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MASTER

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ACCELERATOR TECHNOLOGY PROGRAM

July--December 1981

Compiled by
E. A. Knapp and R. A. Jameson

ABSTRACT

We report on the major projects of the Los Alamos National Laboratory's Accelerator Technology Division during the last 6 months of calendar 1981; the various projects are as follows.

- We have continued work on the radio-frequency quadrupole linear accelerator, which has been adopted worldwide for a variety of applications. We are doing studies of octupole focusing; such studies are a first step toward possible development of a radio-frequency octupole accelerator.
- We have completed the design study on an unusual electron-linear radiographic machine that could obtain x rays of turbine engines operating under simulated flight-maneuver conditions on a centrifuge. In another radiographic linac study, we are investigating a concept that involves the staggered tuning of accelerating cavities or blocks of cavities to significantly enhance the achievable charge transfer through an electron linac operating in the stored energy mode.
- In September we completed the 5-yr Pion Generator for Medical Irradiation (PIGMI) program to develop the concept and technology for an accelerator-based facility to treat cancer in a hospital environment.
- The design and construction package for the site, building, and utilities for the Fusion Materials Irradiation Test (FMIT) facility has been completed, and we have begun to concentrate on tests of the rf power equipment and on the design, procurement, and installation of the 2-MeV prototype accelerator.
- The Proton Storage Ring project has continued to mature.
- The main effort on the racetrack microtron (RTM) has been on the design and construction of various components for the demonstration RTM.
- On the gyrocon radio-frequency generator project, the gyrocon was rebuilt with a new electron gun and new water-cooled gun-focus coil; these new components have performed well.
- We have initiated a project to produce a klystron analysis code that will be useful in reducing the electrical-energy demand for accelerators.
- A free-electron laser amplifier experiment to test the performance of a tapered wiggler at high optical power has been successfully completed.

RADIO-FREQUENCY QUADRUPOLE AND BEAM DYNAMICS

SUMMARY

The radio-frequency quadrupole (RFQ) is a new type of linear accelerator first suggested in a 1970 Russian paper.¹ The RFQ linac is especially suited to the acceleration and bunching of low-velocity high-current ion beams. Typically, it accepts a dc beam from an ion source, bunches it with high efficiency, and accelerates it to a few million electron volts per atomic mass unit. A highly successful full-scale proof test of this idea was carried out at Los Alamos in 1980. At present, the RFQ has been adopted worldwide for a variety of applications. The studies of octupole focusing are a first step toward the possible development of a radio-frequency octupole accelerator.

PROGRAM TO SOLVE LAPLACE'S EQUATION IN THREE DIMENSIONS

An important parameter in the design of RFQ linacs is the peak surface electric field on the RFQ vanes. In many cases, particularly for high beam currents, the accelerating and focusing electric fields should be as high as possible without exceeding the sparking limit. Until recently, a two-dimensional model has been used to calculate the peak surface fields, ignoring effects of the vanes' longitudinal modulation. A newly developed program, CHARGE-3D, solves Laplace's equation in three dimensions and allows the surface fields to be determined on modulated vanes. With this program we have learned that often the modulation significantly raises the electric fields, and this must be fully taken into account in our design procedures. CHARGE-3D also allows us to determine the strength of the higher focusing harmonics produced by new RFQ vane shapes that are attractive because of machining simplicity. These focusing harmonics can then be used in simulation programs to determine their effects on beam dynamics.

FINAL BEAM DYNAMICS FOR CERN RFQ

A final beam-dynamics design for the European Organization for Nuclear Research (CERN) RFQ was described in Accelerator Technology (AT) Division's previous semiannual report (January-June 1981). This linac accelerates protons from 50 to 520 keV in 1.38 m. After the CHARGE-3D program was written, we used it to calculate the peak surface electric field on the pole tips of the CERN design. This field was 20% higher than previous two-dimensional estimates, and a slightly revised design was made to reduce the peak field.² In this revision we held the vane length constant, and the average radius of the pole tips and the vane voltage were reduced to obtain a 24.9-MV/m peak surface field. This value corresponds to about 1.7 times the Kilpatrick limit at the 202.56-MHz design frequency. For this new design, the transmission efficiency is predicted to be 90% for a 100-mA input beam.

Steel vane blanks were shipped to Los Alamos from CERN for machining of the pole-tip contours. The AT-Division MAZAK numerically controlled milling machine was used to produce the specified pole-tip shape. This machining was completed in October, and the vanes were returned to the CERN Laboratory. In this collaborative effort with CERN, we also have completed calculations on their ion source extraction system³ and have written a joint paper⁴ describing the overall design of their RFQ linac.

RFQs WITH CONSTANT-CURVATURE POLE TIPS

We have completed an initial evaluation of a new RFQ pole-tip geometry, where the pole-tip transverse radius of curvature is held constant throughout the cell. This new method reduces the extreme variations in the contour on the sides of the poles that resulted when the radius of curvature was chosen to follow the ideal isopotential pole-tip value. Consequently the peak surface field can be reduced, and the vanes can be machined in less time with larger cutters and with an improved surface finish. These improvements are accompanied by an increase in the contributions from higher focusing multipoles.

The program CHARGE-3D, which solves Laplace's equation within a modulated RFQ cell geometry, has allowed a comparison of the surface fields and the multipole content for both the old and the new pole geometries. Procedures have

been developed to take into account the effects of the new geometry and to allow a simulation of the beam dynamics including the higher multipoles. As a new step in the design procedure, the cell-geometry parameters are modified to maintain the correct design values for the quadrupole and acceleration multipole terms.

The results so far show that from 5 to 15% reduction in peak surface field can be obtained for radii of curvature between $0.5 r_0$ and r_0 , where r_0 is the average pole-tip radial aperture.⁵ In the RFQ being designed in collaboration with the French Laboratory at Saclay, a fixed radius of curvature equal to r_0 gave equivalent beam performance to that from the ideal potential function, when the cell-geometry modifications were made as described above. Because of these positive results, we are recommending that the fixed radius-of-curvature vane geometry be considered for all new RFQ designs.⁶

OCTUPOLE FOCUSING--TRANSPORT AND ACCELERATION SYSTEMS

The RFQ linac is capable of accelerating high-current, low-velocity ion beams. In accelerator systems comprising an RFQ and higher velocity accelerating structures, the beam-current bottleneck still typically occurs within the RFQ. This limiting beam current is quite high in most cases, but linacs with even higher currents may be required in the future. We have begun a study of high multipole systems to determine their capability for focusing and accelerating very high currents.⁷ We have chosen first to examine a radio-frequency octupole transport system and have developed a smooth-approximation analytical description that includes the conditions for input radial matching of a zero space-charge beam. Further, we have constructed a multiparticle beam-dynamics simulation program that accepts the low-current matched beam and gradually increases the beam current as it is transported. This results in a matched high-current beam, and this procedure can be used to determine the saturation current limit of a periodic octupole system. As expected, at high currents the beam develops a hollow radial distribution that reduces the space-charge defocusing. For accelerating with an octupole linac, we have constructed a formulation that includes the potential function, accelerating and focusing efficiencies, and the geometry of the radially modulated pole tips.

LINAC DESIGN STUDY FOR ORNL

We have completed a conceptual design study for a proton linear accelerator that might replace the electron-accelerator neutron facility (ORELA) at Oak Ridge National Laboratory (ORNL).⁸ Our main goal for this study was to design the best linear accelerator that would accelerate protons to 100 MeV in single bunches at a 1-kHz bunch rate. The desired single-bunch intensity was 5×10^{11} protons per bunch, and the time width of the output bunch was to be less than 1 ns.

The design concept consisted of a scaled-up, high peak-current duopigatron ion source, followed by a fast beam chopper, which injected a pulsed beam into a 40-MHz RFQ. The beam leaving the RFQ was injected into an 80-MHz drift-tube linac (DTL) at 5 MeV. At 40 MeV, a transition was made to a 160-MHz DTL that accelerated the beam all the way to 100 MeV.

The design was successful in meeting the main goals stated above except for the output beam intensity, which was 2×10^{11} protons per bunch. The cost estimate for the linac structure plus rf power hardware was about \$50 million, and additional development would be required for the high peak-current ion source. The high cost is related to the use of low-frequency DTL structures, which have low shunt impedance and large fill times, and which were required to provide the high peak-beam-current capability. We recommended that alternative ideas be carefully evaluated to see how they compare with this high-current linac scheme.

LINAC BEAM-DYNAMICS DESIGN FOR ACCELERATOR STUDIES

The preliminary design of a 2- to 5-MeV, 425-MHz DTL was modified after SUPERFISH data were obtained. The final PARMILA design gave a 40-cell linac, 2.39 m long. The synchronous phase was -40° , the electric field gradient was 2 MV/m, and all quadrupoles were 2.54 cm long with a strength of 18.33 kG/cm.

We chose a transport section of three elements (1.40-cm drift, 18.33-kG/cm permanent-magnet quadrupole, 3.17-cm drift) to join the linac to the RFQ. New matching subroutines for PARMILA were written to assist with the transport design.

Beam-dynamics calculations were made through the entire system, using beams of different sizes and currents. For the "design" beam, the ratio of input to output emittance in the linac was 0.95 in the x-x' plane and 1.05 in the y-y' plane. Beam envelopes were judged to be smooth and acceptable for the design beam and for the larger and smaller beams studied.

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ELECTRON LINEAR ACCELERATORS

TURBINE ENGINE LOADS SIMULATOR

SUMMARY

Turbine engine radiography has been used successfully on stationary test stands of engine manufacturers for some years. Radiography has not been applied, however, to the study of turbine engines operating under simulated flight-maneuver conditions, where engine components are subjected to inertial forces. An important part of such an application would require a radiographic system that could provide information regarding the effects of different loadings on the internal clearances and distortion of a gas turbine engine.

DISCUSSION

The Turbine Engine Loads Simulator (TELS), proposed for the Arnold Engineering Development Center (Arnold Air Force Station, Tennessee) is a test facility that will expose operating gas turbine engines to simulated maneuver acceleration and gyroscopic loads, with a radiographic system that will provide essential information regarding the distortions of internal engine components and the subsequent changes in clearances between adjacent parts.

The general specifications for the x-ray source to satisfy the radiographic requirements include bremsstrahlung end-point energy: 10 MeV; radiation dose-rate: 3000 rad/min at 1 m; and source spot size: 1.25-mm diam. A stroboscopic capability of up to 15 000 rpm also is desired so that a particular turbine blade, for example, can be repetitively imaged for each rotation of the turbine engine. In addition, the x-ray source should be capable of operating in the acoustic and mechanical environment associated with an operating gas turbine engine while being subjected to facility-induced inertial loads of up to 21 g's.

A variety of accelerator configurations have been studied. C-Band (5-GHz) and S-Band (3-GHz) systems with the rf source near the axis of the centrifuge,

as well as an S-Band system with the rf source in the x-ray head, were considered.

An S-Band accelerator with a klystron rf system mounted near the axis of rotation has been recommended for the TELS application. This configuration minimizes the components required to operate in the high inertial and vibration environment. Such a system appears to require minimal development while offering high operating flexibility and reliability. Preparatory to a final design, it has been recommended that all components to be located in the x-ray head be studied experimentally under simulated TELS conditions. The TELS design study has been completed and a final report has been written.¹

RADIOGRAPHIC LINAC STUDY

SUMMARY

A concept involving the staggered tuning of accelerating cavities or blocks of cavities can significantly enhance the achievable charge transfer through an electron linac operating in the stored energy mode. By so doing, the output bremsstrahlung flux can be increased by an order of magnitude over a conventional approach without any significant degradation in emittance growth or energy spread. Given a suitable injector, a 1500-rad/pulse, 50-MeV radiographic linac would appear promising at an operating frequency of 400 MHz, and a 150-rad/pulse, 50-MeV radiographic linac at 1300 MHz. Multiple pulsing would also appear feasible.

DISCUSSION

Investigations have shown that radiographic experiments requiring whole-object thick-section radiodensitometry place a premium on the amount of charge delivered to a bremsstrahlung target, with an optimal energy possibly near 20 MeV.² On the other hand, for experiments requiring peak radiation flux concentrated on a region significantly smaller than the radiographic object, a different emphasis, on beam energy, is required.

Although an accelerator optimized for one class is apt to be quite different from one designed for the other, there are areas in common. Assuming that a structure has been selected and the accelerating field normalized to Kilpatrick, then for that class of experiments, which is charge dominated,

$$q \propto \frac{1}{f^{1.5}} \frac{(\Delta u/u)}{\cos \phi} ,$$

where q is the charge, f is the operating frequency, $(\Delta u/u)$ is the fractional energy extraction, and ϕ is the synchronous phase angle. For the second class, which is energy dominated,

$$R \propto \frac{W^{2.8}}{f^{1.5}} \frac{(\Delta u/u)}{\cos \phi} ,$$

where R is the on-axis bremsstrahlung radiation intensity, and W is the energy of the electrons impacting on the bremsstrahlung target.

In the interests of cost, it is desirable to operate at the highest feasible frequency. It is then necessary to maximize the ratio of

$$\frac{(\Delta u/u)}{\cos \phi} .$$

In conventional stored-energy design, ϕ is customarily zero and $(\Delta u/u)$ is limited by the allowable output energy spread. For a $\pm 2.5\%$ energy spread, $(\Delta u/u)/\cos \phi = 0.1$.

There is, however, a possibility that the ratio $(\Delta u/u)/\cos \phi$ can be increased significantly. Let $W = ET \cos \phi L$, where E is the peak accelerating field at any instant during the beam pulse, T is the transit-time factor, and L is the accelerator length. The quantities T and L are constants for a given design. Using subscripts i and f for the initial and final pulse values

for W , E , and ϕ , the energy spread can be minimized by making $W_i = W_f$. It then follows that

$$\phi_i = \cos^{-1} \cos \phi_f \left(1 + \frac{\Delta u}{u} \right)^{1/2},$$

with the operational requirement that ϕ be varied from ϕ_i to ϕ_f in consonance with the field slump. Although this in principle minimizes the energy spread caused by field slump, another source of spread is introduced because, for a micropulse of width θ , a nonzero synchronous phase angle has an associated energy spread of

$$\frac{\Delta W}{W} = 2 \tan \phi \sin \frac{\theta}{2}.$$

This source of spread, however, can be minimized by operating alternate cavities or blocks of cavities at plus and minus ϕ 's. Both the phase modulating and phase sign alternating can be accomplished by tuning alternate cavities or blocks of cavities to a frequency above and below ($\pm \Delta f$) the reference (injector) frequency by an amount

$$\pm \Delta f = \frac{\phi_i - \phi_f}{360 t_p},$$

where t_p is the beam pulse duration.

Depending on the permissible output energy spread, the charge and/or the radiation intensity can be increased by as much as an order of magnitude over the conventional approach with the caveat that space-charge effects have not been included yet. This undoubtedly will have a significant effect, especially in experiments in which charges in excess of 100 μC may be desired, but the advantage of the staggered tuning should still apply.

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PIGMI PROGRAM

SUMMARY

Clinical trials of the radiation susceptibility of cancers to various types of particle beams have been under active study during the past 10 yr. The effects of pions, heavy ions, protons, and neutrons are being investigated. Most of this work has been done at physics research institutes, where the accelerators' primary characteristics and operating schedule are oriented toward the physics studies, with the medical research as a secondary objective. After the start of the pion program at LAMPF, a study was initiated by the US National Cancer Institute in 1976 to develop the design and to test certain components of accelerators whose dedicated purpose would be for cancer radiotherapy in a hospital environment. This program, named Pion Generator for Medical Irradiation (PIGMI) was recently completed.¹⁻³ Significant advances in accelerator technology were made, indicating that economical and reliable dedicated machines can be produced.^{4,5} Further, the design can be configured to produce any of the particle beams that may eventually be desired.

CONCLUSION OF THE PROJECT

In September, we completed a 5-yr funding cycle in the program to develop PIGMI. The objective was to develop the concept and technology for an accelerator-based facility to treat cancer in a hospital environment. Because funding for such a facility has not been obtained, we are searching for other possibilities to extend this technology and to apply it in other areas.

In concluding the PIGMI project we have assembled a report covering the final status of the program.⁴ The accelerator developments, accelerator engineering design, facility design, and costs are included. Other recent reports include a complete description of the 30-keV PIGMI injector, several new engineering designs for radio-frequency quadrupole linacs, and the possibilities for applying PIGMI technology to a high-efficiency linac for radioisotope production.⁶⁻⁹

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FUSION MATERIALS IRRADIATION TEST FACILITY

STATUS

Funding limitations delayed the start of construction of the Fusion Materials Irradiation Test (FMIT) facility. However, the design and construction package for the site, building, and utilities was completed by the Architect/Engineer (AE). In December 1981, Los Alamos began to concentrate on tests of the rf power equipment and on the design, procurement, and installation of the 2-MeV prototype accelerator: injector, low-energy beam transport (LEBT), and RFQ. The goal is an operational 2-MeV accelerator by February 1983. Except for the linac tank and first 15 drift tubes, all FMIT accelerator-related design was stopped, with restart dependent upon additional funding.

Liason with vendors supplying the rf equipment was increased to help them solve their technical problems and to make them aware of the need to adhere to delivery schedules.

The preparation of the prototype building continued. The 10-ton crane was installed and is operational. The test stand for the first rf power unit was electrically wired and connected to the water-cooling system. The injector's cooling system was connected to the building's cooling water.

The office building is nearly ready for occupancy.

ACCELERATOR

Injector

The injector was operated in support of the evaluation of various beam-diagnostics techniques. The design and construction of components for the LEBT was continued. A major effort was directed toward improving the operation quality of the analyzing magnet and of the high-voltage power supply.

A method based on field mapping, followed by computer analysis of the mapping data, was developed to allow for precise machining of the edge angles required for the analyzing magnet. The result is a significant reduction in

beam aberrations as the beam is transported through the magnet and the production of the axially symmetric beam profile that is optimum for injection into the RFQ linac structure.

The control circuit for the high-voltage supply was redesigned, improving its operation into the reactive load (ion source and extractor). The grounding system was reworked to provide lower inductance single-point grounding.

Cracks in the copper structure supporting the high-voltage extraction aperture were caused by the use of improperly cast material. The structure was replaced 5 months ago with one made from certified OFHC copper. No cracks have occurred.

The RFQ Linac

Calculations during this period showed that the peak electric fields in the RFQ were 1.9 times the Kilpatrick criteria instead of the 1.7 design value. However, constant radius-of-curvature vane tips were proposed as a method for reducing the peak field back to the design value, while keeping the same length.

Cost-effective measures were developed for RFQ fabrication as a result of consultations with vendors who originally bid for the job. Noncritical tolerances and machining operations were identified and were relaxed or eliminated.

Beam Diagnostics

A complete version of the noninterceptive beam-characterization system was installed and operated on the prototype injector's LEBT. The sensors consist of mirror-based optical assemblies that present to a TV camera, simultaneously, four cross-sectional profiles of the beam. Three such sensors were installed before, at, and after a beam waist that is symmetric in the transverse plane. The video frames from these sensors (totaling 12 beam profiles) are multiplexed into a video digitizer and transferred to a disk file of the PDP 11/60 control computer. An automated data-preparation computer program reads the files, selects the profiles (video lines) of interest, does a background subtraction, and transfers the data for the profiles to a computer-based tomography reconstruction program. A large selection of data-handling routines were evolved

for inspection and manipulation of the raw data or of the resultant beam-characterization arrays. Individual lines may be displayed, averaged, or modified; projections can be made to either axis; contour or isometric plots can be made of the full TV frame or array.

The reconstruction code can be used for either spatial distribution reconstructions (using data from a single sensor) or for transverse-emittance reconstruction (using data from all three sensors). The plot or tabulation is presented on the screen within 20 s of the command to collect the data.

The hardware components have proved to be very simple to set up and are reliable for extended periods of operation. As an example of the capability of the system, an isometric plot of the beam's density distribution is shown in Fig. 1; a contour plot of the beam's transverse emittance is shown in Fig. 2.

Fig. 1.

Isometric plot of the spatial density distribution as reconstructed by the MENT algorithm from four projections of beam light intensity at a single location.

Fig. 2.

Emittance distribution equal intensity contours as reconstructed by the MENT algorithm from projections of beam light intensity. The contours shown enclose approximately 99%, 87%, and 47% of the total intensity.

A test fixture needed to verify performance of the beam-position-monitor (BPM) lobes (which are being installed in the linac drift-tube bores) was designed, fabricated, and shipped to the Hanford Engineering and Development Laboratory, Richland, Washington. Also, an operation manual for the fixture was written.

We have been working on a dc transducer to provide a noninterceptive and continuous measure of beam current in the LEBT. We have now installed the transducer in the LEBT and it is providing accurate measures of the current.

The rf System

The development phase of the rf power system is nearing completion. The vendor has solved the problem of spurious oscillations by redesigning the screen grid-control grid region of the output cavity to duplicate the geometry that was used by EIMAC, the manufacturer of the 8973 rf power amplifier tube, in their test stand. This modification, in combination with proper ferrite loading of the cavity, has eliminated the oscillations.

The vendor for the 14-in. coaxial transmission line, in cooperation with Los Alamos, has completed an acceptable design for the motorized breakaway section that is used to attach/detach the transmission line to the rf coupling loop in the tank. Also, an acceptable design was generated for the device to short the transmission line when the associated rf power amplifier is being maintained or replaced. This vendor is currently correcting the construction of directional couplers that failed to meet specifications.

Los Alamos has completed and successfully tested a prototypical low-power rf (LPRF) system with feedback controls for both phase and amplitude. Two LPRF systems providing 100 W of power were assembled and were used to drive a resonant load with $Q = 8000$. The tests showed that, as predicted, multiple rf drives required precise phase and amplitude control of the individual systems plus cavity field control to give good overall performance. The tests showed the system meets the required specifications; thus, fabrication of components for the prototype accelerator was started.

Facility Control System

In this reporting period the emphasis shifted from FMIT Instrumentation and Control (I&C) to development of the controls necessary to operate the prototype accelerator. The configuration of that system has continued to evolve as we gain more understanding of the requirements and in response to a decrease in the scope of the program.

The distributed computer system is a "star" configuration of DECNET with a PDP 11/70 at the center, controlling the console. There are four main branches, each with an 11/23 in a CAMAC crate. The branch that had been defined as the "dc power/vacuum" node has been eliminated. The vacuum system will not interface with the computer, and the dc power functions will be picked

up on another node. However, the accelerator diagnostics system, which formerly shared a node with the Injector Controls, now occupies a separate node. This change was necessary because of the heavy load of computation and communication now recognized as required by diagnostics. In addition, to facilitate preprocessing in the diagnostics node (minimizing communication traffic), we added a Winchester disk for mass storage and a fast floating-point processor.

The injector node was further modified by adding an auxiliary processor, which has its program stored in nonvolatile memory. This feature permits the rapid restart of the injector node without downline loading of the software. This rapid restart capability was required because the operating environment of the injector results in frequent crashes of that node. Extended periods without control were not tolerable.

Two changes also were made to console hardware. The first of these changes added two more (four total) control knobs to each console position. This was required by injector start-up procedures.

The second console modification was the addition of a small push-button panel that controls certain functions, which previously were going to be controlled by a fixed display on the touch panel. This change simplified the software design and eliminated a problem of burning the CRT with a fixed display.

During this period the overall structure and requirements of the software system was fixed, permitting rapid development of the individual software elements. The software will have a hierarchical structure (Fig. 3) and will be data-base driven.

Considerable difficulty has been experienced with the hardware and software of the color graphics CTR system that was purchased for the FMIT prototype console. The software problems have been resolved but the display still has a degree of flicker that an operator will find uncomfortable.

A communications link is being established between the FMIT prototype computer system and an Instrumentation Subsystem (ISS) node at Hanford, which will facilitate the participation of FMIT I&C personnel in software development.

Fig. 3.
Software design layout.

Drift-Tube Linac

Fabrication of the prototype linac tank and drift-tube assemblies continued. All peripherals (slug tuners, rf drive loops, and rf monitor loops) are in various stages of procurement.

Much mechanical design effort was directed toward providing the AE with design information needed to complete the construction package.

The FMIT linac tank design was reviewed when 90% complete. The review directed a number of modest changes that are being incorporated. The thermal and stress analyses were continued with no areas of inadequacy being revealed.

An early test of the concept of using multiple rf drives into a single resonant load will provide an important verification of the FMIT accelerator design. To provide a test load, the prototype tank will be equipped with a dummy drift-tube (DDT) structure made of stainless steel. The length of the DDT is approximately the same as the length occupied by the 15 individual drift

tubes that will be installed for normal operation. Using a stainless steel DDT lowers the Q of the tank; therefore, 600 kW (or perhaps 1.2 MW) can be used to drive the tank without generating excessively high electric fields. The system will allow operation only at a low duty factor but will be adequate to test the concept.

HEBT and Beamstops

The designs of the major components of the high-energy beam transport (HEBT) received increased attention because most of these components have long procurement times. Final designs of the 25- and 30-cm quadrupole magnets were started. Preliminary designs of the steering and FMIT bending magnets were completed.

The quadrupole magnets have a unique design. The yoke is split and the coils are wound so that the top half of the magnet can be removed, thus simplifying repair or replacement of the beam tube situated in their bores. This feature will be particularly useful in the FMIT application in which the beam tube and magnets are expected to become radioactive. The coils are wound with mineral insulated wire and, therefore, will be highly resistant to radiation damage.

The steering magnets are a window-frame design with a capability of bending a 35-MeV deuteron beam through 0.5° . The bending magnet is a 45° magnet with an index number of ~ 0.5 and with edge angles. The bending-magnet coils are also wound with mineral insulated wire.

The beamstop design was simplified as a result of the project directive to focus efforts on only the 2-MeV prototype tests. Graphite tiles will not be brazed to the surface exposed to the beam. The tiles were to eliminate the radiation produced by the 5-MeV beam of H_2^+ ions; at 2-MeV beam energy the problem does not exist. Final design of the beamstop is in progress.

Cooling, Vacuum, and dc Power

The prototype building's cooling-water system was tested and accepted. Piping and instrumentation diagrams were developed for the prototype accelerator; these show all control valving and instrumentation.

The bipolar horizontal and vertical steering circuit was breadboarded and tested while connected to the steering coils in one of the drift-tube quadrupoles. The closed-loop circuit supplies up to 40 A in either polarity, with continuous transition through zero current in response to local adjustment or to a remote computer-supplied bipolar signal. The linearity is 0.62% and the set-point resolution is 0.05 A. The control and monitoring circuits are protected by using optical isolation amplifiers. Assembly and schematic diagrams for the steering-control panel are 90% complete.

Another type of horizontal steering using quadrupoles is required. The approach is to unbalance the current flow in the excitation windings of the quadrupole. This circuit was also breadboarded and tested into a quadrupole. The circuit adds 40 A to two of the windings, at the same time shunting 40 A from the other two while 700 A are flowing in the windings. The circuit is bipolar with smooth transition through zero and is either locally or remotely controlled. The current linearity is 0.3% and the set-point resolution is 0.05 A. The equality of the currents being shunted and added is within 0.5%.

An evaluation program generated improved approaches to detecting vacuum leaks in the large vacuum vessels that are typical FMIT components. The usual method of using a mass-spectrometer helium leak detector (MSLD) is usually characterized, for large vessels, by the requirement for a large expensive auxiliary vacuum system and by poor response time. Two commercially available alternatives exist: one is a contraflow MSLD, the other is a halogen leak detector.

The contraflow-type helium leak detector is specially designed to maximize the diffusion of helium backward through the MSLD diffusion pump. The unit is portable, does not require a good vacuum in the structure being tested (sometimes atmospheric testing is adequate), and does not use liquid nitrogen. We have measured a sensitivity of 1×10^{-9} STP cm^3/s of helium at 0.1-torr nitrogen pressure.

The halogen leak detector is a probe-type instrument with a sensitivity of 1×10^{-7} STP cm^3/s for Freon and with a very fast response time because it draws a large (0.8 STP cm^3/s) gas sample through the probe tip. Under ideal conditions we have measured a Freon leak of 1×10^{-9} STP cm^3/s . The instrument is portable and was used at the fabrication site of the prototype linac tank. Several leaks were quickly and accurately located.

PROTON STORAGE RING

SUMMARY

During this reporting period, Title II design of the Proton Storage Ring (PSR) tunnel and equipment building was completed by the project AE. Preparation of these drawing packages has involved an extensive and intensive effort, especially with regard to specification of utilities, radiation shielding, and wiring runs.

A detailed beam-spill model was developed for the PSR, and radiation protection and activation questions were comprehensively examined. This study resulted in somewhat greater thickness of shielding above the Ring tunnel, a decision to use low-sodium aggregate in the concrete (for reduced activation by the beam), and more conservative beamstop designs. The PSR Preliminary Safety Analysis Report was completed during this period. It contains a very thorough discussion of all conceivable safety issues affecting the project, especially radiation safety issues. The PSR project plan has continued to mature, with every segment of the project now having had at least a first pass at Program Evaluation Review Technique (PERT).

We now briefly review the highlights of PSR equipment development and procurement programs, beginning with the LAMPF injector.

A first direct-extraction H^- ion source prototype has been fabricated by modification of a source previously used on the FMIT test stand. This source has been installed on the LAMPF test stand and has produced H^- beam currents of up to 8 mA at 200 keV with a satisfactory emittance. This performance is within a factor of 2 to 3 of the goal.

A 6D particle-tracking code is being developed to allow comprehensive optical design (including space-charge effects) of the new H^- low-energy transport line. Much of this code has been written and debugged; comparison with experimental results obtained from tuning the present H^+ transport line is in progress.

A conceptual design of the LAMPF switchyard upgrade has been completed. Some work has been initiated on detailed optical design of the new switchyard and the front end of Line D, but the bulk of it remains to be done. An expert from the CERN Proton Synchrotron (PS) Kicker Group has been engaged to provide

input on design of the new switchyard kicker magnet. Based on promising model circuit studies, we have decided to develop a fast-kicker magnet driver that uses a high-current transistor amplifier rather than a switched pulse forming network (PFN). This approach will permit arbitrary adjustment of pulse length and the desired high degree ($\pm 0.3\%$) of amplitude regulation. A scaled-down version of this circuit has already been satisfactorily demonstrated for driving the Ring orbit bump magnets.

The six tape-wound injection-line quadrupoles have been delivered, and the injection-line dipole magnet package (five units) has been sent out for bids. Details of the H^- beam-halo stripping scheme have been worked out and second-order optics studies have been carried out for the injection line.

An order for eleven 4-in.-aperture, 36° bend laminated magnets (the main Ring dipoles) has been placed, with delivery of the prototype unit scheduled for September 1982. The 10 production units will be ordered after the prototype has passed acceptance tests. A single-particle resonance-mapping program has been initiated to examine the feasibility and location of higher multipole magnets in the Ring.

Good progress has been made on development of a fast-tuning scheme for compensating the time-dependent beam loading in the high-frequency rf buncher. The design approach is based on use of a low-loss microwave ferrite immersed in a rapidly modulated magnetic field. A model tuning cavity has been fabricated and sufficient testing has been done with various ferrite materials to demonstrate that the required tuning range and low power loss can probably be attained. An order for the rf power source, a 110-kW uhf-TV transmitter package, has been placed.

As a result of extensive calculations on the details of the capture process in the high-frequency bunching mode, the design frequency and rf amplitude have been changed (from 603.75 to 503.125 MHz, and from 1.5 to 1.8 MV). The calculations have revealed that it may be necessary to implement a longitudinal phase-space matching device (bunch rotator) in the transport system between the linac and the Ring.

A conceptual design has been worked out for the low-frequency rf bunching system. The cavity is to be a conventional quarter-wave ferrite-loaded resonator, using Phillips 4H ferrite rings already on hand. A unique feature of the system is the use of a low-impedance cathode-follower driver to reduce the

overall longitudinal impedance seen by the beam to 20 Ω or less. This minimizes the impact of beam-induced voltages and permits tuning by small changes in the drive phase and amplitude.

A cold-test model of the damper amplifier tube being developed by Eimac was delivered and met all specifications. First working tubes are expected within a month.

Production of the BPM multiplexer units is nearly complete. Design of the injection- and extraction-line BPM sensors has been completed and a revised design of the Ring BPM sensors is being considered. A new requirement is that these units must fit inside the Ring quadrupoles to save straight-section space.

With the recent addition of appropriate staff to the project team, a comprehensive review of the PSR timing and rf synchronization chain has been initiated. Much of the complexity is centered about the various pulse-selection options controlled by the H^- beam chopper; therefore, the first part of this review is directed toward an understanding of how PSR and Weapon Neutron Research (WNR) interact with LAMPF in manipulating this device.

The extraction transport quadrupoles have been designed, and the drawing package is now out for bids. The system consists of twelve 4-in.-diam units and eight 6-in.-diam units.

The extraction-kicker modulator test stands have been modified to accept the new 5-in.-diam EG&G thyatron switch tubes, and new high-power matched loads have been built. Extensive component-lifetime tests for the modulators are planned.

The VAX 11/750 controls computer has been received from DEC and installed next to the WNR facility control room. The machine has been up and running for several months and is beginning to be used for PSR-related physics and engineering calculations, through a network of user access terminals. The VAX is connected to an LSI 11/23 node for system software development, an ongoing effort. The design and status of the PSR I&C system (in particular the software) has been comprehensively reviewed, and user-compatible (control) channel-listing forms were developed. The bulk of the channel-listing effort for all PSR equipment systems is anticipated during calendar year 1982.

In the following sections, we discuss in more detail several PSR systems involving substantial R&D effort.

THE 500-MHz BUNCHER FOR PSR

Substantial progress has been made on the capability to tune an rf cavity by externally changing the magnetic properties of ferrite material placed in the cavity. We have found materials that can be used in the cavity without substantial reduction in Q . With this rapid-tuning technique, the change in impedance of the buncher cavity during beam loading and unloading can be tracked, enabling use of an rf transmitter with substantially lower power output.

After information gained at Georgia Tech from a short course on the use of ferrite materials for microwave applications, a coaxial cavity resonator was built and several ferrite materials were tried. Of those materials, Ampex CVG-630 gave a total tuning range of 43 MHz at 500 MHz, with a 10-MHz tuning range over which the Q of the cavity was not seriously degraded. Based on this information and some additional consultation with staff at Georgia Tech, several materials from other manufacturers were also tested, and we chose the material* that gave the best results. In this case, the best results are defined by the widest tuning range and the lowest degradation of the cavity's Q . This material gives a 10-MHz tuning range for a 3% ferrite volume in the cavity at 500 MHz. A prototype configuration is now being designed.

LINE D BUNCH ROTATOR

Studies of beam injection into the PSR demonstrate that it is desirable to install an rf cavity, termed a "bunch rotator" in the Line D beam-transport system. The cavity will aid in matching the LAMPF H^- beam to the longitudinal phase area available for injection into the PSR.

The PSR longitudinal phase-space capture area, generally referred to as a "bucket," is delimited in the coordinate δs (the longitudinal position relative to a nominal origin) by experimental requirements for the pulse length delivered to the WNR target. The $\delta p/p$ (describing the fractional deviation

*G-810 developed by Trans Tech of Gaithersburg, Maryland.

from nominal particle momentum) must be limited to be within the PSR acceptance range. Figure 4 shows a bucket for the short-pulse mode, which produces a "good" momentum spread ($\delta p/p < \pm 0.2\%$) and a full-width 1-ns pulse. This bucket defines the minimum phase-space area for containment of 10^{11} particles and provides a conservative target area for injection. The bucket dimensions can be expanded by nearly a factor of 2 in both dimensions without exceeding operating parameters. However, it is desirable to maintain a small bucket so that (1) the stored beam pulse is sufficiently narrow to produce at WNR a neutron pulse whose duration degrades to instrumental resolution minimally, and (2) the stored-beam transverse amplitude has a minimal dispersion component. The small beam dispersion in turn facilitates transport to the WNR target, decouples dispersion from other dynamic processes (such as injection) that determine beam transverse distribution, and allows control of dispersion magnitude; these features provide management of an important variable in optimizing beam characteristics.

Particles placed within the minimal bucket of Fig. 4 will be contained in that area throughout injection (as space-charge forces increase with the number of particles), if suitable programming of the rf cavity voltage is applied during the injection cycle. The longitudinal structure of the particle distribution arriving at the PSR must lie within the area of phase space defined; particles that lie outside the bucket will be lost to longitudinal capture in this scheme.

Fig. 4. Longitudinal phase-space plot with the origin referenced to the nominal beam. The area outlined by the characters "X" is the minimal PSR 500-MHz rf bucket. The dashed ellipse outlines the presumed rms beam, emergent from the linac with a presumed 0.1% centroid momentum deviation. The solid ellipse outlines this beam after transport to the PSR. The figure demonstrates that the unrotated beam from LAMPF is not well matched to the PSR longitudinal acceptance.

The expected longitudinal dimensions of the beam at the end of the linac are shown in Fig. 4 as a dashed ellipse that outlines the longitudinal projection of the expected nominal rms beam, that is, a bunch 1.2 cm long, $\pm 0.1\%$ fractional momentum spread, and containing 3.3×10^8 particles.

In addition to the bunch momentum spread, long- and short-term variations in the bunch centroid momentum (average momentum) have been experimentally observed. The long-term fluctuations approach 1% and, fortunately, can be corrected through a feedback device that measures beam energy and varies the tune of the final linac tank. Short-term momentum fluctuations (within a few microseconds) cannot be corrected because of inherent device-time constants but have an rms amplitude $< 0.1\%$.

With this information on the LAMPF beam, it is not difficult to calculate the beam's expected longitudinal distribution upon arrival at the PSR, ~ 120 m from the linac. The results of such a calculation (with 0.1% added to the centroid value of $\delta p/p$) are shown in Fig. 4 as the solid ellipse. The bunch spreads in length during flight because of its initial distribution in momentum. The momentum spread is additionally enhanced by space charge; that is, the mutual repulsion of particles in the bunch increases the momentum spread. Consequences of this latter effect have only been specified within a range of final values because of imprecise knowledge of the particle distribution within the bunch and the particle-wall interaction. The solid ellipse in Fig. 4 represents a model that combines extreme representations of the physical situation and hence probably overestimates the effect of space charge. However, this analysis represents the most unfavorable case likely to be encountered. The main consequence of Fig. 4 is to demonstrate that the beam transported from LAMPF is not well matched to the PSR longitudinal acceptance if the minimal 500-MHz rf bucket is used.

The proposed rotator cavity will accomplish the desired matching to the Ring by providing to the beam a longitudinal impulse of the correct magnitude and phase to decrease the momentum spread. When appropriately placed in the transport line, the rotator will perform other desirable functions that aid in the matching problem. It will minimize the beam momentum spread, regulate the beam centroid momentum, decrease the longitudinal size of the bunch, and decrease the phase of the beam centroid relative to the PSR rf phase. The first two effects are direct consequences of the last two. The first two effects occur because an off-momentum particle arrives at the rotator cavity

(set to a nominal phase of 180°) at a phase deviation that increases with momentum deviation. In the case of a cavity excited with a linear waveform and placed at a great distance from the linac, momentum correction is exact for both the bunch spread and centroid momentum. A sinusoidal waveform introduces nonlinearities into the results; cavity parameters that minimize beam momentum spread provide a decreasing centroid correction as the centroid-momentum deviation increases. In addition, the beam outlines in phase plots deform from elliptical shapes and are not defined by a single momentum-spread figure.

These statements have been translated into mathematical formulae and computer programs to determine optimum bunch-rotator parameters. In Line D a buncher location has been established in the waterfall area, 160 m from the linac. This position is nearly optimum for cavity optical performance and features a small beam size as well as a length of line free of other transport devices. At the waterfall, an ideal cavity requires a 3.4-MV gap voltage to perform as required. An additional voltage of about 10% is necessary to account for finite gap effects. Cavity frequency is set at 800 MHz to use existing design; frequencies as low as 200 MHz could be used with correspondingly higher voltage requirements but with improved linearity as the frequency is decreased. The rotator cavity should be phase locked to a LAMPF 800-MHz reference signal, and on a longer time scale its phase should be referenced to a measurement of beam-pulse arrival time at the end of the linac.

The calculated effect of the bunch rotator on the beam longitudinal structure is shown in Fig. 5, which plots the beam momentum spread versus flight distance from the linac at a 3.4-MV cavity voltage. The figure also shows the regulation of the beam centroid with inclusion of nonlinear effects; note that results are relatively insensitive to the space-charge model used.

In Fig. 6 the achieved match to the PSR 500-MHz bucket is shown for an initial centroid momentum deviation of 0.1%. Distortions (from the nonlinear cavity waveform) limit the momentum deviation that can be matched to less than $\sim 0.2\%$. This figure is within the limits of the fast energy fluctuations observed.

The proposed scheme hence adequately performs the required matching and can be implemented using existing technology. Further development may be necessary to synchronize the cavity phase with the actual beam timing.

Fig. 5.

Plot of momentum deviation versus flight distance from the linac with a 3.4-MV, 800-MHz cavity placed at 60 m. The solid line shows the bunch rms spread. The dashed lines show the centroid momentum deviations for initial spreads of from 0.1% to 0.4%. Bunch spread and momentum regulation are improved by the rotator cavity.

Fig. 6.

Longitudinal phase-space plot similarly showing the minimal rf bucket. The rms beam outlines for a range of initial centroid deviations after rotation are shown, and the improved match to the PSR is demonstrated.

THE 3-MHz BUNCHER

In the long-pulse operating mode, protons from LAMPF are injected into the PSR, stacked into a single bunch, and allowed to circulate. An external force must be applied to hold these circulating protons to a prescribed distribution. A single bunch, filling about three-quarters of the ring, is desired; this provides a 270-ns-long bunch with a 90-ns gap for extraction. A 3-MHz rf buncher will be used to apply this force. A conceptual design for the 3-MHz bunching system has been prepared and a program to produce this system has been initiated. The basic system concepts and some details of the proposed system follow.

The 3-MHz bunching system comprises three major subassemblies: (1) a cavity structure that contains the bunching gap and provides a means of isolating other PSR components from the bunching voltage; (2) a power amplifier that produces a 10 000-V, 3-MHz sinusoidal voltage across the bunching gap; and (3) a control system that regulates the bunching voltage and counteracts undesirable

beam-induced effects. Interaction between the very intense (45-A peak) beam current and the bunching system is the major deciding factor in the selection of a design concept. Properties of the various subassemblies may be adjusted in a variety of ways to control this beam-loading interaction. The particular concept incorporated in the PSR system design is to minimize control-system requirements by providing a low-impedance amplifier almost impervious to these beam-induced effects. A control system capable of completely controlling the beam-loading interaction also will be constructed but will be required to compensate only for effects the amplifier cannot accommodate. Besides providing back-up capabilities, this concept allows complete testing and commissioning without live beam. Table I summarizes some of the more important system parameters.

The bunching cavity will be a balanced coaxial structure ~ 3 m long with a single ceramic insulated gap centered in the structure. The cavity will contain a total of 40 Phillips 4H ferrite cores (35 cm o.d., 20 cm i.d., 2.1 cm thick), providing a distributed inductance of 16 μ H. Distributed capacitance is estimated to be 70 pF; therefore, additional fixed capacitors totaling 130 pF will be added across the gap to achieve a 3-MHz resonance. Saturating field windings will be incorporated to fine tune the cavity resonance and to provide control for beam-loading compensation. Excitation will be applied to each end of the gap, tentatively through half-wavelength transmission lines.

TABLE I

BASIC PARAMETERS OF THE 3-MHz BUNCHING SYSTEM

Frequency	2.795 MHz
Bunching voltage	Programmable to 10-kV peak
Cavity structure	Balanced coaxial, ferrite loaded, center fed
Cavity-tuning scheme	Saturating field, single-turn winding
Number of cavities	1
Number of gaps per cavity	1
Amplifier type	Push-pull, Class A, common-anode configured

Provisions for direct feed also will be incorporated. A mechanism incorporating either air pressure or electric driving devices will force together the gap corona rolls to provide high-quality gap shorting during PSR operation in the alternative short-bunch mode.

A push-pull Class A common-anode-configured power amplifier will provide the bunching voltage. Output impedance in the tens of ohms can be achieved with such an amplifier, reducing to an almost negligible amount its susceptibility to beam loading. To keep the average power dissipated by the amplifier low, the stage will be gated to its on state only during beam stacking and storage times. Tentatively, the amplifier will be located in the equipment building and will be connected to the cavity through half-wavelength transmission lines. Further study is under way.

COMPUTER NETWORK START UP

The PSR I&C system design calls for a network of computers so that the operators have a good understanding of the whole facility and the ability to control it. Four of the six LSI-11/23 computer systems had been delivered when the VAX 11/750 central computer arrived in July. The VAX 11/750 is a powerful computer with an excellent operating system and language support. In the early stages of the I&C system's development, there was a considerable amount of computer power available; therefore, a terminal network was installed for the physicists and engineers working on the PSR, as well as for the I&C section. In addition, there was a need for small data-acquisition systems for testing power supplies and other devices being developed for the PSR.

Thus, two networks have been installed and are operating. The computer network now consists of the VAX 11/750 connected to a single LSI 11/23 node; for software development this is all that is required. It had been decided to base this network on commercial devices and software to get the network established. It was recognized, however, that local networks are a rapidly evolving field and that when the remainder of the network was to be purchased, it might be prudent to change the choice of hardware and basic network software.

Another aspect of the computer network design is that all the support and development for the LSI 11/23 computers is done by the VAX 11/750. Thus, a

major attained goal was to successfully generate on the VAX 11/750 both the operating system and the DECNET software for the LSI 11/23.

Figure 7 shows the two networks. The VAX 11/750 system is at the top of the diagram with the peripherals, and to the left is the DMR-11 connection to the LSI 11/23 system in a CAMAC crate. This is the development system for the PSR control software, and it includes a CAMAC serial highway, which is not shown in the diagram. This system is in the PSR Staging Building because of lack of space in the WNR Control Building. The computer-terminal network is shown in the lower right of Fig. 7. There is a terminal and a dial-in modem in the computer room in the WNR Control Building. Also situated there is a set of local-area modems for the remaining lines. These modems ensure reliable data transmission over long lines and protection for the computer and terminals from the surge voltages usually associated with lightning strikes. Multipair cables are installed between the WNR Control Building and the other two buildings housing the PSR effort, the AT-Division Office Building, and the PSR Staging Building. In these buildings are central sets of local modems and cabling to the individual points where terminals are required. To give flexibility in the connection of terminals, switching jacks are included with the sets of modems, allowing any terminal to be connected to any port.

The use of the VAX 11/750 for physics and engineering codes has escalated rapidly since the computer became available in September, and it is already clear that the computer will provide a most useful service to the project at this stage. It has also proved to be a most reliable machine, with no unscheduled stoppages from hardware problems for the first 5 months of its operation.

ELECTRONICS

The electronic design of the transverse damper and beamline vertical- and horizontal-steering systems has received significant effort recently.

The transverse damper is needed to stabilize the circulating bunches against destructive instabilities induced by resistive-wall effects. The damper beamline sensors will determine the coherent transverse motion of the proton bunches as they circulate in the machine, and a broadband power-pulse amplifier will develop a bunch-restoring force to reposition misaligned bunches to the desired equilibrium orbit.

Fig. 7.
The two networks of the PSR computer system.

A major element in the active damping system is the broadband pulse amplifier, which must furnish nanosecond pulses to a deflection structure at rates >16 MHz at a level of 5-kW peak power. A distributed amplifier (D/A) configuration consisting of 20 power tetrodes has been selected for this service. Progress on the D/A has been made in the design of both the grid and plate transmission-line structures and in the design of the dc power-distribution system for the screen voltages of the amplifier's power tubes. Work on a special power vacuum tube for D/A service for the PSR has also continued at EIMAC Inc. The tube under development (EIMAC 2226) will have a broader bandwidth than other candidate tube devices used for D/A service, and it will permit larger current pulses per tube to be delivered to the deflector than any other known active device qualified for D/A service.

EIMAC has delivered a prototype tube for static parameter testing. Values for all the static parameters have been determined including input capacity (54 pF), output capacity (10 pF), grid-line impedance (11 Ω), and control and screen-grid resonance effects (none observed below 700 MHz); all parameters are within expected tolerances. The first fully active tube is currently under test at EIMAC, with delivery to Los Alamos expected in early 1982.

A one-tenth scale model of the final D/A has been fabricated to permit evaluation of the grid-to-grid and the plate-to-plate coupling lines and to provide data on bandwidth and load-matching properties. This device was tested and all design aspects were within bounds. The information gained in testing this model is currently being applied to the fabrication of a full-scale D/A, which will use the EIMAC tube.

PROGRAMMABLE BEAM STEERERS

To distribute the injected protons in a controlled pattern throughout the desired cross section of the beam, the injected beam is deflected in a programmed pattern in both the vertical and horizontal planes. Beam movement, and hence the proton distribution, is controlled by programming the magnetic field of a single-turn deflector as the beam passes the device. The vertical-plane movement requires a current-versus-time function resembling a series of cusps (Fig. 8a), each cusp becoming smaller in amplitude as the time-into-cycle increases. The horizontal-current pulse function begins at a large value but

thereafter monotonically decreases rapidly throughout the machine cycle (Fig. 8b).

A full-scale model of the vertical programmer power system has been fabricated and tested. The device consists of a ± 500 -A, 50-kHz bandwidth power amplifier. Twenty field-effect transistor (FET) devices were used as the final current-developing stage. A feedback arrangement, Fig. 9, was used to make the actual magnet current match the time-amplitude history of the programmed input wave. The model device was connected to a 500-nH steering magnet and tested. Figure 10 shows the voltage (top) and current (bottom) waveform produced. The

Fig. 8a.
Vertical-magnet current wave.

Fig. 8b.
Horizontal-magnet current wave.

Fig. 9.
Power electronics for magnet-current programming.

Fig. 10.
Model magnet-pulser waveforms.

current cusps shown (reaching 500 A at the start of the cycle) are in close agreement with the requirements for the overall vertical system. Tests also were made on programming the horizontal wave with good results to 1000 A. Current levels to 1500 A will be investigated with the addition of more power FETs in the final stage. These tests demonstrate the successful approach to development of complex, programmable, current waves in reactive-magnet steerers. Current levels to 1500 A will be investigated with the addition of more power FETs in the final stage.

H⁻ ION SOURCE PROGRAM

The requirement for high-intensity H⁻ ion beams for the WNR PSR has necessitated the development of a new H⁻ ion source. The present H⁻ ion source at LAMPF is a charge-exchange source and is limited to low-intensity operation. Although the development of a higher intensity charge-exchange source is certainly possible, such a source would have fundamental limitations on beam brightness and would be inadequate for LAMPF operations. Various types of direct-extraction H⁻ ion sources have been developed in the past few years for other accelerator applications, such as the magnetron sources at the Fermi National Accelerator Laboratory and at the Brookhaven National Laboratory. These sources have adequate peak current, but are limited to low duty-factor operation. A different approach is needed to provide an adequate quality source for the PSR, and it was necessary for LAMPF to undertake a development program to provide such a source.

Fortunately, high-current H⁻ sources recently have been developed in the Lawrence Berkeley Laboratory fusion program to provide intense neutral-beam injection. To make use of this type of ion source for accelerator operation, additional development is necessary in the area of high-voltage extraction of high-brightness beams. A similar development program has been carried out at LAMPF in improving the brightness of the proton beams from the LAMPF duoplasmatron. It was decided to develop a scaled-down version of a suitable neutral-beam injector ion source to provide a relatively low-current but high-brightness beam. The initial goal of this program is to obtain an ion source that will produce H⁻ beams with the same intensity and beam quality as the H⁺ beams now used for production at LAMPF.

Ion Source Concept

The ion source concept most closely meeting our requirements is the self-focused, cusped-field source developed at Berkeley by Ehlers and Leung.¹ A schematic diagram of our first prototype, based on the Berkeley concept, is shown in Fig. 11. A cusped-field magnetic bucket is used for confinement of a low-density hydrogen plasma. A converter electrode in the form of a spherical cap is immersed in this plasma and biased several hundred volts below plasma potential. The production of H^- ions is effected at the surface of the converter electrode mainly by desorption of hydrogen atoms because of positive ion bombardment. These H^- ions are self-focused into a converging beam by the spherical plasma sheath at the converter surface. This beam propagates through the plasma to an exit aperture in the magnetic bucket and then is accelerated by a high-voltage extraction system to the desired operating potential. For

Fig. 11.
Prototype cusped-field H^- ion source.

these beams to be useful in an accelerator application, the extraction system must suppress a high electron flux with a minimum distortion to the H^- beam. A static dipole magnetic field and a biased exit electrode, termed a plasma-repeller electrode, are used to effect this electron suppression. The development of these concepts is now being pursued both at Berkeley and Los Alamos and is expected to produce an accelerator-quality H^- ion source.

Experimental Program

An experimental program was undertaken at LAMPF to demonstrate the feasibility of using this ion source concept for the PSR. A small cusped-field ion source and a ground-level test stand, which had been previously used in the development of intense H^- ion beams, were obtained. The ion source was modified to accept a converter electrode, a standard duoplasmatron beam-extraction system, and a plasma-repeller electrode. The aperture in the plasma-repeller electrode, together with the size of the converter, was chosen to produce a small-emittance ion beam, a choice that subsequently has been found to be too restrictive for optimum operation. Nevertheless, these modifications and design choices did permit a low-current prototype source to be built.

The ground-level test stand was refurbished and the necessary modifications were made to test the prototype H^- ion source. The ion source produced an 8-mA-dc beam of H^- ions at 200 eV, which was the current expected for this prototype design. The source then was mounted on a high-voltage test stand and H^- beams were extracted at energies up to 100 kV. These beams were momentum analyzed and emittance data were taken with a standard LAMPF emittance-scanning system. In the initial high-voltage tests, problems were encountered in obtaining proper cooling to the accelerating structures on the test stand. This constraint limited the arc power that could be run safely in the ion source and thus the H^- beam current that could be obtained from the source. Nevertheless, H^- beams up to 4 mA_p at 10% duty factor were successfully extracted and transported to the emittance scanners. Emittance measurements taken with the scanners (Fig. 12) confirmed that the emittance of these beams is indeed within the designed geometrical admittance of the prototype ion source. Stable, quiet operation of this source was achieved in these first tests.

Fig. 12.
Horizontal emittance distribution for
a 4 mA_p H⁻ ion beam.

Experimental Results

The initial results obtained with this first prototype ion source demonstrate the feasibility of using an H⁻ cusp-field-type ion source for accelerator applications. High-quality beams at 100 kV of 4 mA_p were obtained, and further tests with a cooled version of this design yielded beam currents of 8 mA_p. The emittance of the extracted beam can indeed be defined by the geometrical admittance of the ion source, which was 0.08 cm·mrad (normalized) in these first tests. The H⁻ beam fraction typically is 95% of the total extracted ion beam.

Electron loading was small (as evidenced by current drain on the high-voltage power supply) but certainly was not completely eliminated, because there was significant x-ray production. The rise time of the extracted H⁻ beams was several microseconds. No other significant transients in beam current were observed with unanalyzed beam. Voltage modulation of the converter electrode permitted rapid (several microseconds) current modulation of the extracted beam. We expect that further development of this self-focusing, cusped-field-type ion source will result in an ion source that will produce the desired beam currents for the PSR application with the high brightness required for high-duty accelerator operation.

REFERENCE

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THE NBS-LOS ALAMOS RACETRACK MICROTRON

SUMMARY

The NBS-Los Alamos racetrack microtron (RTM) is being built as part of an accelerator research project whose goal is to determine the feasibility of building high-energy, high-current, continuous-beam electron accelerators using beam recirculation and room-temperature rf accelerator structures. This joint project of National Bureau of Standards (NBS) and Los Alamos was initially funded in September 1979 by the Division of Nuclear Physics, Department of Energy.

The major effort on the project in the second half of 1981 has been on the design and construction of various components for the demonstration RTM. The important parameters of the machine include 5-MeV injection energy obtained by the use of a 100-keV gun followed by a cw linac; 15 passes through the microtron with a 12-MeV energy gain per pass, for a final 185-MeV energy; and a design cw current capability of 550 μA . Figure 13 shows the layout of the RTM. Los Alamos has the responsibility of building the rf power system, the rf chopping and bunching system, the rf beam-position monitors, and the control system. In the following sections our progress during the last half of 1981 is described in detail.

Fig. 13.
NBS-Los Alamos racetrack microtron.

ACCELERATING STRUCTURE

Considerable progress was made on the disk-and-washer (DAW) structure during this period. The DAW structure supports numerous modes with frequencies above and below the operating-mode frequency. These modes were studied in DAW Test Cavity 3 and the results were presented in a paper on the DAW structure¹ and also are summarized in Fig. 14. Of special concern is the proximity of the TM₁₁-like modes to the accelerating mode. We hope to tune the structure to avoid these modes in the 2.4-m-long preaccelerator structure (Fig. 15), which is in the later stages of construction. The structure is 2.4-m long and is bolted together with stainless steel flanges at three places. It consists of two ends and two sections, each slightly longer than 1.1 m. One end piece has an rf coupling iris to the WR-430 waveguide. Only one vacuum port is required, because the structure is so open that vacuum conductance is no problem for a structure of this length. Longer sections will require vacuum ports.

The DAW structure is quite complicated to fabricate because there are several hydrogen furnace-brazing steps and copper plating of stainless steel parts. Figure 16 illustrates the various braze joints and the copper-plated Y-stems. In addition, some parts had stainless steel flanges brazed on with 50% gold, 50% copper at 970°C. The washers are made by brazing blanks (with water channels machined in them) together with Palcusil 5, at 810°C. These brazed parts are then machined to their final shape.

Two problems were encountered with the washer fabrication. The first was that 4 washers out of 38 leaked after machining to final shape. Visual inspection showed gaps in the

Fig. 14.
Brillouin diagrams of some modes in the DAW test cavity.

Fig. 15.
Preaccelerator structure showing the waveguide coupling, the vacuum port, and the water-cooling channels.

Fig. 16.
DAW structure showing order of braze joints.

braze joints of a large fraction of the washers; these gaps probably result from stress in the copper caused by machining the blanks from the large copper billets that were used also for the disk sections. The billets were annealed before machining, but the annealing should be done after the parts are rough machined to shape, and then finish machined before the washer blanks are brazed. This should prevent the gaps from developing between the copper parts. The second problem with the Palcusil-5 braze joint in the washers occurred when the washers were exposed to the Cusil braze of the Y-stems at 780°C. The Palcusil-5 joints, that had been tight, developed leaks, and the gaps became more visible. All leaking Palcusil-5 joints in these washers were repaired successfully with Cusil. However, the end piece with the waveguide connection also had a Palcusil-5 braze, to form water-cooling channels. This end piece developed gaps in the Palcusil-5 joint that leaked when the waveguide was brazed on with Cusil. The joint could not be repaired with Cusil, and the piece had to be taken apart and redone. In the future, Palcusil 15, which melts at 900°C, will be used on all joints that previously were brazed with Palcusil 5.

Problems also were encountered with the copper-plated stainless steel Y-stems. The copper plating "blistered" at furnace-brazing temperature, and

the stainless steel surfaces that had only a nickel strike for brazing to the copper were badly oxidized. The blistering was traced to oil contamination in the copper-plating baths. (The oil had dripped from an overhead crane.) The second time, the copper plating on the Y-stems survived the preheat, but the surfaces to be brazed again (which had a nickel strike and a 30-s copper strike) were badly oxidized. Inspection of these surfaces showed that the nickel and copper apparently had disappeared. This problem was solved by giving these surfaces a much heavier, 5-min copper strike. All 114 joints between stainless steel, plated with a 5-min copper strike, and copper were successfully brazed with Cusil.

In conclusion, the DAW structure is difficult to build, but the major problems have been solved; in the future, DAW structures should be built successfully, with less trouble.

THE rf CHOPPING AND BUNCHING SYSTEM

Both rf deflection cavities were built and delivered to NBS for assembly in the 100-keV beamline. The buncher cavity also was completed but was not delivered to NBS because it was needed for testing the chopping and bunching rf drive systems. The rf testing of the deflection system showed that driving both the TE201 and TE102 modes in the square deflection cavities with phase and amplitude control requires two 75-W tube-type rf amplifiers.

A source of reliable 1-W 2380-MHz solid-state amplifiers finally has been found. These amplifiers are used to drive the 500-kW klystron and 75-W tube-type amplifiers. The in-house effort to develop 1-W amplifiers was successful, but the commercial source was considered cheaper and more reliable because it was very well protected against mismatched loads. This amplifier actually can provide 2 W of rf power; therefore, more losses in the transmission lines could be tolerated.

X, Y, Z BEAM-POSITION MONITORS

The x, y, z beam-position monitors will measure position, relative phase, and beam intensity at various locations in the RTM. These monitors need

response time short enough to respond to a 40-ns-long beam pulse as it circulates through the RTM. The transit time for one orbit will be ~ 100 ns. Therefore, $Q \leq 40 \text{ ns} \times 2\pi \times 2.38 \text{ GHz}$ or $Q \leq 600$. Tests performed with the rf deflection cavities showed that Q s as low as 100 could be obtained with the use of probes that couple to the electric field of the TE102 or TE201 modes; thus it is possible to have response times as short as 7 ns with this type of cavity. The x, y, z beam-position cavities have been designed, and an order for a prototype fabrication has been placed. The tuning of a low- Q cavity is not critical; therefore, no tuners or temperature control is required.

THE RTM CONTROL SYSTEM

The hardware and software effort on the RTM control system advanced substantially during the latter half of 1981. In the area of hardware development, we completed and shipped another secondary station control system to NBS in Washington, DC and installed updated software there. We participated in a program review in Washington, at which the hardware was demonstrated. Individual Multibus control-system boards were completed and fabricated. These included the quad stepping-motor controller board, complete with limit-switch indicators for each controller; the binary link board, which provides 24 lines of binary status data and 8 lines of binary control data; the link interface to the primary control station; and the console-printer interface board, which provides interrupt-driven control of the operator's front panel and interface control of the Centronics line printer.

In the area of software development, the secondary-station console interpreter was completed and largely debugged, providing excellent operator control of loop and monitoring functions at the secondary station in a custom engineering language, which presupposes no detailed operator knowledge of the system or the software for its use. We also completed writing the console service code and the data-base editor codes. This total software effort amounts to about ten thousand lines of code and occupies 32-k bytes of Erasable Programmable Read Only Memory (EPROM) in the main single-board computer.

We participated in the 1981 Linear Accelerator Conference in Santa Fe, New Mexico, October 19-23, and our paper on the control system appears in the proceedings.²

THE RTM rf SYSTEM

The second 2380-MHz klystron was tested at the vendor's plant and shipped to Los Alamos. The 1072-kW, 65-kV power supply was installed at Los Alamos during the summer. Severe problems were found with the crowbar unit of the power supply; repairs to solve these problems were made during October. The large (400-gpm) deionized water system required for testing the klystron and power supply was ready in early November. By late November the first klystron had been tested to 500 kW, the rated output power. The klystron passed its acceptance tests at Los Alamos, but there were problems in the body-current protection circuit. Investigation of these problems showed that the output voltage of the large power-supply had 15% ripple, rather than the specified 1%. Several weeks were spent trying to find the cause of this ripple, and finally an engineer from the vendor came to find the problem. The exact cause of the problem could not be located. The testing sequences were terminated by water getting into the power supply oil tank. The problem appeared to be in the transformer/rectifier portion of the power supply, which was returned to the vendor for repair. The vendor disassembled and baked the coils to dry out the system. After assembly, the transformer/rectifier appears to pass the acceptance tests at the vendor's plant, although the vendor can only test the device to 9% of full-load power. We are pressing the vendor to complete the tests at full-load power before the unit is returned to Los Alamos. The second power supply has been delivered to the NBS in Washington, DC and is being installed.

The design of the NBS rf system essentially is now complete.³ Most of the individual parts are on order, and the construction of individual chassis is beginning. Waveguide layouts for the high-power tests at Los Alamos and the actual accelerator at NBS have been prepared and the parts have been ordered. The crowbar that was furnished with the power supply is physically too large for the NBS installation, so a smaller oil-filled unit has been designed and construction has begun.

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THE GYROCON RADIO-FREQUENCY GENERATOR PROJECT

SUMMARY AND STATUS

The gyrocon was rebuilt with a new electron gun and a water-cooled gun-focus coil late June of 1981. The new gun and coil performed well: the beam could be focused down to a 1-cm-diam spot on the phosphor screen and could be deflected into a hollow circle. The deflection cavity had to be conditioned with rf power before enough fields could be supported to deflect the beam. The screen was removed and the bender-cone magnets installed. At beam currents below 0.5 A, peak output powers of 200 to 400 W per output were realized. However, the field in the output cavity remains constant for beam currents between 0.25 and 2.5 A and for beam voltages between 60 and 120 kV. A series of inductive irises were placed in the output waveguide to alter the coupling of the external load to the cavity. A modest improvement in output power, to 500 W per waveguide, was obtained but the output-cavity fields remained the same.

Work on the project ceased in August when the FY 81 funds were expended; the highest output power that had been reached was 1000 W. The problem seemed to be a strong multipactor level in the output cavity. Because of the multipactor, most experimental variables (beam voltage, beam current, bender magnet settings, and even the frequency of the output cavity) had very little effect on the experimental performance. Measurements with uncalibrated probes indicated that fields in the output waveguide had approximately equal amplitudes at each of the first four frequency harmonics. The multipactor discharge evidently was preventing a traveling wave from being set up in the output cavity. The output fields were establishing a standing wave in azimuth, and the beam could not transfer much energy into this standing wave. The voltage minimum of the output field probably was in the region at which the multipactor discharge was taking place. Thus, impulse excitation of a nonresonant cavity was occurring, and the output was rich in harmonics. We attempted to drive the output cavity from an external generator, but the multipactor level was also seen from that direction, and the output cavity would only accept ~500 W from each output loop, with higher powers being reflected. Funding for FY 82 did not arrive until late December; work on the project will resume in January 1982.

KLYSTRON ANALYSIS-CODE PROJECT

SUMMARY AND STATUS

A project to produce a klystron analysis code that will be useful in reducing the electrical-energy demand for accelerators was initiated in October 1981. The computer model chosen is a ring model, and time is the independent variable. A set of electron rings is followed through the various cavities and drift spaces that constitute a klystron. Each ring can change its radius, azimuthal angle, and axial position, but the ring is assumed to remain circular and on the axis.

The code is written in FORTRAN, and more than 1250 lines of code have been written to include the initial beam generator, the space-charge routine, a simple cavity subroutine, and a piecewise-linear solenoidal field subroutine. Thus, klystrons consisting of several cavities and drift spaces within a piecewise-linear solenoidal field may be analyzed by the code. A variety of test runs have been made to verify the correctness of the code; several errors have been found and corrected. For some test cases, there was good agreement between the new code and older, disk-model codes; however, serious disparities remain in other cases. When these disparities are found, both codes must be carefully examined and the errors removed.

All sections of the code that have been written will be generalized as time permits. For example, the initial beam generator can be generalized to accept electron rings from one of the electron-gun analysis codes regularly used within the division. A more elaborate calculation of the cavity of fields, either within this code or from SUPERFISH, also would be a useful improvement. The only section of the code that has not been written is the iterative gap-field calculation.

The beam current is now calculated and a gap field is calculated from the knowledge of the cavity impedance. However, the gap fields alter the beam current, and this changes the gap-field amplitude and phase. Thus the gap fields must be calculated iteratively; this will be implemented soon.

LOS ALAMOS FREE-ELECTRON LASER EXPERIMENT

SUMMARY

A free-electron laser (FEL) amplifier experiment^{*} to test the performance of a tapered wiggler at high optical power has been successfully completed. A well-separated two-component electron energy distribution has been obtained that is characteristic of a tapered wiggler. Energy-distribution spectra and extraction efficiencies have been measured as a function of initial electron energy, energy spread, emittance, optical power, and spatial and temporal misalignments of the laser and electron beams. A maximum efficiency of ~4% was measured and good agreement between efficiency and a one-dimensional theory was obtained.

BACKGROUND

John Madey¹ and his coworkers at Stanford conceived the first FEL and successfully built one to operate at $3.2 \mu\text{m}$.² Their major goal, to achieve sufficient optical gain to assure oscillation, was accomplished by constructing a long (5.3-m) untapered wiggler and by operating with a high (2-A) electron-beam current. These conditions unavoidably led to saturation of the output at a low optical power (20 MW) and to a low extraction efficiency ($\leq 0.25\%$) for conversion of the electron's energy into light.³ Among other measurements, Eckstein and his coworkers followed the evolution of the spectrum of light emitted during the build-up of the oscillation and the concurrent change with time of the electron energy distribution.⁴ Because of the low extraction efficiency, the total spread in electron energy caused by the generation of light was less than 1%.

^{*}Work performed under the auspices of the US Department of Energy with the support of the Air Force Office of Scientific Research, the Defense Advanced Research Projects Agency, and the Naval Systems Command.

Since the Stanford experiment, many workers have developed schemes for enhancing the efficiency of FELs. The simplest involves a tapering of the wiggler, either in wavelength or in field strength, so that electrons can remain resonant with the optical field throughout the wiggler's length, even though they lose a large fraction of their energy in that passage.⁵ The degree of taper is matched to the optical power for which the wiggler is designed to operate. Unfortunately the taper introduces problems. The gain of an untapered wiggler is not too high, but the gain of a tapered wiggler is even lower at those low power levels at which oscillations must start. Because of this "start-up" problem, the taper cannot be made too extreme unless special efforts are made to increase the small signal gain. Since gain is proportional to electron current, a profitable approach is to increase the current as much as possible until the beam's quality, that is, the energy spread and emittance, begin to deteriorate.

The FEL experiment recently completed at Los Alamos is an amplifier experiment, designed to use a tapered wiggler to measure its efficiency and gain and to have sufficient diagnostic capabilities so that any problems associated with the interactions taking place in the wiggler will be revealed clearly. Following the approach presented above, the electron current was made as high as possible (5 A), and the taper in the wiggler period was increased to 12%, trading against the small signal gain, which fell at this point to a minimum acceptable level (3%). With this taper, the wiggler performs best at 0.5-GW optical power. The gain rapidly falls for higher optical powers.

In designing the experiment, particular emphasis was placed upon the electron beam diagnostics. Computer simulations had shown that the wiggler interaction should produce a maximum energy spread of ± 7 to 8% and that copious detail would be present in the form of peaks and valleys in the distribution.⁶ To reveal this detail, a spectrometer analyzing system was devised with an energy resolution of 0.1% or better. It employs a fluorescent screen as a target for the electrons and a remote TV viewing system looking at the screen. A particular advantage of this system is the two-dimensional nature of the output. Not only can great detail be seen in the energy spectrum, but orthogonal deflections caused by the finite emittance of the beam and by instabilities of various kinds can be seen readily.

As a result of the emphasis on electron beam diagnostics, design tradeoffs made optical diagnostics difficult to perform. The results of our optical tests will be reported later; here we cover four topics: a brief discussion of the overall system; the measured performance of the major components; the results of the electron beam diagnostics; and a concluding discussion, comparing the results with one-dimensional theory. In other publications we report on our earlier work on planning and designing the experiment,⁷⁻⁹ on the optical diagnostic techniques used,¹⁰ and on preliminary results.¹¹⁻¹³ Detailed discussions of the overall system were given in previous progress reports: LA-8592-PR, LA-8736-PR, and LA-9131-PR but a brief review of the system is included below.

SYSTEM DESCRIPTION

Accelerator

Figure 17 is a plan view of the beamline, showing most of its major components; the accelerator, labeled ACC, was designed and built specifically for this experiment. It consists of an injector, a fundamental-frequency buncher, a single accelerating tank, and an rf system operating at a 1.3-GHz frequency with a 20-MW peak power. The injector provides a 70-keV electron pulse with a peak current of a few amperes and a duration of ~ 5 ns. After bunching in a single-cavity fundamental buncher, the electrons are accelerated to ~ 20 MeV in a standing-wave, side-coupled accelerating structure. This structure consists of 24 coupling cells and 25 accelerating cells, the first four of which form a tapered- β section with an initial β of 0.75. The linac operates in the stored-energy mode with an ~ 8 -MeV/m gradient.

Beam Transport

The beam-transport system includes the bending, focusing, and steering parts of the beamline. To obtain collinearity of the electron and laser beams, it is necessary to provide a bend in the electron beamline. A doubly achromatic system consisting of three dipole magnets (D in Fig. 17) is used to bend the beam by 60° . Focusing and steering is accomplished by a pair of quadrupole

- ACC - 20 MeV electron accelerator
- D - Dipole magnet
- QT - Quadrupole - Triplet
- V - Valve
- VS - View Screen
- BS - Beam Scraper - removes low energy electrons
- WIG - Permanent Magnet Wiggler
- S - Spectrometer

Fig. 17.
Plan view of the beamline showing the major components.

triplet magnets (QT in Fig. 17) and by several steering magnets located at appropriate positions along the beamline, along with a number of view screens, labeled VS, and current transformers. A beam scraper (BS in the figure) is located in the middle of the second dipole magnet where the energy dispersion is the largest. This scraper is used to remove the low-energy tail of the

electron's energy spectrum and to reduce the overall energy spread of the transmitted electrons to $\pm 0.5\%$ or less.

Wiggler

The wiggler (WIG in Fig. 17) provides a spatially periodic magnetic field. It is composed of 314 nearly identical SmCo_5 permanent magnets, each 0.5 cm by 0.5 cm by 3.5 cm long. The magnets are arranged to provide 40 periods of the magnetic field, covering 1.0 m, and a matching section at each end. Figure 18 shows a section of the partially assembled wiggler near its center; Fig. 19 shows a matching section near one end; and Fig. 20 shows an overall view of the wiggler cartridge being inserted into its vacuum chamber. The matching sections consist of a pair of rotatable magnets that can be adjusted to provide a smooth transition from zero to full magnetic field at the ends of the wiggler. The peak field at the center of the wiggler is 3.1 kG and the aperture for the electron and laser beams is almost 9 mm. The wavelength of the magnetic field is tapered by $\sim 12\%$. The wiggler is equipped with magnetic shields and trim coils to assure the proper electron trajectory within

Fig. 18.
Central part of wiggler showing the magnets and their mounting technique. The central fluorescent screen is inserted through the large rectangular hole on the side.

Fig. 19.
Entrance of wiggler showing one member of rotatable pair.

Fig. 20.
Wiggler cartridge being inserted into vacuum chamber. The trim coils and magnetic shield surround the vacuum chamber. Three pneumatic actuators to insert fluorescent screens can be seen on the right, the corresponding TV viewing systems on the left.

the wiggler. Movable fluorescent screens, viewed by TV vidicon cameras, are provided at the entrance, middle, and exit of the wiggler to assist in the alignment and superposition of the beams. Many of these auxiliary devices can be seen in Fig. 20.

Laser

The CO_2 laser consists of a reinjection oscillator/preamplifier (developed for the Los Alamos Antares laser fusion program) and a Lumonics Model 600 final amplifier. It operates on a single line (P20) of the CO_2 10- μm band and in a single longitudinal and transverse mode. It has a 1-GW peak power with a pulse length variable from 1 to 10 ns. The laser beam, transported by copper mirrors, enters the vacuum beamline through a salt window (lower right, Fig. 17). The beam is focused near the center of the wiggler; the spot size is close to the diffraction limit.

Diagnostics

The diagnostics include an electron spectrometer (S in Fig. 17) to measure the energy spectrum of the electrons leaving the wiggler and an optical detection system to measure the amplification of the laser beam leaving at the top right of Fig. 17. The electron spectrometer consists of a dipole magnet that bends the electron beam by 90° , a fluorescent screen, and a vidicon TV system viewing the screen. With this system, the electron energy spectra taken with

and without the laser beam can be compared for various initial electron energies, different optical powers, and other combinations of variables. These measurements provide the data from which the energy gained or lost by the electrons can be calculated.

Table II gives a listing of the design parameters of the accelerator, laser, and wiggler. In the next section we discuss the measured performance of each.

COMPONENT PERFORMANCE

Accelerator

Although the current drawn from the pulsed electron gun increases steadily with heater power, the current leaving the accelerator saturates at 0.9 A and, when adjusted to allow an energy spread of $\pm 0.5\%$, the current leaving the scraper and entering the wiggler saturates at 0.4 A. We normally operate below saturation with a 0.35-A wiggler current.

The electron current occurs as a series of micropulses, ~ 30 ps long (according to computer simulations) and separated from each other by ~ 0.77 ns. The whole pulse train occupies ~ 5 ns. Figure 21 is an oscilloscope trace of a current pulse showing the partially resolved micropulse structure. The value of the peak current is 20 to 30 times the average current, but is of consequence only to measurements of gain and has no effect upon the electron energy distribution function.

Figure 22 shows an energy-distribution measurement of the unperturbed (by the laser) electron beam when the scraper is fully withdrawn. The FWHM is $\pm 0.1\%$, but a long tail containing much of the current stretches to lower energy. A heavy copper block can be inserted into the beamline (at position BS on Fig. 17) to block this tail. We normally adjust this "scraper" near the -1% point of Fig. 22 and, for use in computer simulations, approximate the resulting truncated distribution with that shown by the dashed line. To reveal fine structure, we sometimes narrow the distribution further; when we need high current, we broaden it further.

View Screens 3 and 4 are used to measure emittance. The electron beam is focused on Screen 4 and its radii measured on both 3 and 4. The emittance is

TABLE II

NOMINAL EXPERIMENTAL DESIGN PARAMETERS

Optical

Wavelength	10.6 μm
Optical power	500 MW
Strehl ratio	0.5
Rayleigh length	40 cm
Radius of focal spot	0.16 cm
Pulse length	5 ns

Electron Beam

Average electron current	0.3 A
Peak electron current	5 A
Electron energy	20 MeV
Energy spread	$\pm 0.5\%$
Emittance	$\pi \text{ mm}\cdot\text{mrad}$
Radius of focal spot	0.05 cm
Pulse length	5 ns

Wiggler

Length	100 cm
Length of exit/entrance regions	5.0 cm
Taper in wavelength	12%
Max/min wavelength	2.7/2.4 cm
Number of wiggler cycles	40
Total number magnets	314
Magnet size	$0.5 \times 0.5 \times 3.5 \text{ cm}^3$
Gap between magnets	0.88 cm
Peak magnetic field	0.31 T

Theoretical Performance for Nominal Parameters

Energy extraction efficiency	2.8%
Optical gain	3.0%

Fig. 21.
Partially resolved train of micropulses.

Fig. 22.
Energy distribution of unperturbed electron beam.

calculated from $\epsilon = \pi r_3 r_4 / L$, where L is the separation between the screens. Various focus coils on the accelerator have strong effects on the beam emittance; one, in particular, could change ϵ from $\pi \text{ mm} \cdot \text{mrad}$ to $7\pi \text{ mm} \cdot \text{mrad}$. Measuring emittance from beam-spot radii in this way is simple, but consistent errors are likely to occur. However, using this technique, emittance values close to the design value are found, and wide variations in emittance can conveniently be arranged to test their effect on the FEL interaction.

Stability is essential if we are to accumulate meaningful data. By stability we mean drift or jitter in beam energy, current, position, or timing. To eliminate jitter in timing, the electron gun pulse is initiated by the laser pulse. The laser pulse shows ~ 20 -ns jitter with respect to its initiation

and, therefore, to the time of peak rf power in the accelerator. Because of the jitter between the trigger to the gun and the time of peak rf power, there is an $\sim \pm 0.25\%$ uncertainty in the electron beam energy. This uncertainty is

one of the major sources of error in the experiment, affecting not only the value of the incident electron energy but also that calculated for the electron extraction efficiency. Jitter or drift in beam current is small and of no consequence for this experiment. Drift in the trajectories of the beam is never significant.

Beam Transport

Two quadrupole triplets (QT in Fig. 17) were used to focus the beam at the center of the wiggler and to do so with a beam of the desired convergence. This goal was complicated by the existence of extra focusing forces in the wiggler in plane x, perpendicular to the axes of the magnets, and by the absence of such forces in plane y, the midplane of the wiggler. We treated this situation by focusing the beam at the center of the wiggler in the y plane but at its entrance in the x plane. When the optimum convergence angles were chosen, the beam size remained small and constant throughout the wiggler in plane x. This system worked without complications.

Because of their combined achromatic properties, three 60° magnets (D in Fig. 17) were used to achieve the bend in the electron beam that merges it with the laser beam. Without this achromatic property, a beam with a 1% energy spread could not be bent through 60° and then focused to a small spot at the wiggler's center. Various tests of this characteristic were made. First of all, no aberrations of spot shape were detected that were traceable to the 1% energy spread. In addition, we measured the trajectories of the beam for widely different initial energies and found that when this energy was changed by $\pm 10\%$ and the field of the achromatic bend was adjusted to pass the beam, the trajectory and its focal position within the wiggler did not change by more than ± 0.1 mm. This insensitivity to initial energy allowed rapid scanning of energies over the $\pm 10\%$ range without realigning the beam and, in this way, allowed rapid accumulation of useful data before some other parameter drifted significantly.

The spectrometer (S in Fig. 17) is designed to focus the electron beam on the fluorescent screen to produce a bright spot or a weaker horizontal streak depending upon the strength of the interaction with the laser beam. The spectrometer can be calibrated (energy versus position on the screen) in two

ways: from a calculation concerning the behavior of the 90° magnet or from a measurement. We have done it both ways and they agree within a few per cent.

Many fluorescent screens (VS in Fig. 17) have been installed on the beamline and within the wiggler. They can be inserted or withdrawn remotely and allow us to determine the position, size, and possible distortion of the beam at various positions down the beamline. When included in the laser path, they also show the position of the He-Ne reference beam and thus indirectly show the relative position of the CO₂ laser and electron beam paths.

Wiggler

We can test the performance of the wiggler with an electron beam in two ways: see if the electron beam successfully goes all the way through the wiggler, striking the three fluorescent screens in their centers, and see if the spectra and the extraction efficiency agree with theory. A more precise but indirect measurement was made using a tight, fine, current-carrying wire to simulate the electron beam trajectories. The wire could be viewed in open air with a traveling microscope and deflections noted in both transverse directions all the way down the wire. To achieve a straight path, it was necessary to take great care in assembling the magnets. First the strengths of the individual magnets were measured, then they were paired and grouped to cancel each other's aberrations; in this way, deflections of the wire (and the beam) were held below 0.1 mm. Any leftover large-wavelength bends (caused by the Earth's field or by other uncompensated fields--such as power lines, motors, etc.) can be corrected using the trimcoil sets shown in Fig. 20. These coils were used for two other purposes: to see if small arbitrarily placed bends in the electron beam could improve the extraction efficiency, and to purposely develop somewhat larger bends to see what characteristic changes occurred in the energy spectra because of these bends.

We had no problems in passing the beam through the wiggler. No measurable current was intercepted by its walls. In no case could the efficiency be improved by using the trim coils. The entrance and exit regions, composed of pairs of rotatable magnets, performed well. Calculations show that in the absence of a laser beam, electrons pass through the wiggler with zero deflection and displacement. With a laser beam present, however, those electrons that lose or gain significant energy in the wiggler are deflected sideways.

The overall deflections are small--in our case <0.1 mm, <0.1 mrad--but might in other cases be large enough to move the electrons out of the laser beam or to deflect the beam enough to falsify the spectrometer streak. These beam deviations are related to the abrupt nature of the entrance and exit regions that we used; they could be reduced by designing more gradual transitions.

Laser

Figure 23a shows an oscilloscope trace of the power output of the laser system versus time. The droop in the laser pulse occurs because of depletion of the gain medium in the three-pass final amplifier. Figure 21 shows the electron current versus time; it gives only a crude approximation of the true time dependence because the measuring instruments used were unable to reproduce the very rapid changes in current, corresponding to the ~ 30 -ps pulses. The measurement is adequate, however, to show that the five or six micropulses arrive at times during the optical pulse when the power differs by a factor of 2 or so. The timing of the micropulses within their envelope is not reproducible, no effort having been made to synchronize them to the laser pulse. Calculations show that the wiggler's response to a train of micropulses occurring at different optical powers can be well approximated by its response to a single micropulse occurring at the average optical power. Because of the lack of knowledge of the precise timing of the micropulses, we are forced to make this "average-power" approximation in the comparison of theory and experiment to be presented later.

The optical pulse (Fig. 23a) has a small amount of modulation to its amplitude, on a nanosecond time scale. This is caused by the beating of different longitudinal laser modes. At times the beating has been very pronounced, modulating the amplitude by over 50% (Fig. 23b). Electron spectra and, especially, extraction efficiency turn out to be quite insensitive to such modulation.

Two features have been introduced into the laser system to reduce modulation: a reflection grating substituted for one laser mirror to eliminate lasing on lines other than P20, and provisions to allow minor variations in the CO_2 pressure in the gain cells to allow a "peaking" of a single longitudinal mode and the elimination of all others.

Fig. 23a.
Typical optical pulse shape. The five marks above the pulse indicate the approximate positions of the electron micropulses.

Fig. 23b.
Pulse shape when severe mode beating occurs.

If higher optical power is needed, it can be achieved at the expense of a significant deterioration of pulse shape. Correspondingly, lower power requirements normally cause a flatter pulse shape. When a series of measurements is performed at different optical powers, this characteristic variation in pulse shape usually is present also.

The position of the waist of the laser beam, its Rayleigh distance, and its Strehl ratio were measured several times during the experiment, both before and after minor changes in the optical system. All three parameters were found to vary somewhat, but these variations were not large enough to cause significant changes in the energy spectra or in the extraction efficiency. All calculations discussed correspond to the nominal design parameters given in Table II.

Most of the scatter in the data presented below is caused by laser problems. These are of three kinds: random shot-to-shot variations in optical power; transverse drift in the position of the beam's axis; and the occurrence of relatively weak reflections of the beam from the wiggler, which interferes with an accurate determination of optical power. These three problems are discussed below.

Variations in optical power are of no significance in most situations for they can be measured easily. Figure 24, however, shows a case where the problem is more serious; in the figure, efficiency is shown as a function of incident electron energy with optical power held fixed. Since the optical power cannot be held really fixed, two strategies can be devised to handle the relatively minor ($\pm 15\%$) power fluctuations: compensate for them in some way or accept them and realize that some extra scatter in the data will result. We have chosen this second way.

Transverse drift of the beam's axis is caused in our case by a combination of a flexible floor and a long beam path. This problem is quite severe: the extraction efficiency can drop by $\sim 50\%$ in 15 min of drift. We treat this problem by sampling a part of the laser beam just before it enters the vacuum window. We can observe the beam with an infrared-sensitive TV camera, watch for drift, and eliminate this motion with a remotely controlled correcting mirror.

Severe retropulse problems can lead to destruction or pitting of the CO_2 laser mirrors, windows, or Pockels cells. Such severe problems were occasionally seen, but usually we noted a relatively weak parasitic signal that occurred whenever the laser's amplifier system was on, independent of the presence of a signal from the laser itself. This internal oscillation lasted much longer than the normal amplified pulses, thus exciting the laser energy detector out of proportion to its power level. No reliable technique was developed to eliminate the $\pm 10\%$ uncertainty in power caused by this effect.

Fig. 24.
Extraction efficiency versus incident electron energy at an optical power of 0.75 GW.

Spectrometer Data Reduction

Raw data from the spectrometer are in the form of a bright streak on the fluorescent screen and TV monitor,

representing the electrons' distribution in energy. When the laser is off and the initial energy distribution is small enough, the streak collapses into a bright spot, like that shown in Fig. 25a. When everything is working under design conditions, the streak splits into two components, one produced by electrons captured in the "bucket," the other by electrons with the wrong phase to do so. Figure 25b is a photograph of the streak, taken from the face of the monitor, showing two components. Figure 26 shows 13 of the horizontal raster lines taken from the video signal making up the TV frame of Fig. 25b. These 13 lines contain all the information in the streak. Finally, Fig. 27 shows these 13 lines superimposed. The lump on the left is composed of those electrons in the bucket; the lump on the right is composed of those electrons relatively unperturbed by the laser and wiggler. Several sharp dips can be seen on the traces; they are marked by bars on the bottom of the figure. These dips are artifacts, caused by calibration lines ruled on the fluorescent screen. They indicate the resolution that can be achieved with the viewing system. Further processing of this data includes four steps: correcting for nonlinearities in the phosphor and TV systems; calibrating the horizontal scale in terms of energy; combining the 13 traces of Fig. 27 to give a single trace of electron density versus energy; and processing this final energy-distribution

Fig. 25a.
Streak showing single spot of unperturbed distribution.

Fig. 25b.
Streak showing two-component distribution.

Fig. 26.
Thirteen raster lines from Fig. 22b.

Fig. 27.
Superposition of 13 lines. The strong vertical bar represents the position of the unperturbed beam. The star marks the group of electrons in the bucket. The weaker vertical bars indicate the positions of calibration lines drawn on the fluorescent screen. Dips in the various curves at these lines are artifacts.

curve to find the energy extraction efficiency. Figure 28 shows an energy-distribution curve after processing and the theoretical prediction for the same initial conditions.

Alignment System

The relative alignment of the electron beam, laser, and wiggler axes was expected to be a crucial procedure in the performance of the experiment. Coincidence of the axes to much better than 1 mm (the diameters of the beams) is required. The alignment procedure uses a He-Ne laser beam as an intermediate reference beam to which the other systems are aligned. This is done as follows:

- The wiggler is aligned with the beamline using a transit.
- The He-Ne reference is aligned with the wiggler, using two cross hairs carefully centered at each end of the wiggler. The reference beam is projected through the wiggler, and the images of the cross hairs are centered in the beam by moving the reference.

Fig. 28.
Experimental and theoretical spectra
after full processing.

- The CO_2 laser is aligned with the reference by deflecting both beams from the wiggler at its entrance onto two targets, one placed at the focal position of the CO_2 laser and the other much closer to the deflecting mirror. "Burn spots" (thermal images) of the CO_2 laser are formed at both targets, and the position of the reference beam relative to the burn spots is measured. Any off-centering is eliminated by moving the CO_2 laser beam. When the deflecting mirror is removed, both beams penetrate the wiggler in perfect alignment.
- The electron beam is aligned with the reference, using the three fluorescent screens in the wiggler to indicate simultaneously the position of both beams. Steering coils along the beamline are used to bring the beams into coincidence on all three screens. The trim coils around the wiggler allow corrections to be made within the wiggler, but no corrections were needed.

RESULTS

A complete description of the experimental results would include the dependence of the spectra upon every property of the electron beam, laser beam, wiggler, and the interaction terms between these. For example, we might investigate the properties listed below. (The relative effort spent to investigate each property is indicated by S for strong effort, M for medium effort, W for

weak effort, and - for no effort; following the list we will discuss those parameters marked S, M, or W.)

Electron Beam

Average energy	S
Energy spread	M
Current	M
Focal conditions	W
Emittance	M

Laser

Wavelength	-
Wavelength spread	W
Power	S
Focal conditions	-
Strehl ratio	-

Wiggler

Taper	-
Length	-
Field strength	-
Entrance/exit length	-

Relative Beam Orientations

Alignment	M
Bends	M

Shape of Spectra

In a preliminary measurement, the initial electron energy was varied over a wide, $\pm 15\%$ range around 20 MeV, and the spectra were measured with all other parameters held fixed. The shapes of the spectra were compared with theoretical expectations; in general the agreement was good. The spectra were rich in detail, varying in overall width from 10% near 20 MeV to almost zero at the energy extremes. Agreement in detailed shape was not perfect for three

major reasons: (1) The experimental results were obtained for a group of five micropulses recurring at five different optical power levels, whereas the theory was obtained for one pulse at an average power. (2) The spectra are sensitive to changes in initial energy. Changes smaller than our experimental uncertainty in the initial energy can cause significant changes in the details of the spectra. Thus we must adjust the parameters somewhat arbitrarily to find the right theoretical curve for comparison. We never have exactly the right one. (3) There remains a real difference between the experimental and theoretical curves, even when the first two explanations given above are taken into account. Figure 28, for example, shows the best fit between theory and this experimental curve that we could find. The misfit cannot be explained by either of the first two explanations. From comparisons such as this, a major finding of this experiment is that theory and experiment do disagree. In the case shown in Fig. 28, where the bucket is well developed, the discrepancy shows up most clearly in the energy of those electrons in the bucket. They lose $\sim 15\%$ less energy than expected from theory. The net extraction efficiency is closer to the theoretical value than this since the fraction of electrons captured in the bucket and appearing in the low-energy peak appears to be slightly larger than predicted.

In Fig. 28, the average electron has lost $\sim 4\%$ of its energy. If the initial electron energy is decreased sufficiently, the electrons are accelerated rather than decelerated, corresponding to laser absorption rather than gain. A typical electron distribution function with an average electron energy gain of $\sim 3\%$ is shown in Fig. 29.

Extraction Efficiency Versus Initial Energy

The spectra discussed above were processed to find their extraction efficiencies. Figure 24 is a plot of this data, obtained at 0.75 GW, plotted against the initial energy. The major scatter is caused by alignment errors, uncertainties in initial energy, and fluctuations in optical power. The calibration of the horizontal scale can be traced to the design of the bending magnets; it has been arbitrarily shifted by $\sim 1\%$ to improve the agreement with theory. This shift is well within the estimated accuracy of the magnet design. No other adjustment of the data or use of arbitrary constants was involved to achieve the agreement shown.

Fig. 29.
Experimental and theoretical spectra
showing electron energy gain.

Dependence of Efficiency on Optical Power

Figure 30 shows how the extraction efficiency varies with optical power when the initial energy is held fixed near the maximum of Fig. 24. The spectra show that the bucket is well developed for powers above the knee of the curve but disappears for lower values. Figure 31, for example, shows a spectrum taken at a 0.2-GW optical power, that is, just above the knee of Fig. 30. The slope of a line drawn from the origin to any point on the curve of Fig. 30 is proportional to the optical gain of the system at that power level. The gain clearly is a maximum at the knee and falls to lower values at both extremes, the small signal and saturation regimes.

Other Electron-Beam Parameters

Variations in energy spread produced only the results expected from theory: a broadening and blurring of the spectra. No noticeable change to the efficiency was found for the maximum effective spread, $\sim 2\%$. The average electron current was varied from a few milliamps to ~ 400 mA; no change was observed in the spectra. The emittance of the beam was varied from about π mm·mrad up to 7π mm·mrad; no significant changes occurred up to 3π but above that value the spectra changed markedly, and the efficiency

Fig. 30.
Extraction efficiency versus optical power for an incident energy near 20.8 MeV.

Fig. 31.
Experimental and theoretical spectra showing bucket at low optical power.

dropped. Many electrons lost an amount of energy midway between the two groups (Fig. 24), filling in the valley and generating a featureless broad spectrum. The same broad spectrum and reduced efficiency resulted from defocusing the electron beam in the wiggler.

Other Laser Parameters

Similar extensive variations were not performed on the laser beam, partly because they were explored by corresponding electron energy variations (for example, wavelength versus initial-energy variations), and partly because they were hard to perform. The only exception is a series of measurements in which the laser operated on a different line (P19) or with multiple longitudinal modes, giving extreme fluctuations in power during the optical pulse. The spectra observed were not unusual in any way but responded to the average optical power averaged over a pulse.

Relative Alignment

The alignments of the laser and electron beams, with each other and with the wiggler's axis, were varied systematically. Three kinds of misalignment were investigated: a mirror rotation was used to shift the laser beam transversely by known amounts; the trim coils were used to bend the electron beam within the wiggler at known positions by known amounts; and external steering coils were used to inject the electrons off the wiggler's axis by known amounts and, in this way, to excite betatron oscillations. Characteristic variations in the spectra and reductions in efficiency were noted in all cases. Instead of being broad and featureless, these spectra all show a large relatively narrow bump at intermediate energies, suggesting that electrons trapped in the bucket were held there only part way down the wiggler. The sensitivity to misalignment is strong. A transverse misalignment of 0.1 mm gives about a 10% reduction in efficiency.

Misalignment in time was also investigated. The relative timing of laser and electron pulses could be varied by delaying the laser pulse by up to 20 ns in an optical "trombone." Good interaction occurs between the beams over a limited range of delay times. More extreme values give poor overlap of the pulses in the wiggler and a characteristic spectra in which a fraction of the electrons have no energy change. The optimum delay can be chosen easily, using this indication.

CONCLUSION

All of the components as well as the combined FEL experimental system worked well. The extensive alignment and diagnostic features proved especially valuable. Electron energy distributions were easily measured and proved to be rich in detail. Among other things, they clearly illustrated the two-component distribution expected of tapered wigglers. The dependence of extraction efficiency upon initial electron energy and optical power was in good agreement with theory. The sensitivity of the spectra and efficiency to misalignment, bent trajectories, energy spread, and emittance variations was about as expected.

The only significant discrepancy between theory and experiment is in the energy loss felt by those electrons caught in the bucket. Theory says they should lose $\sim 7\%$, corresponding to the taper of the resonant energy from the entrance of the wiggler to the exit. Experiment gives a value of 6%. Extensive reviews of our experimental techniques and computer codes indicate that they are not the cause of this discrepancy. Instead, it appears to be more fundamental. This may be caused by a three-dimensional effect not included in our one-dimensional theory and not well treated by other conventional approaches, as discussed below.

The effect of a bucket in a tapered wiggler is to force those electrons trapped in it to steadily reduce their speed along the axis of the wiggler. This can be accomplished in two ways: by reducing the electrons' energy or by deflecting them sideways. Our computer program includes only the first option. Sideways motion surely can take place. Examples are the wiggles, betatron oscillations, and steady crosswise motion in the midplane. In addition, transverse deflecting forces exist that can increase these transverse motions as electrons move down the wiggler. For example, an electron on the edge of the laser beam feels forces toward or away from the axis due to the gradient in the optical fields. A comprehensive treatment of these forces and these motions has not been carried out but might throw light on the discrepancies mentioned above.

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