Machining of the segments and clamshells from these forgings is in progress by an outside vendor and 90 finished clamshells have been received to date. Furnace brazing of the tank components is under way

Fig. 5. EPA bridge coupler.

using a hydrogen furnace. Sixteen of the stainless steel-to-copper rf joints and five coupling cavities have been brazed with the first-step brazing alloys.

The EPA support structure base rails have been completed and are now being installed in the iron house area of the EPL and the aluminum tank support structure is nearing completion in the LASL shops. The tank alignment mounts have been designed and are being made by an outside vendor; they are scheduled for completion in May.

Design of the EPA bridge couplers is complete and three units are being fabricated. These couplers are essentially copies of the Model K bridge coupler. A drawing of the EPA bridge coupler is shown in Fig. 5.

The 42-in. long x $12\frac{1}{4}$ -in. o.d. x 1-in. wall OFHC copper cylinders for the bridge coupler resonant tanks were cast at LASL. Nine tuning slug assemblies for the bridge coupler tanks are also under construction.

Several of the subassembly brazing operations required for the bridge coupler assembly will be done at LASL. Final braze assembly of the complete coupler will be done at an outside vendor's shop.

All major components for the EPA vacuum system have been ordered or are being fabricated. The 2-in. manual valves for use along the beam line have been received. Initially

a 2-in. pneumatic valve with a closing time of 0.5 sec, according to manufacturers specification, will be used between the last tank and the target. Four-inch valves for the roughing system are on order.

The vacuum manifold is being fabricated outside LASL. The first three sections to be used with the first tank are due for completion early in May with the remainder by the end of May. The pump supports, being fabricated at LASL, are scheduled for completion the end of May.

Four 600 liters/sec ion pumps are on order. The blower pump packages presently on hand will be used to provide the rough vacuum for ion pump starting.

Detail design of the EPA injector support structure and mounting apparatus has been completed, and fabrication of the alignment mounts for the electron gun, the graded β tank (Model M), and the focusing magnets is in progress.

Drawings for the cooling water supply, cooling water return, mixing tanks, and pumps have been approved and the material for these components is on order. Detailed drawings of the tank cooling tubes have been completed and the tubes are scheduled for delivery the first week of May. The components for the tank temperature control system have been ordered. This system is similar to the one fabricated for the 61-cell Model K tank.

Alvarez Accelerator Studies

~ 201.25-MHz High-Power Cavity

The 4-ft, 201-MHz cavity has been driven with rf power to obtain heat load and cooling circuit information. Power levels attained have been limited by the output of the totem pole amplifier. A peak power of ~ 250 kW has been reached corresponding to a peak field of 2.6 MeV/m, 1.1 times design gradient, with a maximum average power of ~ 10 kW at various peak powers and duty factors.

By throttling the flows to obtain accurately measurable temperature differences, the heat loads of the various sections and components of the model were determined. Temperatures were measured by chromel-alumel thermocouples installed in the supply and return water lines. Flow rates were obtained by collecting and weighing return line water. Observed heat load distributions agree well with theoretical values. Also, all circuits are adequate to handle predicted full-power levels. In no case did power dissipation in any circuit vary more than 9% from the value predicted analytically from MESSYMESH.

Thermocouples were installed inside the vacuum envelope to measure the temperature distributions of the drift tube, half-drift tube, and drift tube plate. Measurements were also made on the cavity wall at the uncooled drift tube support saddle area and on the drift tube plate to provide a more uniform distribution.

Because rf pickup caused the precision thermocouple indicator to lock, considerable time and effort were spent providing inductive and capacitive blocking in the thermocouple leads. Readings were finally obtained at all rf power levels.

Although the cooling water flow provided by the water cart is adequate, the temperature control is not satisfactory. Installation of the resistance thermometer, which measured the controlling temperature in the cavity water jacket circuit, was of little benefit. A new control circuit is now being designed and installed.

During rf operation, the vacuum remained at $\sim 9 \times 10^{-7}$ torr.

The tuning slug range measured under power was 138.6 kHz. No sparking was observed when the slug was moved while the cavity was being powered.

A detailed report of the measurements and results obtained from operation of the 4-ft model is now being written.

Quadrupole Magnet Design

Field measurements were made of an early generation magnet having a coil with four turns per pole. The quadrupole was designed to provide a gradient of 5526 G/cm over a length of 2.74 cm or a total strength of 15.14 kG. Measurements at 820 A revealed a peak gradient of 5630 G/cm with a total strength of 21.55 kG corresponding to an effective length of 3.83 cm. These results are in harmony with the empirical expression developed from the experiment described in the previous progress report.

The OFHC copper coil conductor has been delivered and a coil with four turns per pole was wound using early style coil forms. Winding proved much easier than was anticipated even though the new conductor has a wall thickness 50% greater than the tubing used in the past. Although it is much stiffer, it is in the full annealed condition and is virtually impossible to collapse during the winding operation. Special benders are being fabricated to make the preliminary bends and obtain the proper shape at the stem junction.

Recent modifications of the magnetic gradient requirements and bore size have required redesign of the quadrupole magnets. New quadrupole cross section designs and grouping schemes were required. Final design of the pole shapes is essentially complete and the new quadrupole magnets are ready for detailing.

The gradient in the low-energy quadrupole magnet was raised from 5526 to 7970 G/cm; however, the bore radius was reduced from 1.0 to 0.75 cm. This gradient can be achieved at 671 A with a new coil design with four turns per pole. The previous design required 820 A. The quadrupole magnets in the three remaining cavities will still use three turns per pole. Although a much higher gradient is required in the new design, the flux density in the iron will be only slightly higher than for the previous design.

Drift Tube Design

Prototype cavity-one drift tubes are being designed and will be used in the brazing development program. Forging dies for the first cavity drift tube bodies are being made at LASL.

A prototype cavity-one drift tube stem support has been designed incorporating certain features used on the 4-ft power model. This model will be fabricated and used to evaluate its assembly, alignment, and vacuum capabilities.

Multistem Drift Tube Support Studies

Some investigation has been made of the effects of multistem drift tube supports on the rf characteristics of an 8-ft model Alvarez cavity. The conclusion, in brief, is that for a certain configuration of drift tubes stems (for this particular model four 0.794-in. diam stems at 90° positions) the tank becomes almost completely insensitive to any effort to tilt the field pattern of the tank. Also, it appears that the Q of the tank could be decreased by as much as 25%.

This particular model is an 8-ft length of aluminum pipe with a $13\frac{3}{4}$ -in. i.d. The cavity is divided into ten cells of equal length by nine drift tubes which can be supported by any number of stems from one to six. The ends of the cavity terminate in whole cells with movable half-drift tubes in each end-flange of the cavity. Length of cells is 9.625 in. and length of drift tubes is 5.697 in. The individual cells are models of a 92.7-MeV energy cell.

With the drift tubes hung by one vertical stem of 0.794-in. diam from the top, the mode spectrum shown in Fig. 6 was determined. The top five modes could not be determined. The zero mode frequency was 509.5 MHz. A $\frac{3}{8}$ -in. diam brass bead was then pulled down the center-line of the cavity and the change of frequency vs bead position was plotted. With the end-cell gaps set nominally equal to the other cell gaps

Fig. 6. Modes of ten-cell Alvarez cavity with drift tubes supported by one stem.

the tilt of the tank is indicated by Fig. 7. The biggest frequency change caused by the bead in any cell was ~ 16 kHz and the smallest was 11 kHz. Number 1 cell half-drift tube was then pulled out $\sim 1/32$ in. and No. 10 cell half-drift tube was pulled out $\sim 1/16$ in. This gave the best graph for flatness in the tank (Fig. 8). Figure 9 presents the effect of lowering the f_0 of the cavity 22 kHz with No. 20 cell and then raising the f_0 the same amount with cell No. 1. The bead causes the biggest frequency change in No. 10 cell which was the cell adjusted to a lower frequency. This indicates the electric field between drift tubes in this cell is the highest in the tank. Figure 10 shows the f_0 of the cavity lowered 25 kHz by adjusting cell No. 1 and raising f_0 the same amount by adjusting cell No. 10. Here again, the cell which was adjusted to a lower frequency showed the biggest frequency change caused by the metallic bead. Figure 11 is another good example of this and also shows the amount of tilting that can be accomplished by moving the end cell half-drift tubes 0.25 in.

Starting from this field configuration in the cavity, additional support stems were added to each drift tube until a configuration of four stems at 0° , 90° , 180° , 270° , was achieved. Figures 12 and 13 show little effect on the field pattern with the addition of a second and a third

Fig. 7. Support: one 0.794-in. diam stem.
Field tilt: 13%; Cell tuning: none; $f_o = 510.476$ MHz.

Fig. 10. Support: One 0.794-in. diam stem.
Field tilt: 10%. Cell tuning: f_o lowered 25 kHz for No. 1, raised 25 kHz for No. 10. $f_o = 509.698$ MHz.

Fig. 8: Support: One 0.794-in. diam stem. No field tilt. Cell tuning: Nos. 1 and 10 cells adjusted to zero tilt. $f_o = 509.690$ MHz.

Fig. 11. Support: One 0.794-in. diam stem.
Field tilt: 64%. Cell tuning: Nos. 1 and 10 closed $\frac{1}{4}$ in. $f_o = 509.577$ MHz.

Fig. 9. Support: One 0.794-in. diam stem.
Field tilt: 8.5%. Cell tuning: f_o lowered 22 kHz for No. 10, raised 22 kHz for No. 1. $f_o = 509.697$ MHz.

Fig. 12. Support: Two 0.794-in. diam stems.
Field tilt: 69%. Cell tuning: Nos. 1 and 10 closed $\frac{1}{4}$ in. $f_o = 510.997$ MHz.

In Figs. 7 through 17, the x axis is the axial position of the 3/8-in. diam brass bead and the y axis is the cavity frequency.

Fig. 13. Support: Three 0.794-in. diam stems. Field tilt: 62%. Cell tuning: No. 1 closed $\frac{1}{4}$ in., No. 10 opened $\frac{1}{4}$ in. $f_0 = 512.475$ MHz.

Fig. 16. Support: Two 0.794-in. diam stems. Field tilt: 70%. Cell tuning: Same as for Fig. 15. $f_0 = 510.656$ MHz.

Fig. 14. Support: Four 0.794-in. diam stems. Field tilt: $< 1\%$. Cell tuning: Same as for Fig. 13. $f_0 = 514.266$ MHz.

Fig. 17. Support: Four 0.794-in. diam stems. Field tilt: 9%. Cell tuning: Same as for Figs. 15 and 16. $f_0 = 513.953$ MHz.

Fig. 15. Support: One 0.794-in. diam stem. Field tilt: 71%. Cell tuning: No. 1 opened $\frac{1}{4}$ in., No. 10 closed $\frac{1}{4}$ in., 5 in² Cu in bottom of Nos. 2, 3, 4. $f_0 = 509.187$ MHz.

Fig. 18. Modes of ten-cell Alvarez cavity with drift tubes supported by four stems.

stem, respectively, to all drift tubes. In Fig. 14 there is seen to be a striking change in the tank tilt when the fourth stem was installed on all drift tubes. Figures 15 through 17 show the change in field pattern from one to four stems with the tank tilt in the opposite direction (cell No. 10 closed, cell No. 1 opened). In addition to this end-cell perturbation, 2.5 in. x 4 in. x 0.5 in. copper bars (5 in.³) were placed in the bottom of cells Nos. 2, 3, and 4. The sequence of figures shows nothing much happens until the fourth stem is installed on each drift tube. But the field configuration is not as flat as in the previous sequence. Cell Nos. 2, 3, and 4 have a lower field than cell No. 10. This is to be expected since the copper bars in cells Nos. 2, 3, and 4 would raise the frequency of these cells and therefore follow the observed results that the cells of higher frequency have lower field.

With all cell perturbations removed from the cavity the mode spectrum of the cavity with the drift tubes supported by four stems is given by Fig. 18. The top five modes could not be determined. It should be noted that there is no stop band between the upper and lower mode spectra as there is when only one stem is used. The mode whose frequency is 513.5 MHz is equivalent to the zero mode of the one-stem configuration (i.e., electric field on axis is in the same direction in all cells). Measurements of the Q of some of the modes of the cavity in both the one- and four-stem configurations were made, and are summarized in Table 1.

Measurements of the Q of a certain mode with various degrees of cell perturbation or tank tilt were made and are given in Table 2.

It is difficult to determine any pattern of the Q because not enough measurements were made and their accuracy ($\sim \pm 10\%$) is not as good as is needed. However, from this small sample it appears that the Q of the four-stem configuration could be about 25% lower than the one-stem configuration.

Table 1.

<u>One-Stem Configuration</u>		<u>Q</u>
<u>Mode Frequency (MHz)</u>		
Upper band	509.5	22,100
	512.8	20,500
	522.2	21,700
	537.6	20,700
	509.5	20,400
Lower band	196.7	4,800
	207.3	5,600
<u>Four-Stem Configuration</u>		<u>Q</u>
<u>Mode Frequency (MHz)</u>		
	492.5	2,800
	514.3	13,900
	534.3	3,840

Table 2

<u>Mode Frequency</u>	<u>Tank Field Tilt</u>	<u>Q</u>
509.5 One stem	< 2%	22,100
509.5 One stem	$\sim 17\%$ (both end cells opened).	23,200
514.3 Four stems	< 2% (both end cells opened).	16,600
513.9 Four stems	$\sim 9\%$ (both end cells opened) + copper bars in cells Nos. 2, 3, and 4.	14,300

Future plans now call for performing the same tests on the cavity model using stems of different diameters. In addition, a 34-cell air cavity of variable cell length is under construction and will be tested in the same manner.

Computer Studies

Circuit Analog for Waveguide Section with Multiple Drives

A waveguide section with multiple drives has the advantage (as compared with smaller sections with individual drives) that loss of one drive does not mean complete loss of the accelerating fields. The possibility is under study of increasing the remaining drives in a waveguide

section to compensate for one drive being out. For a section with six drives, the effective Q of the whole section is changed $\sim 4\%$ or less if one drive is out. The average amplitudes and phases of the 24 tanks assumed to comprise the section were computed for one drive out. These data were then used to estimate the region in energy-phase space for which particles could successfully traverse such a section. The results indicate that if the other drives are increased sufficiently, the beam would not be lost. However, for the six-drive section considered, the amplitude increase required would amount to $\sim 40\%$ increase in power for the remaining drives.

Circuit Analog for Multistern Alvarez Linac

A computer code (CAPE) has been written which can fit circuit analog parameters, including n^{th} nearest neighbor coupling ($n \leq 6$), to mode spectra data. Different numbers of couplings have been assumed, and the attempt made to fit the resulting theoretical models to data obtained from a 10-cell Alvarez experimental model. Based on the smallness of the variance, the fit with many couplings assumed was found to be better, but not much better, than the fit with near-neighbor and one next-nearest-neighbor coupling only. This investigation is being continued as more information becomes available. A comparison is in progress of the multicoupled resonant circuit model described above with Nishikawa's equivalent circuit model.²

LALA Studies

An interior portion of the LALA code has been altered so that radical dimensional changes in a cavity may be made without substantially increasing required computer time, while maintaining reasonable accuracy. Twenty relaxation factors are used in the calculation of the magnetic field at the mesh points before the resonant frequency is calculated instead of the former three relaxation factors. An advantage of

the modified code is that it is no longer necessary to "build up" a cavity. That is, the dimensions of the cavity are no longer changed by only 1 or 2 mm until the desired shape is reached. This operation necessitated many time-consuming computer runs in the past. It is now possible to put in almost arbitrary F values ($F = rH$) as initial conditions in the mesh. For example, an initial field chosen proportional to $J_0(kr)$ is satisfactory. Problems worked so far in this manner have been solved within a reasonable length of time. Correlation of the Bessel function loaded-cavity results with those obtained from a "built-up" cavity has been excellent.

Previously, it was required that successive F values at every mesh point should not change by more than 0.5% between iterations for valid results. In addition, successive values of λ^2 ($\lambda^2 = \omega^2/c^2$) were not to change by more than 0.005%. Another criterion was that the difference in the voltage along the beam axis of the cavity calculated by a line integral and by Faraday's law should not vary by more than 4%. It has been found that these criteria give shunt impedance values only reproducible within 5%.

The modified code is now being used for design calculations with new criteria. Successive values of λ^2 are being held to 0.0015%. The sum of the differences of the successive F values is held to ≤ 1.5 . The difference in the methods of calculating the beam axis voltage has been on the order of 2-3%. Comparison of theoretical results using these criteria with empirical data has been most satisfactory.

Work is being continued on shunt impedance optimization through the examination of various shape configurations. Preparation of design curves is now in progress for a $\beta = 0.45$ side-coupled cavity with a 1.27-cm beam radius.

Instrumentation and Related Equipment

Beam Position Monitor

A nonresonant beam-sensing device, based on rf induction from the beam, has been developed. The sensor consists of four loops parallel to the axis and at 90° intervals around the wall of the beam pipe. This sensor is much smaller and, being nonresonant, much less temperature-sensitive than the assembly of one TM_{011} and two TM_{110} cavities previously being contemplated for use as a position sensor. A vacuum-tight model is currently being constructed for testing in the mockup program. The sensitivity of this model will be ~ 10 mV/mA for a centered beam.

The beam position is found, independently of the beam current, by a real-time sampling system which determines the beam position about 20 times during a 500- μ sec beam pulse. The sampling system consists of a gated mixer to switch the four signals from the beam sensor, in sequence, to the logarithmic IF amplifier. Two gated clamps at the output of the IF amplifier separate the x and y position signals and normalize them to give position information independently of beam current. A timing circuit guarantees an integral number of sampling sequences for an arbitrary length gate pulse. A complete description of this proposed system will be given in an internal report.

A prototype mixer circuit has been built which exhibits good sensitivity and wide range linearly with ~ 50 dB of isolation when in the off state. The circuit consists of four untuned diode mixers with a common local oscillator injection point. Matching of the mixer diodes appears necessary to insure equal sensitivity of the four mixers over the range of input signal levels.

The logarithmic IF amplifier will be a commercial device of the successive detection type. One unit has been ordered for evaluation.

A gated clamp circuit has been devised and constructed to permit separating and normalizing the position signals. Some further work is indicated in this area to eliminate a gate feed-through problem and eliminate drift of the output dc level.

The timing circuit, developed in the previous quarter and recently improved somewhat, is considered to be satisfactory.

Circuitry to integrate the position samples and prepare the position signal for the computer data collection system is yet to be developed.

Miscellaneous Electronics

By using a surplus IBM patch panel and patch cords and 80 integrated circuits, a logic "breadboard" has been built enabling logic circuits, such as the beam position monitor timing circuit, to be easily assembled and tested.

805-MHz Segment Tuning Fixture

A fixture for tuning segment pairs was designed and built. It is now being installed in the Betatron Vault and will be used in conjunction with the tracer lathe for the tuning of the EPA segments.

The fixture is actuated by a $3\frac{1}{4}$ -in. diam bore pneumatic cylinder. The range of the force applied to the rf joint, using the building air supply, is ~ 0 -660 lb.

Alignment

A helium-neon tooling laser complete with a centering detector target has been ordered for testing and evaluation. If delivered as scheduled, this unit will be used for aligning the EPA. Various fixtures are being designed to adapt the tooling laser to existing optical tooling equipment.

References

1. G. R. Swain, "FARM - A Computer Code for Accelerator Radial Motion Studies," MP-3/GRS-6, March 22, 1967.

2. T. Nishikawa, "Equivalent Circuit and Dispersion Relation for the Multistem Drift Tube Structure," AADD-125, BNL-10834, Brookhaven National Laboratory, Upton, Long Island, N. Y., Nov. 18, 1966.

III. RF POWER SOURCES

Introduction

Measurements of the phase stability of the vacuum-tube multiplier chain developed as a portion of the master frequency source for the accelerator show that the signal is sufficiently pure for frequencies removed from the carrier by more than 500 Hz. Noise closer to the carrier is being introduced by the crystal oscillator and power supplies, a situation which will be improved in later versions. Development of alternate multiplier chains using solid-state devices is being continued.

Closed-loop amplitude control has been demonstrated on the 7835, 201.25-MHz power amplifier and the 805-MHz Amplitrons. Good control was obtained over the dynamic range of the present equipment.

The 8618 magnetically focused triode used as a modulator tube has continued to exhibit voltage instabilities and filament breakage. Machlett Laboratories has made substantial changes in tube construction to overcome these faults; tubes of the new design should be available shortly for testing. These difficulties have resulted in a lack of usable modulator tubes which has retarded the high-power testing of rf components. Some use of the 4CW100,000D tetrodes in the Amplitron test stand has shown promise for the use of this tube as a modulator.

The 7835, 201.25-MHz power amplifier has been operated at peak powers in excess of 3 MW at 6% DF for short periods of time.

The first of the 1.25-MW Amplitrons arrived late in this report period and initial testing shows promise. The tube has been operated at the 1-MW,

6% DF level with gain ≥ 11 dB, efficiency $\sim 50\%$, and a reasonably pure output spectrum.

The Coaxitrons at RCA have exhibited serious difficulty with sparking around the window. This has prevented testing at full duty factor and pulse length.

The first 1.25-MW klystron constructed at Litton has several defects which have necessitated a redesign of the tube.

RF Control Studies

Overall System Design

The automatic operation list prepared for the Amplitron test stand was reworked into a preliminary list for the 805-MHz accelerator module rf operation. As a basic assumption, it was required, for maintenance reasons, that any module may be operated without using the computer or the computer interface equipment. This list involves some seven command functions and 18 data points per module. Preparation of the Amplitron test stand for computer-controlled operation is continuing.

Frequency and Phase Control Studies

Two transistor/varactor multiplier chains have been completed. They use a 2.483-MHz crystal oscillator reference, four varactor triplers to reach 201.250 MHz, and two varactor doublers to 805.000 MHz. These are now ready for tests of phase stability, spurious components, and noise. The transistor/step-recovery diode multiplier chain is under development and is $\sim 60\%$ complete. The step-recovery diodes have a decided advantage in that they are capable of high-order multiplication, thereby substantially reducing the number of stages of multiplication; however, the filtering required to isolate all but the desired frequency complicates the design.

The vacuum-tube multiplier chain, two sections of which are shown in Fig. 19, has undergone extensive testing to determine AM

Fig. 19. Experimental vacuum tube multiplier chain. Top: 6.283 to 100.625 MHz doubler stages. Bottom: 201.25 to 402.5 MHz doubler.

noise levels, phase stability, and mutual coherence between the two output frequencies (201.250 and 805.000 MHz). The procedures for and results of these tests are outlined below.

First, the reference generator must be capable of producing an accelerator cavity field which, in the absence of outside disturbances, remains within tolerance. Thus, the field tolerances must be interpreted from the viewpoint of the generator output, and in such a form that experimental verification of the stability is possible.

If a practical oscillator, oscillating at a constant mean frequency but containing random instantaneous phase or frequency fluctuations, is compared to a perfect oscillator at the mean frequency, the rms phase error in a period, τ , can be expressed¹ in the time domain as

$$\sigma_{\theta}(\tau) = \sqrt{E \left[\left\{ \dot{\theta}(t) \otimes p_{\tau} \left(t + \frac{\tau}{2} \right) \right\}^2 \right]}, \quad (1)$$

where $E[]$ denotes the "statistical average", $\dot{\theta}(t)$ is the instantaneous frequency fluctuation of the imperfect oscillator, and $\otimes$ indicates the convolution of $\dot{\theta}(t)$ with a rectangular pulse, $p_{\tau}(t)$ from $-\tau/2 \leq t \leq \tau/2$.

By using Fourier transforms, the right side of Eq. (1) can be expressed in the frequency domain as

$$\sigma_{\theta}(\tau) = \tau \sqrt{\frac{1}{2\pi} \int_{-\infty}^{\infty} S_{\dot{\theta}}(\omega) \left(\frac{\sin \omega\tau/2}{\omega\tau/2} \right)^2 d\omega}, \quad (2)$$

where the mean-square spectral density, $S_{\dot{\theta}}(\omega)$, of the instantaneous frequency fluctuations is weighted by the filtering effect of the time interval, τ , over which the instabilities have accumulated their effect. $S_{\theta}(\omega)$, the mean-square spectral density of the instantaneous phase fluctuations, is related to $S_{\dot{\theta}}(\omega)$ by $S_{\theta}(\omega) = \omega^2 S_{\dot{\theta}}(\omega)$. Equation (2) is important because $S_{\dot{\theta}}(\omega)$ and $S_{\theta}(\omega)$ are functions which can be readily measured.

The smoothing effect of a filter on Eq. (2) is as follows, where $H(j\omega)$ characterizes the filter:

$$\sigma_{\theta}(\tau) = \sqrt{\frac{1}{\pi} \int_{-\infty}^{\infty} S_{\theta}(\omega) (1 - \cos \omega\tau) \left| H(j\omega) \right|^2 d\omega}. \quad (3)$$

If the accelerator structure is treated as a singly resonant cavity, its filter function can be written

$$H(j\Delta\omega) \approx \frac{1}{1 + j\Delta\omega/\Delta\omega_{1/2}}, \quad (4)$$

where $\Delta\omega$ is a small frequency shift from the cavity resonant frequency and $\Delta\omega_{1/2}$ is the half-power off-resonance frequency.

If $S_{\theta}(\Delta\omega)$ is constant, Eq. (3) can be solved in terms of the specification on the accelerator field to determine the maximum $S_{\theta}(\omega)$ permis-

Fig. 20. Schematic for measurement of spectral density, $S_{\theta}(w)$.

sible in the reference source for measuring times in the range of interest. Then

$$\sqrt{S_{\theta \max}} = \frac{\sigma_{\theta}^2(\tau)}{\Delta w_{\frac{1}{2}} (1 - e^{-\Delta w_{\frac{1}{2}} \tau})} \quad (5)$$

and

$$S_{\theta \max} = \left[\frac{(0.667)^2}{4 \times 10^4 (1 - e^{-8\pi \times 10^4 \tau})} = \frac{(\text{deg})^2}{\text{cps}} \right]^{\frac{1}{2}}, \quad (6)$$

$$\approx 3.34 \times 10^{-3} \frac{\text{deg}}{\sqrt{\text{cps}}} \quad \left| \tau > 10^{-5} \text{ sec} \right.$$

for a cavity with a loaded $Q = 10,000$ at 805 MHz, and limiting $\sigma_{\theta}(\tau)$ to $\pm 2/3^\circ$.

The phase spectral density, $S_{\theta}(w)$, at the desired frequency can be measured as shown in Fig. 20; this is done by driving identical multiplier chains with a common source, phase comparing the outputs, analyzing the spectral content of the result, and assigning the noise on an rms basis to each multiplier. The phase bridge output is given by

$$\frac{E_{\theta}(t)}{\theta(t)} \approx \frac{Gk(2E^2)^{n/2} n}{57.3} = \xi \frac{\text{volts}}{\text{deg}}, \quad (7)$$

where G is the comparator gain and k and n are the detector efficiency and detection law, respectively. By treating the analyzer filter as singly resonant with bandwidth $= \Delta f_{\frac{1}{2}}$ and the recorder time constant as τ_r , the spectral

density, $S_{\theta}(w)$, for each multiplier can be calculated from the recorded voltage, E_a , using Eq. (5), assuming a constant $S_{\theta}(w)$ over the analyzer bandwidth:

$$\sqrt{S_{\theta \max}} = \frac{E_a (\text{peak factor})}{\sqrt{2} \xi \sqrt{\Delta f_{\frac{1}{2}} (1 - e^{-\Delta w_{\frac{1}{2}} \tau})}} \frac{\text{deg}}{\sqrt{\text{cps}}}, \quad (8)$$

The peak factor weights the statistics of the phase noise against the analyzer meter, which is calibrated to read the rms value of a pure sine wave. This factor is ~ 1.13 for gaussian noise in the analyzer band. In most cases, τ_r is long and the exponential can be ignored. The $\sqrt{2}$ assigns half the noise power to each chain.

The factor ξ can be determined directly using the manual phase shifter. The hybrid ring phase bridge provides inherent discrimination against AM on the multiplier outputs (usually very small) and provides self-error evaluation when one signal is split between both inputs.

Measurements of the tube multipliers operating on batteries demonstrated AM levels of > 110 dB below the carrier at 60 Hz from the carrier, and > 120 dB between 100 Hz and 1.5 MHz from the carrier.

A measurement of $S_{\theta}(w)$ at 805 MHz is given in Fig. 21 for the tube multipliers using dc supplies operating from the ac line and driven with a simple, relatively unstable, crystal oscillator. The specification of Eq. (6) is met down to ~ 500 Hz and then levels off. A large part of the noise near the carrier is due to the crystal oscillator and power supply ripple; a source such as the Hewlett-Packard Model 107B and the refined construction techniques of a final design should result in a 1-W source that far exceeds the stability required by Eq. (6). Such a cushion will ease the problem of amplification and distribution of the reference along the machine.

Fig. 21. Phase fluctuation spectral density, $S_{\phi}(\omega)$, of 805-MHz output of an experimental reference source using a vacuum tube multiplier chain. $\xi = 0.0365$ V/deg. Upper trace taken with Hewlett-Packard 302A analyzer, $\Delta f_{a1} = 3.5$ Hz. Lower trace taken with Hewlett-Packard 310A analyzer, $\Delta f_{a2} = 108$ Hz. Background from measurement system with phase bridge inputs shorted or autocorrelating input from one multiplier was less than $10 \mu\text{V}$, or 2×10^{-5} deg/ $\sqrt{\text{cps}}$.

The 805-MHz output of the multiplier chain is derived from the 201.25-MHz stage; thus, the stability at 201.25 MHz is at least as good as that demonstrated in Fig. 21. At the frequency transition in the linac, the mutual coherence between these harmonically related frequencies is of utmost importance. Mutual coherence can be measured in the same manner as shown by Fig. 20 and Eq. (8), except with the hybrid ring replaced by a matched, resistive tee to which the 201.25-MHz output and an attenuated 805-MHz output are applied. The resulting mixture is split in another tee and detected in the same manner. The ξ factor of Eq. (7) is found directly with a manual phase shifter in the 805-MHz input.

Preliminary measurements with the tube multiplier chains indicate that the spectral density of phase fluctuations from mutual coherency of the 201.25 and 805-MHz outputs is $< 10^{-3}$ deg/ $\sqrt{\text{cps}}$ from 250 Hz to 1.5 MHz away from the carrier.

Since the completion of the foregoing tests, the tube multiplier has been on a life test. Both chains now have accumulated ~ 4000 h of operation with no failures or detectable change in quality of signals.

Amplitude Control

Three complete amplitude and phase control units are being constructed for use with the Amplitron, klystron, and 7835 test stands. Some circuit design has been done on interface amplifiers for the output of the phase control units.

The amplitude control units and power supplies are complete. A new gate circuit which switches the dc voltage to the integrator is simpler than the diode gate formerly used, and operates successfully. Photographs of the klystron units are shown in Figs. 22 and 23. Preliminary closed-loop experiments with hard-tube modulator control of the high-voltage dc have been performed on the 7835 and on the 100-kW and 1.25-MW Amplitrons. Series integrator compensation was provided, resulting in ~ 50 -kHz correction bandwidths. Both the light-pipe and 5-MHz rf high-voltage interface units were used; rf output and pulse current were employed as the controlled functions. In each case, good control was obtained over the dynamic range of the equipment. Subsequent experiments will investigate faster loops and system performance in more detail.

All circuitry is housed in standard Nuclear Instrument Modules. Wherever more than one circuit card is installed in a single module, a special hinging arrangement allows easy access to all cards. All coaxial inputs and outputs are floating from the chassis to reduce ground currents.

Fig. 22. Klystron amplitude/phase-control bin.

Fig. 23. Klystron amplitude - control module.

Components

The characteristics of several types of commercial mechanically and electrically actuated phase shifters at 201.25 and 805 MHz were investigated in detail. Tests on a production run of twelve 805-MHz phase bridges showed that, with careful assembly, good reproducibility was obtained, but that the null frequency of the

entire group differed slightly from earlier models. This is apparently due to slight systematic differences in the printed circuit boards used for the center conductors.

805-MHz Power Amplifiers

Coaxitron Program

The present Coaxitron was used to power Models L and K. The total running time was small; this was due, in part, to the lack of 8618 modulator tubes.

The 15191B Coaxitrons have experienced severe difficulty with window sparking; this has prevented any extensive power runs at RCA.

Amplitron Program

Operation: The first 805-MHz, 1.25-MW Amplitron arrived at Los Alamos late in this report period. No substantial amount of running time has been achieved but preliminary observations of the tube's behavior indicate the following: (1) Power gain is in excess of 11 dB. (2) Power output is possible at the 1-MW level and 6% DF. (3) The output spectrum appears reasonably clean. (4) The efficiency is ~ 50%. (This somewhat low value is apparently due to magnetic field imperfections.) (5) Further shaping of the magnetic field should be undertaken for optimum overall performance. (6) The tube had not been run at high peak powers at Raytheon, yet it required very little processing to operate at the high power levels. These results are quite encouraging.

Substantial difficulties were experienced with the Amplitron test stand during these preliminary tests. These difficulties apparently stem from rf leakage from the cathode of the Amplitron and circuitry problems in the interim 4CX100,000D modulator. Satisfactory solutions have been found in most cases.

Crossed-Field Theoretical Program: As stated in the preceding progress report, an analog computer investigation was started using single-electron equations of motion to study the

performance of a crossed-field microwave tube operating in the cyclotron regime. This work has been completed and has produced some interesting results. It has been shown, for example, that, given a reasonably ideal situation, electron bunching can be achieved based on the cycloidal motions. These motions occur in the trajectories of electrons that have passed through a very narrow gap across which is applied a high-frequency voltage. It has also been shown that the energy spread within this bunch is narrow regardless of where in the crossed-field device the bunch is detected. This point is illustrated by Fig. 24 which shows a plot of angular position (θ) vs time for 120 particles which enter the rf field of the input gap evenly spaced in time. The particles are all moving at synchronous angular velocity (circular orbits) at the time they encounter the input gap. For the orbital energy represented by these synchronous particles, their equivalent voltage is 711 V. The particle, depending on when it arrives, receives a variable accelerating or decelerating impulse by the rf field and the resulting motion is plotted.

Figure 24 is a nonlinear Applegate diagram (in cylindrical coordinates) and is the corollary of the linear diagram used to describe bunching in the klystron. However, unlike the klystron with a correspondingly low-intensity beam, the electron trajectories do not cross each other. The additional energy imparted at the input gap appears as a cycloidal motion of the particles superimposed on their synchronous velocity. Like the klystron, bunching of the electron tends to center on the synchronous particle (which passes the input gap while the rf voltage is passing through zero); but instead of occurring at one point, the bunch follows this particle over a long, angular range beyond the input gap.

The significance of this result is more clearly seen when the kinetic energy of the electrons is plotted against rf phase angle as in

Fig. 25. The kinetic energy plotted is

$$T = \frac{1}{2} m (\dot{r}^2 + r^2 \dot{\theta}^2). \quad (9)$$

The rf phase angle is measured relative to a synchronous particle which passed the input gap when the applied voltage was zero and increasing, and, after drifting between gaps, was picked up at the output gap. The arrival of this particle at the output gap is shown as zero rf phase angle in Fig. 25, where Eq. (9) is plotted for three different angular positions of the output gap relative to the input gap. These positions are shown in Fig. 24 and were selected as points where bunching of the particles seems particularly effective. The slope of the angular displacement traces across one rf cycle in Fig. 24 corresponds roughly with the double-humped energy traces of Fig. 25. This is because most of the kinetic energy is azimuthal rather than radial, i. e., the $r^2 \dot{\theta}^2$ term in Eq. (9) predominates. It is also seen in Fig. 25 that, in all cases, the kinetic energy is relatively constant throughout the bunch and is approximately equal to the synchronous particle energy. For comparison, a representative plot of kinetic energy in a klystron is shown in Fig. 26. It is apparent that the energy spread is much larger in this case. The significance here is that all the energy in the crossed-field bunch could be extracted at the output gap such that most of the bunch particles are stopped by exciting the output cavity. This could not be done in the klystron because many particles would be turned back down the drift tube with disastrous results. It appears that the bunch energy can be used very effectively in such an idealized crossed-field application as described here.

The current and power of the beam were estimated. The number of particles swirling around the cathode at a rate of 120 per rf cycle is only $\sim 1.7 \times 10^{11}$ /sec whereas calculations for a typical crossed-field tube indicate that a current density in the electron sheath of 30 A/cm² is more realistic. Thus, the power calculations are for very low current tubes. In Fig. 27 is a plot of current vs rf phase angle made at a hypothetical output gap as the bunch swings by.

Fig. 24. Applegate diagram in cylindrical coordinates for crossed-field amplifier.

Fig. 26. Applegate diagram and energy distribution of electrons in klystron.

Fig. 25. Kinetic energy of electrons in cylindrical coordinates.

Fig. 27. Bunched current as seen at output gap.

One bunch will pass per cycle of input gap rf. A harmonic analysis of these current spikes yields the following:

$$F = 1.35 \text{ GHz}; i(t) = 49 \times 10^{-9} - 23.6 \times 10^{-9} \cos t \dots, A$$

$$F = 2.78 \text{ GHz}; i(t) = 56.7 \times 10^{-9} - 42.9 \times 10^{-9} \cos t \dots, A,$$

where only the dc and fundamental terms are given since it is assumed that the output cavity is excited into resonance by the fundamental only.

If the electron bunch is stopped at the output gap, this corresponds to an extracted energy of $11.4 \times 10^{-17} \text{ kg-m}^2/\text{sec}^2$ per electron or a voltage of 711 V. The power content of the beam thus becomes:

$$F = 1.39 \text{ GHz}; P_{\text{DC}} = 34.8 \mu\text{W}$$

$$P_{\text{FUND}} = 11.9 \mu\text{W}$$

$$F = 2.78 \text{ GHz}; P_{\text{DC}} = 40.3 \mu\text{W}$$

$$P_{\text{FUND}} = 21.6 \mu\text{W}.$$

Thus, the power developed by this cyclotron regime-type operation can be reasonably high (e.g., $\sim 1 \text{ kW}$) when a realistic amount of charge is present. Actually, however, space-charge forces at these higher current densities prevent this power from being developed as indicated by experimental findings published for cyclotron-type crossed-field tubes used to generate sub-millimeter wavelengths. By using the figures given above, an estimate of electronic efficiency can be made on the following basis:

$$\eta_e = \frac{P_{\text{FUND}}}{P_{\text{DC}}}.$$

For $F = 1.39 \text{ GHz}$, $\eta_e = 34.2\%$; for $F = 2.78 \text{ GHz}$, $\eta_e = 53.6\%$. As expected, the higher the operating frequency (for a given set of the other parameters), the better the efficiency, since the bunching becomes tighter about the synchronous particle.

Klystron Program

100-kW Klystrons: The 100-kW klystron normally employed as the Coaxitron driver has been used to power Model M for processing and electron acceleration.

The 100-kW klystron in the Amplitron test stand has been used as the driver for the 1-MW Amplitron.

Procurement of parts for the construction of another 100-kW klystron is in progress. This amplifier will be used to drive the EPA buncher section. The amplifier is scheduled for completion in August.

1.25-MW Klystron Test Stand: The entire test stand is complete, except for mounting the klystron socket, and has been tested to 85 kV at low power.

1.25-MW Klystron Procurement: The first 1.25-MW tube has been completed. A series of tests were conducted at Litton's San Carlos plant starting about March 27. Results were disappointing in that the maximum power output obtainable was $\sim 500 \text{ kW}$ and beam efficiency was very low, $\sim 14\%$. Power gain was excessively high and the tube seemed to be oscillating. A series of diagnostic tests was conducted through April 19. These tests show: (1) The output cavity is not properly matched to the output waveguide. (2) The input coupling is badly mismatched. (3) There is beam interception in the region of the second cavity. (4) Beam focusing seems improper in the gun region.

Litton plans to rebuild the tube, making the following changes: (1) Replace the output cavity and window assembly. (2) Correct the mismatch to the input cavity. (3) Add a magnetic pole piece near the modulating anode. In addition, Litton is redesigning the tube socket which failed on test.

Theoretical Program: Application of the LALA computer program to the cavities used by Litton for their 1.25-MW, 805-MHz klystron has been successfully completed. By starting with the analytic solution for a right circular cylinder, the final cavity shape, as specified by Litton, was reached through a series of 19 separate

Fig. 28. Electric field computed by LALA for Litton's 1.25-MW, 805-MHz klystron cavities.

computer runs. Each run changed the dimensions by a small amount and used the previous run as input data. The final configuration and electric-field distribution is shown in Fig. 28. In Fig. 29 is a plot of the variation of resonant frequency, ZT^2 , and Q as the program converged on the final shape. The final frequency is somewhat under 800 MHz. The ZT^2 is just over half of that of the linac cavities. This low value is attributed to the klystron cavities not being shaped for maximum shunt impedance.

201.25-MHz Power Amplifier Program

Intermediate Power Amplifier (IPA)

The IPA is currently being used to power the 4-ft Alvarez model as well as to provide the drive for the 3-MW main amplifier (7835).

3-MW Final Power Amplifier

The 3-MW, 201.25-MHz main amplifier (7835) has been operated at a 6% DF with peak output powers in excess of 3 MW, a power gain of ~ 14 dB and a dc-to-rf conversion efficiency somewhat in excess of 60%. Although the performance of the amplifier would appear to be

Fig. 29. Convergence from initial circular cylinder to the final klystron cavity shape.

satisfactory, the accumulated operating time at full power is too limited to permit a meaningful assessment. The evaluation program has been and continues to be plagued with switch-tube problems. The modulator was originally constructed with parallel Machlett 8618's. These, however, exhibited a strong tendency to long-pulse, presumably due to secondary emission. Pending a solution of this problem by Machlett, parallel tetrodes (EIMAC 4CW100,000D) were installed as an expedient. These, in turn, proved to be difficult to control over the wide operational range demanded by the evaluation program. Two usable 8618s were recently received and installed. These occasionally long-pulse, but operation is possible.

Floating Deck Modulator Development

Tube Choice

It has become apparent that it will be desirable to have rf sources that can operate with an arbitrary time sequence of accelerator beam loading. This requirement has little influence on the rf sources themselves, but it does have considerable effect on the design of modulators, since for a given power supply level, the modula-

tor anode must absorb the excess power not needed for beam loading during that pulse. The amount of excess power depends on the dynamic impedance characteristic of the rf amplifier; in particular, it will be necessary to increase greatly the power capability of the 7835 modulator.

The modulator requirements for the 200-MHz, 7835 amplifier and the 805-MHz Amplitron/Coaxitron amplifier are quite different as can be seen from Table 3; consequently, it has been decided to develop two entirely different modulators.

Table 3.
Modulator Characteristics

	<u>7835</u>	<u>Amplitron</u>	<u>Coaxitron</u>
Peak output voltage, kV	30	50	45
Peak output current, A	220	40	80
Average anode dissipation, kW	350	50	120
Bandwidth, MHz	0.075	1	1

Two different types of switch tubes will be evaluated for the 7835 modulator--a pair of Machlett ML-7482PVs and a pair of EIMAC 4CW250,000Vs. The ML-7482PV is a conventional triode and the 4CW250,000V is a tetrode. It will be necessary to use two tubes in parallel for the 7835 modulators. At the present time, the tetrode appears to have some advantages over the triode, but testing will have to be done before a decision is made as to which tube will be used. These modulators are in the design stage.

For the Amplitron/Coaxitron modulators, two other tubes are being tested--the Machlett 8618 and the EIMAC 4CW100,000D. The 8618 is a magnetically focused triode and the 4CW100,000D is a tetrode.

The tetrode modulator appears to have several advantages over the triode models. Because of the much higher power gain of the tetrode, it seems feasible to eliminate the dc amplifier on the modulator deck and drive directly

from ground. The tetrode has the additional advantage of being essentially a constant-current device. If the output of the modulator is shorted, the load current will increase only 10%.

The decision as to which tube will be used must wait until the work on the tetrode modulator has been completed and Machlett has time to eliminate the faults in the 8618.

Modulator Testing

At the present time, there are three modulators on hand, using a total of four 8618s. There are now two 8618s at LASL of which one is unstable above 30 kV. Eight tubes, including a replacement for the defective tube now in use, are due for delivery. Beginning with the last tube delivered, Machlett has made substantial changes in the tube design with the aim of curing the voltage instability and filament breakage problems. It remains to be seen if all the tubes of the new design are satisfactory.

There are no plans for building another modulator for the 8618s until it is determined that the tubes will perform satisfactorily.

The new tetrode modulator is being designed specifically for use on the Amplitron; it can, however, also be used for a Coaxitron. One version of this new modulator is partially constructed. One 4CW100,000D has been installed in the old Amplitron modulator in the Mockup Building; so far, at voltages up to 52 kV, this tube has performed quite well.

Interface Crossing

Three interface schemes have been investigated and the rf link and the pulse transformer have been selected for further investigation. The light-pipe crossing scheme is being put aside for now since its speed is greater than needed and it requires a considerably more complicated high-voltage deck on the modulator.

A 30-MHz, 2-kW peak, rf interface unit is being constructed and will be used on a tetrode modulator. The output power is such that no amplifiers will be required on the modulator deck; only a rectifier and filter will be needed to drive the grid of the switch tube.

A large pulse transformer capable of 5-kV output has been constructed and tested. The frequency response is -3dB at 25 kHz, which is too low for the present modulators.

Reference

1. E. J. Baghdady, R. N. Lincoln, and B. D. Nelin, "Short-Term Frequency Stability: Characterization, Theory, and Measurement," IEEE-NASA Symposium on Short-Term Frequency Stability, NASA-SP-80, Nov., 1964.

IV. ACCELERATOR CONTROL AND INSTRUMENTATION

Introduction

The design, construction, and testing of various devices and systems for the Mockup Program were continued this quarter toward the twin goals of evaluating the control system design concepts and developing a prototype control system. Delivery, installation, and acceptance-testing of the entire Systems Engineering Laboratories SEL-810A computer system were completed. Although some difficulties have been experienced with various parts of the computer system, satisfactory progress has been made toward developing programs and checking the computer interface equipment. Many of the systems programs for operating the computer and its peripheral units are in semifinal form and numerous other systems and application programs are in various stages of development.

Approximately half of the computer time this quarter has been used to assist in the checkout of control system interface units. The initial dynamic checkout of the Computer Interface Unit

(CIU) and the Driver-Terminator (D/T) chassis indicated severe problems with cross-talk, ground loops, and signal reflections on the lines which did not show up in static tests. Elimination of these problems required the complete rewiring of all interchassis connections in the control room and redesign of the D/T chassis. This has been accomplished and the system now appears to perform satisfactorily. Checkout of the CIU is nearing completion and the next step will be to integrate it with the interface equipment at the module. The prototype equipment for the control console has been installed and checkout is proceeding. The lessons being learned from these activities will be of benefit in designing the final control system.

Implementation of the remote computer control of the Amplatron test stand has progressed whenever the stand was not in use. The Remote Information and Control Equipment (RICE) has been installed and partially checked by taking binary data. Connection of the various data and command channels to the Module Interface Unit (MIU) in the test stand is well along. This work will be completed as the Amplatron test program permits and the test stand will then be tied into the computer system.

Design and development of special instrumentation and control packages have been continued. An inexpensive electronic temperature control system was developed which controls accelerating cavity water temperature to 0.1°F and gives a reading of the temperature. It has yet to be tested under rf power conditions.

Detailed systems design work for the control and instrumentation of the Electron Prototype Accelerator (EPA) was started this quarter. Drawings were prepared for the installation of racks, wireways, and junction boxes, and for the power distribution within the accelerator enclosure. Panel layouts and control circuit designs were started and wire and cable requirements are being defined. A major effort

will be required during next quarter to develop the computer control system for EPA.

Work on various radiation monitoring and safety systems has been continued. Both the Model L accelerator and the Alvarez mockup have required a considerable amount of work in this area. The basic requirements have been established for the radiation monitoring and safety system for the EPA and instruments have been ordered.

To assist the Injector Ion Source program, a design study was completed of a system for automating the measurement of beam emittance and the presentation of the data on the digital display scope in the control room.

Data Acquisition and Control System

Control Computer

The delivery of the SEL-810A computer for the Mockup Facility was completed when the disk and display scope passed their respective acceptance tests. The disk was accepted Feb. 3 after a 14-h test during which the disk was exercised at its maximum rate. A total of 10^9 bits were transmitted without error; this is at least 100 times better than required for the present application. The display scope was accepted Mar. 23 after correction of three design faults detected by LASL acceptance test programs.

Since installation, the computer has required a level of maintenance which is higher than hoped for but not inconsistent with that to be expected from a complicated new piece of equipment. Five LASL engineers and technicians took an intensive one-week maintenance course for the SEL-810A, conducted by an SEL instructor. Since then, LASL personnel have performed the maintenance, except for one occasion when an SEL engineer was called. The number and severity of malfunctions is now decreasing and this is thought to indicate an end to the shakedown period and the start of relatively trouble-free operation.

Programming

About half the available computer time has been dedicated to checking out LASL-built interface equipment, mainly the CIU. Numerous short programs have been written to aid in this work, including one which allows a technician to select with a light pen one of several programs to exercise the CIU during troubleshooting operations.

The remainder of the computer time has been invested in developing programs. Exec, Disk-Driver, and Initializer are in their final form in the sense that they contain no known errors and no significant changes are anticipated in the near future. The Type-In, Type-Out, and Print programs which operate in conjunction with Exec have been debugged. The Scope Driver is being merged with Exec for a final test. The logic of the CIU Driver has been debugged and awaits installation of priority interrupt lines for the final timing tests. The Data Scan program has been debugged as far as possible in the absence of the CIU. All the programs required to service the operator's console, except for the line-by-line display program, have been written and await the availability of the console for checkout. The first draft of an interpretive program to process the instructions associated with turning on the Amplitron test stand has been completed.

The SEL software programs have been appreciably upgraded. Debug, Update, Assembler, and Loader are now available from disk. The second pass of the symbolic program for Assembler now comes from the disk. These innovations have markedly reduced the handling required for paper tapes. The Update program has been revised to eliminate deficiencies. Assembler and Update are being modified to run under Exec so that new programs can be developed on-line.

A Vary program, which will enable the accelerator operator to perform parametric studies on-line, has been started. That portion

which draws grid lines and labels scales has been debugged. The remainder of the work involves interfacing this package to the type-writer, CIU, and display scope programs.

Driver-Terminator

The D/T chassis serves to interface approximately 65 signals between the computer and various LASL-built devices. It also conditions signals between the CIU and the various RICE units. A dynamic checkout of the original chassis showed severe cross-talk problems resulting from the use of common ground returns and ribbon wiring. In addition, the driver-terminator circuits did not respond as fast as required. These results forced a complete redesign of the D/T chassis to utilize terminated coaxial signal lines and faster circuits. The redesigned chassis was built, installed, and dynamically tested; it now appears to perform satisfactorily.

D/T-CIU Power Supply Chassis

Fabrication and checkout of the D/T-CIU power supply chassis was completed. This chassis contains a 3.6-V, 10-A power supply and a special indicator lamp supply (55 V dc and 1 V ac) for the CIU chassis, plus a 3.6-V, 3-A power supply for the D/T chassis.

Prototype Computer Interface Unit

Static checkout of the CIU using the computer simulator was completed. Status indicator lamps were added to the unit and the chassis was installed in the CCR. When the D/T chassis became available, dynamic testing of the CIU with the computer was initiated and it now appears that the CIU is performing properly. More specifically, all computer instructions to the CIU are correctly decoded by that unit and the required information is reformatted and transmitted to the selected RICE along with appropriate timing signals.

In the case of Data Take (DTK) instructions, the DTK Delay and Aperture signals are correctly generated and transmitted, and simulated data from the RICE are loaded into the CIU memory. These data can then be transferred to the computer memory via the block transfer channel (BTC). In this procedure, parity of the data in the CIU memory is checked and, if incorrect, an error indication is generated to alert the computer. For Command (CMD) instructions the Command Busy Buffer (CBB) in the CIU transmits correct status information to the computer upon request and generates a priority interrupt when the simulated unit becomes free. Finally, the Cycle Counting Clock (CCC) increments correctly and responds to computer inquiries by transferring its contents to the computer. The CCC is used to count the computer cycles which have elapsed since the start of the last accelerator pulse.

The CIU will now be tested in tandem with the RICE under control of the CIU Driver program.

Prototype Remote Information and Control Equipment

The prototype RICE was connected to its associated input/output chassis and bench-tested with simulated CIU commands and control signals. All binary and analog data and command channels were exercised using simulated data sources and sinks. After bench-testing, these chassis were installed in the Amplitron test stand and the power and interconnecting wiring was done.

In order to investigate potential noise problems, the RICE was turned on and left statically in its most noise-susceptible condition while the 100-kW Amplitron was run through its noisiest operating region. The rf noise did not appear to cause interference in the RICE logic. However, it was discovered that spurious line noise caused by contactors, etc., could trigger the RICE logic; this defect is being corrected.

Module Interface Unit

Wiring to Burndy terminals in the Amplitron test stand is complete for Binary Commands, Binary Latches, and Binary Data. Wiring for Pulse Commands is complete for stepping motors but not for limit switches or potentiometers. Wiring to RICE I/O is complete except for Binary Commands.

Injector System

Light Link

A transmitter-receiver was completed and checked out for use in the ion source experiment. A breadboard linear version was built and some preliminary tests run on it. The results indicate good linearity and range. More detailed tests are planned as soon as time will permit.

Further work on the ion source test stand control and the injector control system design has been delayed due to the work load in other areas.

RF Module Control

201.25-MHz Modules

Installation of the cable tray system for the 201.25-MHz test stand has been completed.

An intercom system has been installed to permit communications between the test stand and various building entry points. This system is used to control access of personnel to the area during operations which generate a high level of radiation.

805-MHz Modules

Modifications preparing the Amplitron test stand for either local or computer control are about 90% complete. Modifications to several control panels and systems have been completed with some minor changes still to be made to meet changed criteria. Channel listings and wiring schedules have been completed for all

channels within the module for wiring to the MIU. Installation of interrack wiring is essentially done and checkout of the RICE unit is in progress.

The high-voltage power supply has been modified to allow operation of the Amplitron test stand or the klystron test stand. Changes to the high-voltage supply for computer control will be implemented as shutdown time allows.

Accelerator Module Control

Temperature Monitoring and Control

Thermistors have been ordered for use in magnet high-temperature alarm systems. These thermistors are made from polycrystalline barium titanate which has quite low specific resistance. However, when this material is heated to its Curie point, its resistance increases by several orders of magnitude over a range of a few °C. By choosing Positive Temperature Coefficient thermistors with a proper Curie point, simple but reliable high-temperature alarms can be made which consist only of a thermistor, a normally operated relay, and a power source.

Two electronic water-temperature control systems have been completed and installed: one for Model K and one for the 4-ft Alvarez tank. Studies are under way to determine optimum system parameters for controlling tank temperature by sensing cooling water temperature, tank temperature, and relative rf phase.

Auxiliary Operational Support Systems

Control of the turn-on and turn-off of the rf modules and injector is performed by a timing system called the "master pulser." A prototype unit has been operational for some time with a manual control unit in the Mockup. Presently, the system is being integrated into the computer which will then have the capability of modifying the pulse parameters.

The fast shutdown and rf permissive systems will be made in prototype form for the

Mockup. The final design for the prototype is awaiting the checkout of the RICE-CIU system. This will verify the design of the transmission system which will also be used on the shutdown and rf permissive systems.

Operational Support Systems

Communications

The distributed areas and the distances involved between the CCR and the EPL require small changes in the communications system. New arrangements of the system of interphone channels are being considered, particularly in regard to the guard channel, to avoid overloading the circuits. For public address, it is planned to distribute a larger number of speakers throughout the area to avoid regions of high-intensity sound.

Radiation Safety Systems

Model L: Duplicate cables for all ion-chamber readout systems were made so that the systems could be calibrated on the ^{60}Co radiation range with duplicate lengths of cable between ion-chamber and readout systems. Following calibration, Model L operation was monitored with radiation levels as high as several 1000 R near the spectrometer. Leakage current, caused by ionization within the cables, was found to be negligible. Although these cables passed directly over the rf power systems, no interference was encountered.

Alvarez Mockup: Radiation monitoring near the Alvarez mockup has proved a useful guide in determining when resonance is reached. That this would be true is evident from the relation $x \propto E^{1/2}$, where x is the x-ray emission level and E , the rf field within the tank. Normal rf techniques measure E ; hence, a large gain in sensitivity to resonance is obtained. The x-ray emission is undesirable for high duty factor operation and will be reduced if possible. Tank cleanup decreased the emission slightly.

An understanding of the physics and physical extent of the no-beam x-ray emission might indicate ways to reduce the emission further. Therefore, measurements were made on the x-rays from the short Alvarez tank. A γ -ray spectrometer was used to determine the x-ray spectrum. The flux rate was not sufficiently low for reasonable dead-time loss until the scintillator was placed 50 ft from the Alvarez tank. Extensive experiments with lead apertures backed by brass were carried out to yield a satisfactory reduction of the Compton scatter peak. A measure of the time dependence of the x-ray spectra was obtained by gating the pulse-height analyzer so that it observed scintillator pulses for 100- μ sec intervals at differing times throughout the pulse of rf.

It was expected that during the cavity fill time the x rays would be lower in energy, but no change was observed. The spectra did, however, shift as expected with rf power level. The observed very strong dependence of the x-ray emission on the cavity rf field far exceeds theoretical predictions relating particle energy and target material. An analytic effort was made to include a field-dependent variation of the emitting area. Computer runs of the resulting formulation gave results which do not fit experimental data as well as an assumed constant emitting area.

Observation of the inside of the Alvarez tank after operation showed discolored areas at several spots on the walls and on one drift tube face only. The cause of these discolored areas is not known, but if it were due either to emission or to ion bombardment, the x-ray source may not be confined to the drift tube faces. A γ -ray pinhole camera is under construction to determine the extent of the x-ray source.

Electron Prototype Accelerator: A radiation monitoring system for the EPA and EPL has been planned. The selection of sensors is based on calculated values of "worst case" radiation

fields along the accelerator structure. A multi-channel remote-monitoring system has been ordered for evaluation.

An analysis was made of radioactive and noxious gas generation. The results dictated a small revision in the ventilation plans and a requirement for delay before reentry after operation.

TV Systems

Demonstrations were held of several kinds of closed-circuit TV systems. These led to the tentative conclusion that a high-resolution system would be most useful. Potential applications of TV systems are being reviewed to guide a decision as to choice of system. A beam profile monitor and analysis system is described in some detail below under "Miscellaneous."

Video Control Unit (VCU)

The module VCU wiring was completed and chassis checkout done. Video buffer amplifiers were installed and checked out.

Coaxial cables were installed between the CCR and Amplitron test stand VCU for routing the video signals.

Centralized Control

Injector Control

The equipment used for remote operation of the Model L electron gun through the light links has been functioning satisfactorily. Most problems have been traced to errors resulting from system modifications. The present control system for the Model L electron source is operated manually from the Mockup control room. This source will also be used with the EPA. Preliminary design of the unit which will permit computer control of the source has been completed and most of the parts and hardware procured.

Central Control

The drawings for the Central Control Building were reviewed and a revised layout of the central control and computer rooms completed. As a result, it was suggested that the rooms be enlarged by moving one wall out ~ 3 ft. This will permit better access to the racks and allow extra rack space for installation of equipment associated with experiments or other functions not directly associated with accelerator control.

Mockup Control

Checkout of the CIU uncovered several cross-talk, noise, signal level, and termination problems associated with the wiring and termination scheme used for the CIU, console panels, and computer.

A series of experiments was conducted on single-wire, twisted-pair (shielded and unshielded), and coax cables. Of particular interest were the cross-talk and termination effects on the transmission of high-speed pulses. The results of these experiments and a review of available literature on the subject indicated that a marginal system design had been used. The rack and unit wirings were revised and the new system checked out with much better results.

Checkout of the control console has been started. Basic operation of the status and VF panel is satisfactory; however, there are some cross-talk and noise problems to be solved.

Operator-Machine Interface

Checkout of the console is providing some data on the operator-machine interface. The use of thumb-wheel switches to set data into the system requires too much time and too many motions by the operator. The small triode indicator lights on the status panel have a restricted viewing angle, due to a mounting problem, and limited intensity which make them hard to read under average ambient light conditions. Further design studies are necessary in this area.

Fig. 30. Beam emittance data system.

Miscellaneous

Electron Prototype Accelerator Installation

Construction of the building and installation of EPA facilities are in progress. Installation has been started of electrical duct work and power shielding structure. Power wiring to this structure has not yet been completed. Secondary switch gear and breaker panels for power distribution, transformers, accelerator lighting, and numerous miscellaneous equipment are on order.

Eight control racks are due for delivery at the end of May. Design of the power distribution and rack power wiring is in progress. The rack equipment layouts are approximately 80% complete. A key interlock system for the shielded enclosure entrance has been designed and ordered.

Wiring and terminations schedules of control rack-to-shielded enclosure junction boxes are presently being prepared.

A preliminary list of devices to be controlled and/or monitored has been completed. Detail design of EPA control chassis has been initiated.

Special Equipment

A preliminary design for a beam emittance data system employing closed circuit TV

Fig. 31. Image display and analysis system.

has been developed. The basic operation involves passage of the beam through a series of narrow slits, as shown in Fig. 30, to a scintillator plate (probably of quartz). The scintillation of this plate provides the intensity profile from which the beam emittance data may be obtained. The data are collected by viewing the scintillator plate with a TV camera. The video output will then contain the intensity profile. The signal from the TV camera is fed to an image display and analysis system, represented in Fig. 31. This system provides three readouts of the emittance information: (1) the emission of the scintillator as a series of lines on a TV monitor, (2) an intensity profile perpendicular to these lines, and (3) an emittance pattern or graph generated by the computer for display on the digital scope.

V. ACCELERATOR PHYSICS

Introduction

Minor changes in the design of the linac have been investigated. These include a "tilt" in the accelerating gradient in the first Alvarez tank, small changes in the focus magnet strengths, and a decrease in the radial aperture in the waveguide tanks between 100 and 200 MeV. The overall effect of these changes is to produce a somewhat smoother variation in the fields as seen by the particles, and to place the radial aperture stop for the waveguide linac at the 100-MeV point. The length of the accelerator is essentially unchanged, and the number of 805-MHz rf power stations reduced from 45 to 44.

The LASL-designed duoplasmatron ion source was placed in operation, and measurements of its characteristics have been started.

Alvarez Linac Design and Layout

Some changes have been made in the design of Alvarez tank No. 1. The accelerating gradient in the first tank now increases from 1.6 MV/m at the low-energy end to 2.4 MV/m at the high-energy end. The accelerating field has been "tilted" in this manner to produce a better match for the particle dynamics between tanks 1 and 2. As a result of this change, the tank length is reduced by 84 cm, the number of drift tubes is reduced by seven, and the required rf power is increased by 39 kW.

The magnetic gradients of the quadrupole focusing magnets located in the drift tubes have been increased by 20-50%, in order to reduce the effects of the coupling between the longitudinal and transverse oscillations. The size of the hole in the drift tubes in the low-energy end of the linac has been reduced, to facilitate increasing the quadrupole gradients.

The salient parameters of the Alvarez linac are given in Table 4 (page 36).

Particle Dynamics Studies

Injector Beam Transport

The PARMILA dynamics program, with its representation of the space-charge force, has been used to design a transport system to match the uniform, azimuthally-nonsymmetrical beam required by the quadrupole-focused linac. The system consists of a double-drift buncher and three quadrupole focusing magnets. The overall length of the system is 185 cm. The system begins with a 201.25-MHz buncher cavity which is excited to a peak voltage of 20 kV. The second element of the system is a 402.5-MHz buncher cavity located 30 cm from the first cavity and excited to a peak voltage of 12 kV.

The first and third quadrupole magnets of the quadrupole triplet are 10 cm long and are excited to a magnetic gradient of 337 G/cm. The center quadrupole is 20 cm long and is excited to a gradient of -282 G/cm. The quadrupole magnets are separated from each other by 10 cm, and the center of the quadrupole triplet is 105 cm from the first buncher cavity.

The beam entering the system is a uniform, azimuthally-symmetric, 20-mA beam of 0.75-MeV protons. The transverse coordinates of the beam are spread uniformly over a right-elliptical region of the transverse phase space with a maximum displacement of 0.7 cm and a maximum angular dispersion of 2 mrad, giving an emittance of 1.4π cm-mrad. The beam reaches its maximum radial extent of 1.4 cm in the quadrupole triplet, and is focused to a half-width of 0.28 and 0.33 cm in the horizontal and vertical planes respectively at the entrance to the linac.

The portion of the beam that arrives at the linac within the stable phase limits (about 75%) occupies a transverse emittance of 3.5π cm-mrad in both the horizontal and vertical planes. This apparent growth in the transverse emittance of the beam results from a warping of the transverse

Table 4.
ALVAREZ LINAC PARAMETERS

Cell No.	Tank 1	Tank 2		Tank 3	Tank 4
	1 to 31	32 to 59	60 to 99	100 to 137	138 to 168
Energy in (MeV)	0.75	5.03		41.16	72.33
Energy out (MeV)	5.03	41.16		72.33	100.00
Δ energy (MeV)	4.28	36.13		31.17	27.93
Tank length (cm)	312.8	2000.6		1870.8	1851.0
Tank diameter (cm)	94.0	90.0		88.0	88.0
D. T. diameter (cm)	18.0	16.0		16.0	16.0
D. T. corner radius (cm)	2.0	4.0		4.0	4.0
Bore radius (cm)	0.75	1.0	1.5	1.5	1.5
Bore corner radius (cm)	0.5	1.0		1.0	1.0
G/L	0.21-0.27	0.16-0.33		0.31-0.38	0.38-0.42
Number of cells	31	68		38	31
Number of quads	32	29	39	20	16
Quad gradient (kG/cm)	7.97-2.47	2.5-2.1	1.04-0.94	0.98-0.95	0.95-0.95
Quad length (cm)	2.58-7.69	7.69	15.60	15.60	15.60
E ₀ (MV/m)	1.60-2.40	2.40		2.40	2.40
ϕ_s (deg)	-26°	-26°		-26°	-26°
Power (MW)	0.325	2.848		2.825	2.836
Intertank space (cm)	15.36	85.46		110.69	--

Total length including intertank spaces = 62.46 m (204.9 ft).

phase space by the nonlinearity of space-charge force. The envelope of this beam will have a maximum radial displacement of 0.37 cm in the first Alvarez tank.

Waveguide Linac

In previous LINAC layouts, the radial aperture stop is at 200 MeV rather than 100 MeV. The effects of moving the radial stop to 100 MeV have recently been studied. In the last quarterly report computer results were presented showing how the effective shunt impedance (ZT^2) increases as the beam hole size decreases. Assuming a 1.0-in. beam hole diameter in the $\frac{1}{4}$ -MW driven tanks and a 1.5-in. diam in the $\frac{1}{2}$ -MW tanks, estimates were made of ZT^2 as a function of β . With these estimates, the computer program LINAC was used to design a waveguide linac. An energy gradient of 1.072 MEV/m was found to give a suitable design. The linac

consists of 28 $\frac{1}{4}$ -MW tanks and 72 $\frac{1}{2}$ -MW tanks. The number of power amplifiers required is 43, two less than the previous design.

The field gradients of the quad doublets between accelerating tanks are shown in Fig. 32. The gradient plotted at any tank number refers to the doublet located after the tank. The gradients of the doublets immediately before and after tank No. 29 were chosen to match the transverse emittance of tank No. 28 to the transverse admittance of tank No. 30. These differ because of the sudden increase in the tank lengths and in the beam hole size after tank No. 28.

The x-x' admittance and emittance ellipses are given in Fig. 33. Particles that enter the first tank of the waveguide linac with values of x and x' as shown on the top graph, and those with $y = y' = \Delta E = \Delta \phi = 0$, will leave the last tank with the x and x' values on the lower graph. Figure

Fig. 32. Gradients of quad doublets after each accelerating tank.

Fig. 33. x - x' admittance and emittance.

Fig. 34. x and x' of particles at exit of each tank.

Fig. 35. y - y' admittance and emittance.

Fig. 36. y and y' of particles at exit to each tank.

Fig. 37. $\Delta\phi$ and ΔE admittance and emittance.

Fig. 38. $\Delta\phi$ and ΔE of particles at exit of each tank.

34 indicates the x and x' values of these particles at the exit of each tank. Similar information for the y - y' and the $\Delta E - \Delta\phi$ motion is given in Figs. 35 through 38.

The transverse admittance of this linac, neglecting the effects of errors and coupling, is $\sim 2.5\pi$ mrad-cm. A linac with a 1.25-in. diam beam hole between 100 and 200 MeV is now being studied. It has 44 amplifiers, the same length, and an approximate transverse acceptance of 4.6π mrad-cm.

The question of the effect of quadrupole magnet aberrations on beam size in the waveguide portion of the linac is being investigated. The Stanford computer code TRANSPORT has been adapted so that calculations may be run of the beam transport through the waveguide linac. A preliminary first-order beam trace through the first 43 tanks (100-260 MeV) has been made. Second-order aberration calculations were carried out for the first three tanks; they indicate that chromatic aberrations cause an increase in beam size $< 0.5\%$, assuming a $\pm 0.3\%$ spread in beam momentum. Third-order quadrupole aberrations will now be considered.

Linac Tank Experiments

A facility similar to that at SLAC for testing beam-transport quadrupole magnets using harmonic field analysis is being planned. An old milling machine will be adapted as the test stand and a rotating coil system will be designed. Preliminary tests on one of the Alvarez quadrupole magnets will be carried out at SLAC in order to gain experience with this technique.

A pinhole camera device has been designed for diagnostic studies on the prototype Alvarez tank and will be used to try to determine the location of sources of γ -ray emission in the tank.

Injector Program

Cockcroft-Walton Model

A 750-kV Cockcroft-Walton high-voltage power supply has been ordered. It will be used in the research and development program of the full-size accelerating column with an ion source. The detailed specifications were developed from the Cockcroft-Walton model studies referred to in previous quarterly reports. The high-voltage power supply will operate with a drive frequency near 10 kHz and will consist of five air-insulated stages of multiplication. The unit is conservatively rated at 1-MeV at 13-mA steady state at sea level. It should operate quite satisfactorily at 750 keV at Los Alamos, elevation 7400 ft. Delivery time is expected to be approximately a year.

Ion Source Test Stand

The ion source has been operated to produce 40-keV ions continuously for short periods of time (on the order of seconds). The ion current was limited only by the 10-mA dc capacity of the extractor high-voltage power supply. The ion source expansion cup was large, 1.4-cm diam, and the cup depth was 3 cm. The anode aperture was enlarged during the test by the hot plasma but was no greater than ~ 1.5 -mm diam.

Fig. 39. LASL duoplasmatron ion source.

The LASL-designed Model A duoplasmatron is shown in Fig. 39. Two objectives of the design are to provide sufficient cooling for a high duty factor, possibly 100%, and to provide flexibility in the configuration of the intermediate electrode tip and anode structure. The cathode design is the same as that used at Brookhaven. The field-forming electrodes and the Faraday cup, which also are shown in the figure, will be replaced later by the 200-keV partial accelerating column.

A transistorized pulser has been used to form a hydrogen arc of 500 μ sec at 120 Hz. With a voltage pulse of 92 V, 3 mA of extracted pulse current was obtained. The ultimate goal is to obtain ~ 50 mA under pulsed conditions. Simple time-integrated emittance measurements can be made within the present Faraday cup.

The ion-source vacuum system for pumping hydrogen has worked well. A minor protective deficiency in the ion pump power supply has

been corrected by actuating the main circuit breakers from the protective circuit of the ion gauge. With a 0.025-in. diam anode aperture and with 0.1 torr hydrogen pressure in the arc chamber, the 1000-liter ion pump maintains a pressure of 2×10^{-6} torr. Without hydrogen feed, the system has reached a pressure of 6×10^{-8} torr with the filament running at 28 A at 2.5 V. Except for one interruption caused by an overshoot of pressure when the hydrogen was introduced, the system ran for 300 consecutive hours with the same filament operating at this heater level.

Total integrated dosage delivered to pocket dosimeters placed a few feet from the 40-kV high-voltage dome was negligible when the ion beam was extracted intermittently for about an hour. Short high-voltage conditioning breakdown pulses do give occasional 10 mR/h readings for less than a second on a dose-rate meter. An S.O.P. for the test stand operation has been

Fig. 40. LASL 200-keV Partial Accelerating Column.

written covering radiation, electrical, and hydrogen hazards. Plans have been submitted for enlarging the test stand area for safe operation at the 250-kV level.

Accelerating Column

A partial accelerating column, to be used on the present ion source test stand, has been designed to operate at 200 kV; it is shown in the sketch in Fig. 40. The column should be classed as a high-gradient Pierce column, although the highest gradient on the axis is a very conservative 25 kV/cm.

All metal components which are in regions of electrical fields inside the inner vacuum jacket, are being fabricated from Ti-6Al-4V alloy. The vacuum jacket will be composed of AD-94 alumina rings with Ti-6Al-4V alloy spacers. It was originally intended to use a Forsterite ceramic, but it is not commercially available in such large ring sizes. The outer

pressure jacket of the partial column will be formed of an acrylic, and is designed to withstand 70 psi of SF_6 insulating gas.

The main difficulty in construction of both the partial column and the full column is making strong, vacuum-tight Ti-4Al-4V alloy-to-alumina ceramic seals. The accelerating column is horizontal and the forces on the metal-to-ceramic joints are large. The usual adhesives which cure at room temperature, e.g., vinyl acetate, have a history of marginal tensile strength for this application. A program to investigate various metal-to-ceramic brazing techniques is under way. A similar study is being made at CERN. Both programs aim to produce joints that are at least as strong as the ceramic. The best technique developed at CERN involves wetting the ceramic with titanium hydride at 950°C in a vacuum, then brazing the ceramic to the Ti-6Al-4V alloy with either a Ti-Ni or Ag-Cu eutectic. A technique developed at LASL consists of the single-step process of wetting and brazing using either Ag-27.3Cu-2.5Zr alloy or Ag-26.5Cu-5Ti alloy and either in a vacuum or in an atmosphere of pure argon. So far only small samples have been sealed, and the techniques must be tested for large ring configurations.

Adequate methods have been developed for arc welding Ti-6Al-4V alloy to itself for the construction of the inner electrodes. The procedure involves slow and uniform rotation of the cylindrically symmetrical electrodes in an argon atmosphere while applying a small needle-shaped gas jet to the joint. A smooth fillet is produced which can easily be polished with the rest of the electrode to the required 3 $\mu\text{in.}$ finish. The electrodes are now being fabricated.

Beam Transport

A computer code, BEAMCAL, a general beam transport program for linear focusing lenses using the Kapchinskij-Vladimirskij

Fig. 41. The horizontal and vertical beam profiles for the proposed beam-transport system.

Fig. 42. Effects of a 10% current decrease on the horizontal and beam profiles.

Fig. 43. Split plate for making emittance measurements.

equations for emittance and space-charge effects, has been written. One use of this code has been to calculate the effects of the beam-transport system on the beam characteristics as the ion source current varies during the pulse duration. Figure 41 shows the horizontal and vertical beam profiles for the proposed beam-transport system. The location of the various transport devices are identified in the figure. The analysis has been carried out from the output of the accelerating column to the buncher input. The strengths of the various lenses are adjusted to give a beam with a circular cross section at the buncher. The effects of a 10% current decrease are indicated in Fig. 42. The current loss is $\sim 10\%$, assuming the acceptance of the rest of the transport system is adjusted exactly to the output of the correctly focused system. Analysis of lens aberrations indicates that a 10% loss could also be caused by random quadrupole excitation errors of 0.4% and by emittance variations up to 1.5 cm-mrad.

A study has been made of various devices for measuring emittance. The desired characteristics for such a device are: (a) a sensitivity of 0.1 cm-mrad for a 750-keV, 50-mA beam of radius 0.7 cm at a "waist"; (b) a sampling time down to 50 μ sec; and (c) complete phase-plane mapping with digital information in exposure times less than 1 min. A promising approach is a television/scintillator system. The beam is intercepted by a plate with either narrow slits or pinholes to determine phase-plane positions. The subsequent expansion is due to transverse momentum and is measured on a downstream scintillation plate. A short time sample is obtained by gating an image intensifier between the scintillator and a TV recording camera. The most serious problems appear to be radiation damage to the scintillator and the heating of the slit plate. Two slit plates have been built. One model, shown in Fig. 43, is made of hollow hexagonal tubes. The edges form slits whose width is nearly constant for a beam converging or diverging 30° from a normal incidence. The

hexagonal tubes were spaced with a 2.7-mil foil and fixed in place with epoxy cement. With 15-psi water pressure, the average temperature rise for 1 kW steady heating is 10°C . Another model which has four slits spaced 3.5 mm apart will be used on the 30-kV ion-source test stand.

Double-Drift Buncher

The Many Rings Averaged (MRA) program was continued on a somewhat reduced scale. A movie was made using the MRA computer program output display showing the ballistics of the beam particles as a function of time in both real space and phase space. The movie clearly demonstrates the basic principles of the double-drift buncher and gives a graphic picture of the particle interplay under forces of space charge.

Besides LASL's problem, two additional problems using MRA were run. The first one was for CERN, where the current is very large (250 mA). The second one was for the Rutherford High-Energy Laboratory (RHEL) in England, for their PLA machine. In both the CERN and RHEL programs, the frequency of the second cavity is kept the same as that of the first cavity. This is in contrast to LASL's program where the frequency is doubled for the second cavity. In general the results were as expected. The efficiency of the double-drift buncher using a single frequency is less than that of the harmonic buncher. The single-frequency double-drift buncher has the advantage of a simpler rf system, but its lower efficiency causes a greater beam loss.

Beam Diagnostics and Transport for EPA

Preliminary designs were made of beam profile monitoring equipment and beam scrapers for the EPA. Beam profile monitoring can be done easily at low beam intensities by using scintillating screens; the use of alumina appears promising because of its high radiation

resistance. At high beam currents, a rotating tungsten vane paddle wheel design is being considered. The vanes increase in length around the wheel so that as the wheel turns more of the beam is intercepted by or scattered by these vanes. In this way, an integral beam profile curve can be obtained.

Conventional water-cooled copper blocks with ionization chamber monitors can be used for beam scraping but they cannot withstand continual bombardment at the full EPA beam power. Therefore, an input collimator employing a tapered water-cooled aluminum tube is being considered, and a model is being built to test this design.

The study of quadrupole magnets to effect beam steering is being continued. The approximate solutions previously obtained are being checked using a modification of LALA. The effect of fringe fields and the determination of the aberrations introduced by this method of steering will be investigated using the LASL computer program, STEFFEN, which is a first-second-, and third-order, zero-current beam-transport calculation.

Experimental Area

Pi and Mu Channels

A literature survey concerning muon channels and ironless quadrupoles is nearing completion.

Program MUANGLE producing the in-flight (π, μ) decay cross section and the muon momentum as functions of the decay angle in the lab has been written for the CDC 6600 and is now ready to be used.

A survey of suppliers has been started in order to determine if any existing or some scaled-up version of an existing design of a dc power supply might be used for feeding bending magnets in the experimental area and the quadrupoles of the Alvarez linac.

Biomedical π^- Facility for LAMPF

An interesting possible use for the high current of the LAMPF accelerator is the production of a secondary beam of π^- mesons for biomedical research. Of all the particles produced in the interaction of 800-MeV protons with heavy nuclei, the π^- is the most promising for this purpose because each pion deposits 30 MeV of energy at the end of its range when it is stopped in water. This energy is in the form of several short-range, heavily ionizing particles which look like a "star" in a nuclear emulsion. This π^- star radiation provides a way of depositing energy at a point deep inside a biological sample while depositing only a minimum of energy in the intervening tissue.

A calculation of the energy deposited by a π^- beam as a function of depth in water was performed on the IBM 7094 computer. The results for two interesting cases are presented in Figs. 44 and 45. For Fig. 44, a beam with a momentum spread $\Delta p/p$ of 2% FWHM was chosen, the central momentum was adjusted to give a mean range of 15 cm in water, and the beam cross section was 1 cm x 1 cm. The energy distribution, range distribution, dose distribution, and isodose contours in the median plane (which contains the beam axis) are presented. For Fig. 45, $\Delta p/p$ was 26% FWHM and the mean range was 15 cm. For this case, the energy released per star was increased to 100 MeV, which is equivalent to assuming that the relative biological efficiency (RBE) of the star radiation is 3.3. In addition, the pion energy distribution was given a slight slope which serves to flatten out the dose distribution. It should be emphasized that the calculation does not include beam contamination or nuclear interactions of the pions in flight.

A preliminary design was completed for a π^- beam channel suitable for use both as a therapy tool and for general biomedical research. This channel provides an achromatic, parallel beam whose cross section is adjustable from

1 cm x 1 cm to 10 cm x 10 cm and whose $\Delta p/p$ is adjustable from 2-30% FWHM. The mean momentum is adjustable from 0.250 MeV/c, corresponding to a π^- range in water from 0-50 cm. If the channel is used with an 80 g/cm² tungsten target in the full intensity LAMPF primary beam, it will be possible to achieve a dose rate (calculated from the star contribution only) of 100 rads/min in a 10 cm x 10 cm x 10 cm volume at a mean depth of 15 cm in water. The design of this channel was based on conventional iron bending magnets and iron quadrupole magnets very similar to those already in use at other laboratories.

A preliminary design was completed for the facilities necessary to make use of the π^- beam. Two distinct choices were possible for the design, namely, whether the pion beam would emerge from the shielding in the horizontal plane or in the vertical plane. Since the economic and therapeutic advantages and disadvantages of each type of beam were not known, a decision was made to study both beams until a clearer understanding of these factors is obtained.

Two conclusions were reached which may also be of some importance in the design of the experimental area. The first is that a considerable reduction in cost can be made by using nearly spherical geometry for shielding the target cell. The second is that beam transport systems of the type proposed for the π^- beam suffer from the problem of a large beam size in the quadrupoles following the second bending magnet. This may limit the maximum target size which can be used unless it is given considerable attention during the design of the optics.

Fig. 44. Energy, range, and dose distribution of π^- stopping in water. Energy release = 30 MeV/star; $\Delta p/p = 2\%$ FWHM.

Fig. 45. Energy, range, and dose distribution of π^- stopping in water. Energy release = 100 MeV/star; $\Delta p/p = 26\%$ FWHM.

VI. PROJECT SCHEDULING AND FACILITIES PLANNING

Introduction

The IBM PERT Cost II scheduling of LAMPF has progressed to 85% completion of the Work Breakdown Structures, the checkout on the computer of two subnetworks, derivation of a summary network, and preparation of a 1050 card deck. From this work it is expected that a preliminary Program Management Network will be obtained within about 30 days.

To accommodate the expanding office and laboratory requirements of the R&D program, planning and construction on modifications to existing buildings have been continued and the new Electron Prototype Laboratory (EPL) is now approximately 65% complete.

Site and building activities for LAMPF now range from preliminary planning to actual construction. The initial phase of foundation study has been completed. Construction was started and is now about 16% complete on the site preparation work. Criteria are being developed for a consolidation of accelerator construction and maintenance space into a single Equipment Test Laboratory Building (ETLB) and the Title I engineering for the Laboratory-Office Building is essentially complete. Title II design has been initiated for a second phase of the site water and sewage systems. Proposals have been solicited from local engineering firms for design of the site substation.

LAMPF Scheduling Activities

At present the LAMPF Work Breakdown Structure is about 85% complete. During this period, network diagramming efforts have resulted in extensive modification to the Structure; this is a natural occurrence in a network analysis and was therefore expected.

Standard codes for "Resource Category" and "Cycle" have been established for all phases for the project. These codes are compatible with

the IBM PERT Cost II program being employed. As previously explained, only the time portion of the program will be utilized.

The Preliminary Program Management Network (PPMN) is being rapidly developed. The PPMN will include planning down to and including Level III of the Work Breakdown Structure. At present, two subnetworks (INJK for the injection system and RFPS for the rf power system) have been integrated and are running together on the computer. Four more subnetworks, at various stages of development, are being prepared. Initial versions of the PPMN will not include a subnet for site and buildings. Data from the latest version of the Construction Barchart will be integrated with the accelerator subnetworks to obtain a schedule for the entire project. The PPMN will be a Level I summarization of the data contained in approximately 2500 data cards of which about 1050 are already prepared.

During this period, computer summarized networks have been obtained. One of these networks will become the PPMN and a later version will become the Management Summary Network.

Facility Activities for the R&D Program

Two approaches are in progress to alleviate the office space problem associated with the continuously increasing project staff. First is the expansion into portions of the recently completed Physics Analytic Center. The consequent relocation of other offices will soon follow. Second, the remodeling of eight house trailers obtained from government excess is in the final planning stages.

Laboratory modifications for the R&D program included completion of all provisions for the 1.25-MW klystron test stand, construction of a new modulator test stand, final engineering for an additional modulator test stand, and enlargement of the ion source laboratory.

Construction of the EPL has progressed very well. The foundations and floor were poured

and the building has been erected. Interior utility and service work is under way. The total facility is now about 65% complete and beneficial occupancy is expected by early June.

LAMPF Site and Building Activities

Geologic and Foundation Studies

The first phase of soil load-bearing properties on the Mesita de Los Alamos has been completed and the draft of a final report has been issued for review. Since negligible creep had been detected previously under conditions of normal building load, an effort was made during this period to determine the upper limit or yield point for the surface tuff. The load was increased to 17,000 lb/ft², at which point some failure occurred but it was completely localized to the loaded area. It was observed that deformations up to this loading agreed very well with theoretical predictions based on elastic response to Newmark stress calculations. These results are very encouraging and are being utilized for determination of the parameters that will be employed in the final test phase when actual building elevations are reached in the excavation work.

Site Roads, Grading, and Utility Work

On Feb. 2, 1967, bids were opened for the site preparation contract. The low and successful bidder was Burn Construction Co., Las Cruces, N. M., at a contract price of \$481,070. Work started on Feb. 27, and is now approximately 16% complete. Clearing and grubbing are done, over 4500 ft of 8-in. water line are in place, the cut and fill work on 1½ miles of access road is essentially accomplished, and excavation has started on the accelerator beam channel.

Accelerator Building Design

Title II engineering of the injector and 201.25-MHz accelerator buildings was held at the 87% completion point as previously reported, except for the specifications now being written by

Giffels and Rossetti. This level will be maintained until approximately 90 days prior to the scheduled construction start.

Further design of the 805-MHz buildings has been held in abeyance until the main power amplifier type has been determined. The preliminary cost analysis work for these buildings produced a substantial design improvement. It has been found that clustering of the rf modules would have both utilitarian and economic advantages. To achieve such advantage, however, it became necessary to lower the beam channel by 4 ft. The latter change has now been incorporated into the site preparation plans and issued to the contractor for cost negotiation.

Equipment Test Laboratory Building

Additional consideration of project space requirements resulted in an improvement of accelerator assembly and maintenance facility plans. In previous designs, duplicate areas had been distributed along the accelerator. In this period, it was decided that a much more efficient operation could be achieved if such space were consolidated into one building. The criteria for this so-called ETLB have now been collected from the technical groups and are being prepared for final approval and submission to the A-E.

Laboratory-Office Building Design

A contract was negotiated on Feb. 9, 1967, with W. C. Kruger & Associates, Santa Fe, N. M., for design of the Laboratory-Office Building. To date, several preliminary studies have been completed, and an architectural treatment concept has been approved. The completed Title I documents will be received for review on May 1, 1967.

Utility Work

Giffels and Rossetti have been instructed to proceed with Title II plans and specifications for the second phase of the site water and sewage

system. This work is now in progress so that bidding can be scheduled as soon as construction funds become available for the water tank, main pump house, and sewage disposal plant.

Design criteria were completed and issued for the site electrical power substation. An A-E Selection and Negotiating Panel was appointed by ALO and has issued requests for proposals. The selection of a local A-E for design of this facility is scheduled for May 8, 1967.