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October 1984-March 1985

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ACCELERATOR TECHNOLOGY PROGRAM

October 1984 -- March 1985

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ABSTRACT

This report covers major projects in the Accelerator Technology (AT) Division of the Los Alamos National Laboratory. The first sections highlight activities of the racetrack-microtron development programs, one of which is being done in collaboration with the National Bureau of Standards and the other with the University of Illinois; the BEAR (Beam Experiment Aboard Rocket) project; work in beam dynamics; the proposed LAMPF II accelerator; and the Proton Storage Ring.

Discussed next is radio-frequency and microwave technology, followed by activities in accelerator theory and simulation, and free-electron laser technology. The report concludes with a listing of papers published by AT-Division personnel during this reporting period.

NBS RACETRACK MICROTRON

The National Bureau of Standards (NBS)/Los Alamos 200-MeV racetrack microtron (RTM) is being built under a program aimed at developing the technology needed for high-current intermediate-energy cw electron accelerators. Los Alamos is nearing completion of the construction phase of the collaboration. Recent progress includes the following:

- Testing of the 100-keV chopper-buncher system demonstrating a normalized emittance well under the design goal of $2.6 \text{ } \mu\text{m}\cdot\text{mrad}$ at currents exceeding the design goal of $600 \text{ } \mu\text{A}$
- Operating the 5-MeV injector linac at power levels up to 50 kW/m , resulting in an accelerating gradient at $\beta = 1$ of 2 MV/m (compared to the design goal of 1.5 MV/m)
- Testing (with beam) the prototype rf beam monitors that measure current, relative phase, and transverse beam position
- Installing and operating the accelerator control system
- Delivering and installing the 5-MeV injector linac at the NBS
- Demonstrating the multitank rf power distribution and control system, including active feedback control loops on phase, amplitude, and cavity resonant frequency on the two injector linacs under full power

UNIVERSITY OF ILLINOIS RACETRACK MICROTRON

The University of Illinois RTM, funded by the National Science Foundation, is being built to support a research program at the Nuclear Physics Department in Champaign/Urbana. This accelerator is a 750-MeV cw cascade microtron and embodies the technology developed under the NBS/Los Alamos collaboration. The technology contributions of Los Alamos include the following:

- Accelerating structure design
- Linac fabrication technology
- Design and development of a modern accelerator control system
- Fabrication of the chopper-buncher cavities and slit mechanisms
- Fabrication of the beam monitor cavities

Recent progress to date includes the following:

- Delivery of the 1-MeV, Stage I microtron accelerator
- Design of the 4.5-MeV injector linacs
- Design and construction of the chopper-buncher and slit system

Systems currently under construction include the 1.7-MeV capture section and the beam-position monitors. The philosophy and architecture of the accelerator control system is continuing to evolve.

BEAR

The primary purpose of the BEAR (Beam Experiment Aboard Rocket) project is to demonstrate the operation of a particle accelerator in space. The objectives of the experimental program are (1) to develop space-qualified accelerator components, (2) to investigate space craft charging effects, and (3) to observe propagation of a neutral particle beam in the upper atmosphere. The following beam parameters have been defined for BEAR; they apply to the beam properties at a target 10 km from the accelerator itself:

Ion	H ⁰
Energy	1 MeV
Peak current	10 mA (particle)
Pulse length	50 μ s
Duty factor	0.025%
Beam divergence	1 mrad (included angle)
Spot size	10-m diameter

Assuming a uniform particle distribution in real space, the output beam would yield a peak flux of 13 nA/cm² or 3 pA/cm² on the average. These fluxes should be "sufficient" for particle detectors and "adequate" for scintillators and fluors located on a target package. The output beam would be "marginal" for visual observations of air glow from the ground.

The accelerator package would include the following components:

- Ion source
- Source radio-frequency quadrupole (RFQ) matching section
- RFQ
- Radio-frequency and primary power
- Final-focusing transport system
- Neutralizer cell
- Control and instrumentation

Assuming typical values for mechanisms that limit or degrade the beam current, we see that the ion source must provide ~40 mA and that the RFQ must deliver ~25 mA.

The diameter of the final lens is constrained by the mechanical requirements of the neutralizer cell with which it will be an integral construction and by the necessity to limit chromatic aberrations. A final aperture of 5 cm (diameter) and a normalized rms emittance of $0.012 \pi \cdot \text{cm} \cdot \text{mrad}$ appear to be consistent and achievable values.

To propagate a significant fraction (>80%) of the neutral beam a long distance will require that the accelerator be lifted to an altitude of over 250 km. To achieve this altitude using the rockets currently under consideration will require that the weight of the entire accelerator package be kept to within 1500 lbs.

The main rf power objective of the project is to provide 100 kW of peak rf power, which will be used to drive an RFQ in a rocket-based experiment. The rf pulse duration is 60 μs with a repetition rate of 5 pps, and the frequency is 425 MHz. The prime power source will be batteries, and the entire system must be qualified to withstand the rocket vibration and shock requirements. Two rf systems are being investigated: a solid-state system along the lines of the SPS-40 system built by Westinghouse and a system using planar triodes that has been designed at Los Alamos. The RF and Microwave Technology Group of the Accelerator Technology (AT) Division has designed a cavity amplifier system using planar triode tubes for the same application. It is intended that the planar triode system will be a back-up to the solid-state system and also will provide bench test power for the accelerator.

The triode system will consist of three amplifier stages. The final stage of the three-stage system will use 10 triodes operated in parallel in a single output cavity. It is anticipated that the output cavity will operate in vacuum, thus enabling the center conductor to become the coupling loop to the RFQ without a transmission line of appreciable length.

The triode system has been designed and the parts ordered. Construction was started on the first stage in late February. We anticipate that the system soon will be assembled and tested.

BEAM DYNAMICS

EMITTANCE GROWTH OF PARTICLE BEAMS INDUCED BY SPACE CHARGE

We have used both analytical and numerical techniques to study the behavior of a high-current beam as it evolves from an initial nonstationary phase-space distribution to a final stationary state. The search for mechanisms causing undesired emittance growth in such beams has been an active area for many years, and no satisfactory procedure for calculating emittance growth was known, except for numerical simulation. We have succeeded in deriving a differential equation for continuous beams that relates the rate of change of rms emittance to the rate of change of the residual electric-field energy possessed by beams with nonuniform charge distributions.¹ This analytic formula has been verified by our numerical simulation studies and shows the importance of both the beam current and the initial distribution in determining emittance growth. The differential equation can easily be integrated for the particular case of an rms-matched beam, which results in a formula for emittance growth as a function both of the tune depression and the change in nonlinear field energy. We have used this formula to predict universal emittance-growth curves versus tune depression for different initial distributions. The formula also explains the well-known result of a fixed lower limit for output emittance as input emittance is reduced.

METHOD TO DEFLECT PERIODICALLY FOCUSED BEAMS

Several new accelerator applications require ion beam outputs with high current and high brightness, and the manipulation of such beams demands special techniques. For example, to combine beams by funneling requires special care in the deflection of beams to be combined. While the necessary deflection operations take place, it is highly desirable to contain these beams in a periodic focusing system to prevent irreversible emittance growth.

We have developed a method to deflect ion beams while maintaining periodic transverse focusing. The method uses alternating transverse displacements of the lenses in a strong focusing array. In the example shown in Fig. 1, the input beam first traverses a focus lens whose center is displaced in the positive x -direction by an amount α . Next is a defocus lens displaced in the negative x -direction by the same amount, etc. It is apparent that this arrangement produces a net force on the beam in the positive x -direction. The combined

Fig. 1. Periodic thin-lens array with alternating lens displacements. This arrangement produces a deflecting force on the beam in addition to the usual periodic focusing force.

effects of this deflection force, together with the usual strong focusing force, will determine the beam-dynamics behavior. We have analyzed this type of system using both thin lenses and time-varying lenses of the RFQ type. The thin-lens simulations as well as the smooth approximation applied to the Mathieu equation of motion show that these lens displacements establish a displaced neutral axis about which the betatron motion takes place. Figure 2 shows the result of a thin-lens simulation with a particle injected at the origin parallel to the z-axis. The two curves are drawn through the maxima and the minima of the trajectory flutter. The trajectory flutter has an amplitude that varies linearly with displacement from the z-axis, resulting in a force proportional to that displacement. The lens flutter of amplitude α produces a constant force in the positive x-direction. As shown in the figure, the algebraic sum of these two forces combines to produce a restoring force proportional to displacement from the neutral axis. Our experience with this deflection force shows that a suitable programming of the lens-displacement amplitude will permit a variety of useful beam-dynamics manipulations. Future work will apply this deflection method to the funneling process and perhaps to other beam manipulations that may require strict continuity of the transverse focusing.

FLUTTER AMPLITUDE

TRAJECTORY LENS SUM

Fig. 2. Betatron motion produced by the lens array of Fig. 1. Initially, the particle was injected with zero slope at the origin. The upper and lower curves are plotted through the maxima and minima of the flutter motion. The trajectory is sinusoidal about the displaced neutral axis with a period independent of the lens-displacement amplitude.

SCALING FORMULAS FOR MULTICHANNEL ARRAYS

We have studied the potential for using a multichannel beam array for delivering high current density into a single, final target by independently overlapping the focal spots of the beams.² The constraints imposed by the final lens system and the desired focal-spot size imply a limitation on the maximum emittance per beam. We have used recently published scaling formulas for current and emittance of beams from ion sources to deduce multichannel beam scaling formulas for current and emittance per beam versus the number of beams in the array. We find, for example, that for a given total current, the emittance per beamlet can be made arbitrarily small by increasing the number of beam channels and reducing the current per channel. This approach results in a final current density that increases with the number of beams in the array.

LATHE-TURNED POLE TIPS FOR MULTIPLE-CHANNEL RFQ ACCELERATOR ARRAYS

In designing multichannel accelerator arrays constructed of RFQ elements, it is advantageous to use RFQ poles that are constructed on a lathe. Poles of this type can be stacked so that in cross section they form a square lattice. Each interior pole of the lattice forms a part of four adjacent RFQ accelerator channels, and the use of lathe-turned poles allows these beam channels to be closely spaced. The close beam spacing facilitates combining the output beams by funneling, or allows efficient further acceleration of the beams in another type of multiple-beam accelerator.

The geometrical constraints for lathe-turned poles, together with the lowest order RFQ potential function, have been used to derive relations between accelerator parameters. These relations can be used as a part of the RFQ design algorithm to attain high purity in the electric field distributions produced by lathe-turned poles. Figure 3 shows a single lathe-turned pole and its relation to the z-axis of one RFQ channel. The separation of the lathe axis from the z-axis is R_0 , m is the pole modulation parameter, and a is the minimum-aperture radius. The quantities R_1 and R_2 are the transverse radii of curvature of the pole at the beginning and end of the unit cell of length $\beta\lambda/2$.

Fig. 3. A lathe-turned RFQ pole and its geometrical relation to the z-axis. A two-dimensional array of these poles could form a closely packed multibeam accelerator with a beam channel along every z-axis between the poles.

The following calculation is consistent with the commonly used geometrical approximations, with the pole shape characterized at each value of z by a pole-tip displacement from the z -axis and a pole-tip radius of curvature. Two conditions must be met at the unit cell extremities:

$$R_1 + a = R_0 \quad \text{and} \quad R_2 + ma = R_0 .$$

Eliminating R_0 , we obtain

$$R_1(ka, m) - R_2(ka, m) - (m-1)a = 0 , \quad (1)$$

where $k = 2\pi/\beta\lambda$ and where we use expressions for R_1 and R_2 derived from the lowest order RFQ potential function.³ For a sequence of m values, Eq. (1) has been solved numerically to find corresponding values of ka . The results are shown in Fig. 4 as the curve labeled LATHE. This curve represents an

Fig. 4. Relations between $ka = 2\pi/\beta\lambda$ and the modulation parameter m . The curve labeled LATHE is that required for purity of the electric fields produced by lathe-turned poles. The curves labeled ATS and FMIT are for two operating RFQ accelerators that use conventional pole-tip design.

additional constraint placed upon RFQ design procedures necessary to achieve high purity of the electric fields produced by lathe-turned poles.

Also plotted in Fig. 4 are the ka versus m relations for two operating RFQ accelerators. The curve labeled FMIT is for the 80-MHz Fusion Materials Irradiation Test (FMIT) RFQ, and the curve labeled ATS is for the 425-MHz accelerator test stand (ATS) RFQ. Although both curves cross the LATHE curve, they differ from it considerably in functional form. We conclude that new design algorithms should be developed for RFQ arrays using lathe-turned poles. An excellent two-parameter, power law, least squares fit to the LATHE curve is available for use in developing such algorithms.

THE RFQ AS A PARTICLE DECELERATOR

The RFQ has gained widespread popularity as a low-energy particle accelerator. We have studied the feasibility of the RFQ as a decelerator,⁴ to provide extremely low energy antiproton beams for experiments connected with the CERN low-energy antiproton machine LEAR. Two deceleration-system examples have been considered. In both cases, the beams have been decelerated from 2 MeV by RFQs operating at 200 MHz.

In the first example, we have designed a flexible system that can decelerate the beam to any energy between 20 and 180 keV. The main elements are (1) a matching cavity between LEAR and the RFQ; (2) the RFQ, which decelerates the beam from 2 MeV to 100 keV; (3) an energy-shifter cavity after the RFQ; and (4) a debuncher cavity to allow adjustment of the final energy or phase spreads.

In the second example, the RFQ decelerates the beam from 2 MeV to a fixed low energy of 25 keV. In addition to the RFQ, only a matching cavity is required for this second example, which results in a simple overall system, although not as flexible as the first example.

We conclude that an RFQ decelerator system is possible for such an application and that the degree of complexity depends on the desired flexibility.

SPACE-CHARGE EFFECTS IN BEAM-TRANSPORT SYSTEMS

We have introduced a treatment of beams with space charge⁵ in a continuous linear focusing channel to obtain some practical smooth-approximation formulas and some physical insight for the performance of high-current beams in real periodic-focusing channels that use electric or magnetic quadrupole-focusing elements. The concept of an equivalent uniform beam has been presented, and

the importance for high-current beams of basic plasma-physics quantities, such as plasma frequency and Debye length, has been emphasized. Some limits on current and current density have also been formulated.

DOCUMENTATION OF THE TRACE BEAM-DYNAMICS CODE

The documentation of TRACE (2-D) has been completed and issued as a Los Alamos report,⁶ which has been sent to about 20 institutions in this country and abroad.

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LAMPF II

The proposed LAMPF II accelerator consists of a pair of rapid cycling synchrotrons (a 6-GeV booster and a 45-GeV main ring). The injector will be the present 800-MeV LAMPF accelerator.

During this reporting period, a proposal was completed and submitted to the Department of Energy. The proposal discussed the experimental program, the design of the accelerators, the experimental facilities, and gave a cost estimate. The chapter on accelerator design included the rf power-amplifier design, calculation of beam-loading effects, stability analyses, dipole-magnet design, control systems, beam-diagnostic instrumentation, and active dampers for possible transverse instabilities.

In addition, a set of lectures and lecture notes were prepared entitled "Obtaining the Desired Field." The object of these lectures was to help the LAMPF II project personnel learn about the design of synchrotron bending magnets.

The initial design work for a ferrite-loaded rf cavity has concentrated on plans for a full-scale low-power test model. The vessel structure would be made of aluminum, designed to provide shape changes with minimal manipulation and expense and to either evacuate to $\sim 10^{-5}$ torr or pressurize with SF_6 to ~ 2 atmospheres. The ferrites, the BeO (heat-conduction wafers), and the ferrite cooling ring will be used in the cold-test model as well as in the final cavity design. The detailed drawings for the cold model will be completed during this reporting period and will be out for bid.

Fabrication of the power supplies, control circuits, and the ac power distribution cabinet for a 330-kW rf amplifier has been completed. All parts for the final rf amplifier stage from the vendor were received. Assembly of these components has continued through the period, resulting in an 80% complete amplifier. Assembly of the LAMPF II power amplifier continues in the ETL building at Los Alamos National Laboratory where there is sufficient space to interface the amplifier with the ferrite-loaded rf cavity, sometime before October 1985.

Computer studies to predict the performance of the amplifier driving the cavity have been completed. Data from these studies were used to finalize the capacitive coupling design, the loading design, and the cavity and ferrite-cooling designs. Some parts of the LAMPF II amplifier chain (preamplifiers, etc.) are currently undergoing preliminary check-out.

PROTON STORAGE RING

PROJECT CONSTRUCTION STATUS

Proton Storage Ring (PSR) equipment installation was 95% complete at the end of this reporting period. All major components have been installed, except for the No. 2 extraction septum magnet, injection stripper magnet, two of the orbit-bump-magnet modulators, both extraction septum power supplies, and the stripper magnet power supply. Final alignment of beamline components is in progress, and operational check-out of equipment has begun.

Some electrical connections and diagnostics remain to be completed. Considerable work also remains on final integration of the complete system, including extensive controls-hardware and software testing, but we expect PSR to be ready for first beam on April 22 as scheduled.

CAMAC PROGRAMMABLE FUNCTION GENERATOR

In PSR operation, some equipment parameters are not constant but follow a time-dependent function in synchronism with the machine cycle. This time variation must generally be programmable to permit flexibility in tuning the machine. The typical time span for a function program is 1 ms or less, with incremental function changes required on a microsecond time scale.

The 2.8-MHz buncher requires four programmable control signals, one for the amplitude of the fundamental rf component, one each for the amplitudes of the second and third harmonics, and one for the phase of the rf waveform relative to the beam bunch phase.

Six orbit-bump magnets vertically deform the normal closed orbit at the stripper foil during each injection cycle so that the y-y' phase space occupied by the beam is filled in a controlled fashion and so that the stored beam is moved off the foil when accumulation is complete. The orbit deformation is a maximum just before injection starts and collapses to zero at completion, 750 μ s later. Each magnet requires an independently programmable waveform to allow the orbit bump to be retuned when storage-ring beta functions are adjusted and to ensure that the bump remains truly local (matched).

The third application of a programmable function generator (PFG) in the PSR project is the provision of a current compensation waveform to augment pulse flat-top current regulation in the two switchyard-kicker modulators. Basically, these two units make up the current droop in the pulses generated by the lumped-element pulse-forming networks.

A PFG meeting all these PSR requirements has been implemented as a CAMAC module by Bira Systems, Inc., of Albuquerque, New Mexico. Procurement and testing of 10 units has been completed, and the necessary control software has been developed.

The PFG writes values from its internal memory to a digital-to-analog converter at a clock rate of up to 2 MHz. The signal is then smoothed by an operational amplifier with an RC time constant. By adjusting resistor values, the output range and polarity can be set anywhere between +10 and -10 V. The output signal can be either unipolar or bipolar, and a 50- Ω load can be driven if the output amplitude is within the range +8 to -8 V. The PFG has two memory banks, each with 4096 locations. This feature allows a new program waveform to be loaded into one bank while the other is in use.

The PFG has two trigger inputs, giving it additional versatility. It can be programmed to enter a hold state at the first trigger, maintaining the last function value until it receives a second trigger. The two trigger inputs also permit synchronization of two independent times in the function program with two events in the machine cycle. This arrangement has value, for example, in the 2.8-MHz buncher program because we may wish to vary the beam extraction time arbitrarily, while maintaining a fixed injection-start time. The PFG can also be programmed to end the waveform and recycle to the start of memory at any location.

Figure 5 shows a PSR console display that allows an operator, using either the touch screen or a mouse, to draw and edit function waveforms before loading

Fig. 5. PSR console touch-screen display showing typical programmed function waveform.

them into the PFG. Successful operation of the completed CAMAC function generators has recently been demonstrated, and they have been tested with the three PSR equipment systems that require them.

THE 2.8-MHz BUNCHER SYSTEM TESTS

The 2.8-MHz buncher system, which is now installed in the ring, has been operated at the required 14-kV peak output across the bunching gap, and a measurement of the shunt impedance of the system (as seen by the beam) has been completed. The rf power amplifier, whose design has been described in a previous status report,¹ exhibits a measured output impedance of about 20 Ω at the operating frequency. This is the expected value. Because the amplifier impedance is in parallel with the much larger (4000- Ω) shunt impedance of the ferrite-loaded cavity alone, the effective impedance seen by the beam's image current is essentially the low output impedance of the amplifier. The beam-induced voltage developed by the maximum circulating current (45 A) expected in PSR will therefore be less than 10% of the applied rf bunching voltage and not a significant problem.

Figure 6 shows the impedance seen by the beam as a function of frequency from 1 to 10 MHz. Data were obtained by exciting a wire drawn through the cavity with 15 A of rf current over the frequency range of interest and directly measuring the voltage induced across the cavity gap. The amplifier was connected but was in a quiescent state. Phase analysis indicated that the impedance is primarily resistive throughout the range.

As a further demonstration of proper operation of the bunching amplifier, a roughly parabolic current pulse at 45-A peak amplitude was passed through the wire at a frequency of 2.8 MHz, and the voltage induced at the cavity gap was measured directly. As read from an oscilloscope trace, the maximum induced voltage was about 1200 V, which is within the range where beam-loading compensation can be obtained by adjusting the applied rf phase a few degrees.

The system has performed well in extensive tests and has now been installed in the storage ring. Except for some diagnostic read-outs, interfacing with the PSR controls system is complete, and the 2.8-MHz buncher system is ready for first beam. Implementation of second and third harmonics, believed to be a straightforward task, has been deferred until after turn-on. This additional capability will not be needed until late in the PSR commissioning program when high peak currents are attained.

Fig. 6. Plot of the 2.8-MHz buncher system impedance vs frequency, obtained by wire excitation of the cavity. The triangles and circles represent two different data sets.

ORBIT-BUMP MAGNETS

The orbit-bump magnets distort the normal closed orbit to intersect the stripper foil during injection into PSR. By appropriately programming the current pulses that drive these magnets, the distribution of stored particles in transverse (y - y') phase space is controlled and the beam/foil interaction is minimized. This ability to tailor the phase-space distribution (thus providing a knob for space-charge density manipulation) will likely prove necessary to attain high peak stored currents with suitably low beam losses. The magnets are specialized single-turn air-core devices with low inductance, and are driven by fast transistorized modulators.²

Each modulator provides a peak current of 2500 A (with 7- μ s time response) at a repetition rate of 24 Hz. Output pulses proceed through 18-m-long low-impedance (0.06- Ω) transmission lines to a matched constant-impedance load, which includes the magnet. Because transistor technology is used, great care has been exercised to protect the modulators against high-power transient surges, which could destroy the solid-state components. Extensive development

and modification of the original design has been required to guarantee reliable performance, but the modulator/magnet system now works well.

Testing of bump-magnet programming was done using a prototype modulator interfaced with the PSR controls system. Pulse programming is accomplished by drawing a waveform on a control-console monitor, using a mouse. The waveform is then digitized, stored in a 1024-channel memory and, upon receipt of the proper timing pulse, is delivered to the modulators as a control signal. This format, shown in Fig. 7, is very convenient for experimental determination of

Fig. 7. Oscilloscope traces of bump-magnet field pulse (top), with excitation by a square current pulse (bottom). The magnetic field was measured with pickup coil and attained a value of 125 G. The exciting current pulse had an amplitude of 200 A and a width of 150 μ s.

optimum bump-magnet pulse shapes for the orbit-distortion injection scheme. The control system allows scaling of the pulse amplitude and duration as well as the pulse shape for the individual magnets. Modulator turn-on control and diagnostics are also provided.

The magnets required careful design because of the low inductance and relatively high field homogeneity required. Detailed theoretical and experimental studies³ were done to optimize their physical configuration. The magnet conductors were specially shaped to minimize nonlinearities, and the vacuum feed-throughs were made of nonmagnetic materials to maintain low inductance (about 0.3 μ H). The cylindrical vacuum chambers must have diameters at least three-times larger than the magnet apertures to avoid significant effects from eddy currents induced in the walls. These effects would slow down the magnet time response.

Theoretical predictions of the magnet response^a have been closely verified by measurements. Oscilloscope traces of the field produced by a square pulse excitation are shown in Fig. 7. The magnets have been mapped and have field nonlinearities well within specifications.

At this writing, the required six bump magnets are complete and have been installed in the ring. Four modulators and loads have been completed, all transmission lines have been installed, and the controls software and hardware for the system are finished. A four-unit bump-magnet system, sufficient for first-beam tuning operations, will thus be available at PSR turn-on. The two remaining modulators will be completed and installed a few weeks later, then providing the full design orbit-bump capability.

BEAM-ENERGY REGULATION

Evidence from several measurements performed in Line-D during the past few years shows that the LAMPF beam energy is not sufficiently constant (over long periods of time) to satisfy PSR injection requirements. The energy variation, which can be several million electron volts, is believed to be a consequence of the continuous operational tuning required to maintain a high-quality H^+ beam in the linac. The PSR needs the beam-energy variation to be held to <1 MeV for optimum operation. Although it may be possible by frequent manual retuning to meet this requirement, we have preferred to automate this long-term energy correction to separate energy-dependent effects from the many other variables in PSR operation.

The basic regulation scheme, which is similar to the linac's $\delta T/T$ tuning method, is shown schematically in Fig. 8. Two beam pickups in Line-D, 80 m apart, each produce a pulse doublet with a strong 200-MHz component corresponding to the micropulse arrival rate. The signals are filtered, amplified, limited, and filtered again to produce pure 200-MHz signals of constant amplitude. The two signals are then fed to a doubly balanced mixer (phase comparator) followed by a low-pass filter. The output is a signal proportional to the sine of the phase difference between the pickup signals. Because this difference is inversely proportional to beam energy (through the particle flight time between detectors), it can be used to measure the energy variation from a reference value. The reference value is determined by suitable adjustment of delays in the (phase-stabilized) lines from the pickups.

Fig. 8. Block diagram of the PSR beam-energy-regulation scheme.

The phase-difference measurement can be performed in a gated interval as short as 40 ns, or can be averaged over a period up to the full macropulse length. This flexibility is useful because of the changes in linac beam loading with various beam pulse patterns. After gating, the signal is held and converted to a frequency that is read by the PSR controls system, which then produces an error signal having the appropriate functional relationship to the energy variation. The error signal is transmitted to LAMPF (805 MHz) rf Module 48, near the end of the linac, where it is used to drive a slow (10-s response) phase adjustment, producing the desired automatic correction to the beam energy. Through this same link to Module 48, an assignable knob on the PSR control console can be used to vary beam energy manually over a limited range. This procedure will be useful for scanning the injected beam energy during PSR tune-up experiments.

A 1-MeV beam-energy change creates a 75-ps difference in the flight time between pickups, corresponding to a 5.5° phase difference in the 200-MHz signals. Although it would be desirable to increase the energy-regulation sensitivity by moving the second pickup farther down the beamline, we have placed it upstream of the intended location of the proposed bunch rotator (longitudinal matching device) to avoid future functional interference between the two systems.

To test the phase-difference energy-regulation scheme, we installed a prototype system in Line-D during the 1984 fall run cycle, with pickups placed 60 m apart. Figure 9 shows the output of the doubly balanced mixer after

Fig. 9. Oscilloscope trace of phase difference between two pickups in Line-D. Beam is on during the first 4 μ s. Signal variation during this time is 1.3 V, corresponding to about 3-MeV energy variation.

filtering and amplification. The energy variation seen within the macropulse was caused by various effects in the accelerator. The observed phase-error pulse shape corresponded closely with a position-monitor output at a beamline location where position was sensitive to beam energy. We next manually decreased the phase of LAMPF rf Module 48 so that the beam energy was reduced by about 1.5 MeV. The result of this operation is shown in Fig. 10 where the change is clearly resolved.

Fig. 10. Same display as Fig. 9, but the phase of LAMPF rf Module 48 has been decreased by 10° . The energy change is 1.5 MeV, producing a phase difference signal of about 0.6 V.

In addition to regulating the beam energy on a several-second time scale, the system will provide a useful diagnostic to the LAMPF operator in tuning the linac for optimum PSR operation. It is not clear what the energy stability of the new high-intensity LAMPF H^- beam will be. However, the new energy-regulation system should provide sufficient control and correction to satisfy PSR requirements.

Beam timing pickups for the system have been installed in Line-D and cables have been run to the PSR control room. Some work remains in completing the gating and hold circuits, and in assembling the final system electronics.

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RF AND MICROWAVE TECHNOLOGY

The Very High Power (VHP) Section of the RF and Microwave Technology Group (AT-5) has made considerable progress during this reporting period for projects directly associated with DoD-Army and Air Force sponsorship.

MICROWAVE IRRADIATION TESTING

The development and initial operation of a microwave irradiation testing facility has been completed. The tests consisted of a series of three, conducted in the VHP section with DoD-Army participation. The results of these tests have significantly increased our knowledge of microwave effects on complete systems of interest to the military and have resulted in a much expanded effort for the next 12 months with continuing joint Army and Air Force sponsorship.

MICROWAVE IRRADIATION SYSTEM

The microwave irradiation system for use by the Physics and Life Sciences Divisions has now been completed. This system allows for small-organism irradiation at microwave levels now considered to be harmless. The wide range of pulse and waveform protocols allows for a complete and controlled set of irradiation experiments. Initial designs have been completed to expand the frequency and modulation options to the basic system. An example of the isopower-density contours for one irradiation station is shown in Fig. 11.

MICROWAVE SOURCES

The continued requirement for higher power microwave sources for several near-term military applications has motivated the VHP Section to review the state of the art of relativistic electron-beam microwave sources. This analysis and related pulsed-power surveys are the basis of an effort sponsored by the Air Force to develop compact, self-contained microwave pulsers. This is a cooperative effort with explosives, theoretical, and computational groups within the Laboratory. A final report is now being written.

Fig. 11. Biomedical microwave irradiation systems--field intensity isocontours at 2.7 GHz.

RADIOACTIVE DECAY

Early evidence has surfaced indicating that rf electromagnetic fields may be able to favorably influence the decay rate, thus reducing the half-life of nuclear radioactive decay processes. This unusual circumstance is both believed and doubted in certain communities. The early data appear strong enough, however, to warrant an experiment to test the process. As a result of a collaborative effort with the Subatomic and Research Applications Group (P-3) at Los Alamos, we have outlined a cavity and power-amplifier system for use in this experiment. Group P-3 will fabricate the device and AT-5 will aid in delivering power at 80 MHz for the experiment.

ACCELERATOR THEORY AND SIMULATION

SUMMARY

Most of the theory and simulation results for particular projects have been reported under the individual project, for example, FEL, LAMPF II, etc. Reported here are highlights of code development efforts and new accelerator ideas. The following codes are being worked on: BEDLAM, MAFIA, ULTRAFISH, RFQOPT, POISSON/SUPERFISH, and PARMILA. Two interesting new concepts have been explored, namely, acceleration by implosion of e-beams on a cylindrically symmetric field and laser focusing of particle beams. The first concept does not appear practical at this time, but the second has advantages over magnetic focusing and should be explored further.

BEDLAM

BEDLAM is a fourth-order moment simulation code. The beam at the input to a linear accelerator is specified as a collection of moments of the phase-space distribution. The moment equations, which describe the time evolution of the moments, are numerically integrated. No particles are traced in this approach. The computed distribution, the external forces, and the space-charge forces are computed consistently to a given order of accuracy. Although BEDLAM includes moments to fourth order only, it could be systematically extended to any order. Another feature of this method is that physically interesting and intuitive quantities, such as beam sizes and rms emittances, are computed directly.

We have simulated a section of RFQ linac, neglecting space charge, to test the new code. Agreement with Particle-In-Cell (PIC) simulation was excellent (see Fig. 12). We also verified that the fourth-order solution is more accurate than the second-order solution, which indicates convergence of the method.

In addition, we have discovered a technique for integrating the moment equations symplectically, which could speed up the code by a factor of 4. The fourth-order Runge-Kutta integrator currently used by the code could be replaced by the new first-order symplectic integrator.

Fig. 12. The $\langle v_x^4 \rangle$ moment as a function of time for the moment code BEDLAM and the PIC code. The two curves are practically identical, indicating excellent agreement between the two types of simulations.

BEDLAM has been used to study the third-order aberrations in the ATS low-energy transport line, which is the first practical use of BEDLAM. This problem does not involve space charge, but has nonlinear forces. A special version of BEDLAM, called BEDPMQ, was written for this application; BEDPMQ can simulate beam lines with drifts and permanent-magnet quadrupoles. The input is described in a TRANSPORT-like input file. The magnet fringe fields are computed to cubic order using formulas derived by Klaus Halbach, a Laboratory consultant. Graphical output for the moments and the linear and cubic force constants is generated.

The BEDLAM, BEDPMQ, and RFQOPT codes are now running on the new Sun workstation. We found that although the Sun is not very fast for pure number-crunching problems, it is surprisingly good at running BEDLAM, which has a large amount of complicated logic. The Symbolic Manipulation Program (SMP)

software package for the Sun computer has been delivered, and we will be investigating the suitability of using SMP in further development of BEDLAM. We hope it will be possible to use an SMP code to automatically generate the moment simulation code (BEDLAM) to any given order.

THE 3-D ACCELERATOR-DESIGN CODE DEVELOPMENT

A comprehensive work plan has been prepared for all the 3-D effort in AT Division.¹ The effort involves rf-cavity design codes, magnet design codes, and (possibly) klystron design codes. The initial emphasis is on the rf-cavity codes being developed by an international collaboration between DESY, KFA Jülich, and Los Alamos. This effort involves six areas of code development. During the last 6 months the following progress has been made.

- File structure definition: A direct-access file structure (and a group of associated I/O routines) was defined to provide an efficient and very flexible link between the various programs in the 3-D simulation system. This link will permit the 3-D cavity eigenmode code, the time-domain code, and a new magnet code to share the same input geometry, mesh generator, and output graphic postprocessor. During a visit of the DESY representative, this file definition was refined, generalized, and installed in all existing components of the cavity eigenmode system.
- Mesh generator: The problem geometry is described by the mesh generation code M3, which has been modified to allow more elementary input bodies in a simple free-format way, to allow scaling to arbitrary physical units, to allow repetition of structures in a given direction, and to allow repeated mesh doubling needed for the multigrid-solution technique.
- Resonator eigenvalue matrix generator: The program R3 generates the matrix representation of Maxwell's equations on the mesh given by M3, using Weiland's symmetric finite integration technique. The new version makes more efficient use of core and writes the problem matrix to the disk file for solution by one of the eigenvalue solvers.

- **Eigenvalue solvers:** The older eigenvalue-solver technique developed by Tueckmantel at CERN was removed from the old R3 and made into a separate program, currently named E31. This division of the problem not only provides more buffer space inside the program, but also facilitates the later substitution of the more efficient multigrid eigenvalue solver being developed by B. Steffen of KFA-Jülich. Steffen brought a prototype version of this multigrid solver, called E32, to Los Alamos in March, where it was modified to use the new file structure.
- **Postprocessor development:** A graphics postprocessor, called P3, is being developed at Los Alamos to display and interpret the physics results stored in the standard disk-save file. It currently offers field-vector arrow plots and energy-density isometric plots in any selected cut plane of the 3-D volume of the cavity. Integral quantities of interest, such as the stored energy and power dissipation, have been programmed into the postprocessor and are now being tested.
- **KOBRA:** The KOBRA package of eight programs for the 3-D simulation of ion source guns was obtained from P. Spaedtke of GSI Darmstadt. The codes have been converted to run on the CRAY and have been used on test problems. Some effort has been expended on understanding the code with the aim of writing an English user's guide. Work is also in progress on converting the graphics to a local base that is shared with the general postprocessor P3.

CODE MAINTENANCE AND DISTRIBUTION CENTER

Since 1982, AT Division has been maintaining and distributing the POISSON/SUPERFISH set of codes. These codes, which represent many man-decades of development, are used in the design of magnets and rf-cavities. Documentation for these codes is inadequate. In March we received support from the Department of Energy for maintenance of the POISSON/SUPERFISH codes and a charter for the compilation of a list of all useful accelerator codes. We hope this will be the basis for working on other codes that could be made more accessible by maintenance and documentation. We are already working on documentation for PARMILA as time permits.

In the meantime, we have made the following progress with the POISSON/SUPERFISH codes. The first draft of a new user's manual was critically reviewed. This review will lead to a complete reorganization of the contents. It was found that interpolation and extrapolation schemes used in POISSON to describe magnetic materials were inaccurate and new schemes are being tested. A general postprocessor program, SFOGEN, has been created for SUPERFISH. SFOGEN gives meaningful output for four types of cavities: DTL full cavities, DTL half-cavities, RFQs, and coaxial manifolds.

MISCELLANEOUS CODE DEVELOPMENT

ULTRAFISH is an extension of SUPERFISH (a 2-D rf-cavity code) to include the so-called $m > 0$ modes of cavities with cylindrical symmetry. The program works, but gives inaccurate results for some cavity shapes. We believe that the problem is associated with the boundary equations. R. Gluckstern, a Laboratory consultant, has derived a new set of boundary equations that will be put into the code in the near future.

The RFQ optimizer code RFQOPT is being improved to compute the bunching region more accurately. We expect the simulation will soon be as accurate as the PIC codes. RFQOPT uses a fast 2-D version of the fit-to-ellipsoid method that is used in the 3-D RFQTEP code. An accurate simulation in the optimization code is helpful because it does not require checking designs with a separate simulation code. Because space-charge computation in RFQTEP and RFQOPT is similar to that in BEDLAM, this work may enable us to study the bunching region of RFQs with BEDLAM.

NEW CONCEPTS

A radial implosion accelerating scheme has been proposed² that, in principle, is capable of accelerating gradients of 2 GeV/m. The basic idea is shown in Figs. 13a and b. It can be shown that a cylindrically imploding magnetic field will produce an accelerating field along the axis. The field can be imploded by using radially directed relativistic electron beams. This scheme could be fairly efficient. The acceleration is nonresonant, which implies both easy staging of accelerating sections and the possibility of accelerating slower particles such as heavy ions. The main problem seems to be maintaining the integrity of the machine under repeated implosions.

Fig. 13a. Side view of initial configuration for an imploding e-beam accelerator.

Fig. 13b. View along accelerated beam axis of the initial configuration. The e-beams compress the magnetic field producing an electric field along the beam axis.

In a collaborative effort with C. J. Elliott, Inertial Fusion and Plasma Theory Group (X-1), and J. R. Fontana, University of California at Santa Barbara (UCSB), Channell has proposed a technique³ for focusing particle beams using short-pulse, modest-power lasers that has the advantage of fast, accurate control and high focusing gradients (~ 200 kG/cm). This technique is based on the inverse Cerenkov effect. According to the theory, in a dielectric medium there exists an imbalance between the transverse forces produced by the electric and magnetic fields in the laser beam. The dielectric medium in this case is a gas at 10-atm pressure.

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FREE-ELECTRON LASER TECHNOLOGY

SUMMARY

The free-electron laser (FEL) highlights during this reporting period are listed below.

- FEL modifications and installation of the energy-recovery experiment (ERX) are nearing completion
- A preliminary experiment to verify beam-breakup (BBU) simulations was performed
- Tests of laser-driven photocathodes for advanced injectors are yielding promising results

ENERGY-RECOVERY EXPERIMENT

The first phase of this experiment includes many upgrades to the existing systems besides the addition of the energy-recovery components. Very extensive modifications to the injector and the rf system are under way to improve performance and reliability.

Injector

The injector for ERX is a modification of the injector used on the oscillator experiment (OSX). The modifications to the OSX injector for use on the ERX are based on operating experience with the OSX and on simulations of the beam from the gun all the way through bunching, acceleration, and transport to the wiggler, using the computer program PARMELA.

Because of beam loading and multipactoring effects, the copper subharmonic bunchers were difficult to control in the OSX; the ERX injector was designed to use only one stainless steel subharmonic buncher instead of two. The fundamental buncher used on the OSX injector was also subject to severe multipactoring because it had square corners at the outer wall. The new fundamental buncher has a circular cross section at the outer wall similar to that used in the accelerator. PARMELA simulations showed that the fundamental buncher should be as close to the first cavity of the linac as possible. The new fundamental buncher has been designed to bolt directly on the end of the first cavity of the linac. This configuration minimizes the time space-charge forces

can act on the high charge-density bunch before it is accelerated to high energy in the linac. Peak beam currents of ~ 100 A occur in the first cavity of the linac. No further bunching occurs in the rest of the linac.

PARMELA calculations show that as much as 63% of 3.5-ns-long pulses from the gun, containing 5 nC each, can be accelerated to 20 MeV and transported to the wiggler; 94% of each pulse from the gun can be contained in 1 micropulse and 6% in two satellite pulses on either side of the main micropulse. The gun can be pulsed at a rate of 21.67 MHz for the duration of the 100- μ s macropulse, same as for the OSX.

In the OSX, a large fraction of the beam was lost in the first linac. PARMELA showed that this loss could be prevented and that less emittance growth would take place if the axial magnetic field, used to focus and contain the beam along the 80-keV beamline, were extended over the first linac structure. This axial magnetic field is provided by large solenoidal coils that encompass the 80-keV beamline and the first half of the first linac structure.

The rf System

The rf system built for the FEL oscillator experiment suffered from inadequate time response from the feedback/feedforward controls and poor reliability of components. The reliability problems were enhanced by the higher operating voltages required by the new Thomson-CSF klystrons. The klystrons themselves deteriorated during the oscillator experiment to the point that the gun sections had to be rebuilt.

The rf feedback response is being improved by reducing the length of the control loop and by designing faster circuits. The length of the control loop was shortened from 400 to 70 ft by building a new klystron gallery as close to the experimental vault as possible. The new control circuits are expected to increase the frequency response at 200 kHz by an additional factor of 5. The new circuits are being designed with greater gain margins and fewer set points to simplify their setup. The tighter control of the rf system is expected to reduce the FEL output amplitude fluctuations encountered in the oscillator experiment.

The klystron modulators and protective crowbar are being rebuilt in larger tanks to improve their high-voltage reliability. Modifications of many components are also being made to improve performance. This is especially true for the crowbar. It is being improved to trigger faster and to trigger reliably at low operating voltages. The latter is necessary to protect the new klystrons in the initial conditioning operation.

Two of the klystrons have been rebuilt and tested at high power. Their early failure appears to have been caused by a coating of electrode material on the insulator for the modulated anode. The insulator has been grooved and the electrode geometry modified on the rebuilt klystrons. Improved performance by the crowbar is also considered very important to extend the life of these tubes. The tubes were tested for extended periods with peak output powers exceeding 6 MW. These klystrons are now in transit to Los Alamos. A third klystron should be ready as a spare by May.

Bridge Couplers

The FEL bridge coupler will be used to couple the accelerators and decelerators during the ERX. It will allow continuous variation of the ratio of the fields in the accelerators to the fields in the decelerators over a range of 1:1 to 2:1. In the previous status report, we reported the results of preliminary measurements that were made using a low-power aluminum model of the coupler and two small accelerator structures, instead of the actual structures that will be used in the experiment. The results of these measurements were scaled to the actual structures. From the scaling calculations, the following parameters were predicted for the final structures:

- Waveguide coupling factors
- Bridge coupler to accelerator and decelerator coupling constants
- Quality factors (Q_s) of the coupled structures

During the present reporting period, the low-power bridge-coupler model was coupled to the existing FEL accelerators by the Linac Technology Group (AT-1) to verify the results of the scaling calculations. The parameter values obtained in these measurements agreed very well with the predicted values. These parameters were used to calculate the power requirements for the ERX under various waveguide coupling conditions, beam loading, beam transmission from accelerator to decelerator, etc. Results were presented to the Free Electron Laser

Technology Group (AT-7) to aid them in deciding which conditions were the most desirable for the experiment.

The final copper version of the bridge coupler is in the fabrication stage. Measurements, adjustment of coupling constants, and waveguide coupling-factor adjustments on this copper bridge coupler have begun.

In addition to the above work, field-perturbation measurements have been performed on the higher order modes of the existing FEL accelerators and the newly fabricated decelerators. The results of these measurements will be used by the Accelerator Theory and Simulation Group (AT-6) in the study of beam-breakup effects in the free-electron laser.

Energy-Recovery Stability Calculations

The physical setup for the energy-recovery experiment is shown schematically in Fig. 14. Power fed to the accelerator can come from two sources: the

① OSX accelerator and FEL operating at fivefold increase in average current	④ Two 1.8-m decelerator (energy-recovery) sections
② Isochronous 180° bend on translation table	⑤ Two variable rf bridge couplers
③ Isochronous 60° bend	⑥ Beam dump for 2- to 3-MeV beam

Fig. 14. Schematic layout of the FEL-ERX experiment.

klystron and the decelerator. These sources are connected to the accelerator through the bridge coupler. There is some concern that variations in the beam energy and intensity may feed back into the accelerator to produce unstable oscillations. If the oscillations in the energy become larger than the allowed energy window defined by the beam scraper or by the energy acceptance of the FEL laser-undulator system, then the operation of the system will be unstable. The stability problem has been formulated in terms of equivalent circuit equations using the five complex voltages and currents associated with the five major elements of the system: the klystron, the bridge coupler, the accelerator, the beam, and the decelerator. The voltages and currents are divided into equilibrium and transient parts. We have found the equations for the transient part and have written a computer code to solve the equations numerically. In this way, we can change parameters in the system and look at the stability. The code is nearly debugged.

Schedule

The additional beamline for the energy-recovery system has been installed. The two new linac tanks are completed and are being installed. Most of the present effort is on the new injector and bridge couplers in an attempt to start injector tests by the beginning of May. The energy-recovery tests and FEL physics measurements will continue through the remainder of the year.

BEAM-BREAKUP MEASUREMENT

The purpose of the BBU experiment was to see if one could observe incipient beam breakup of the FEL beam when the beam was displaced from the center line of the accelerator cavity. The beam-position data were collected immediately before and after accelerator tank B and 2 m after tank B. The data were taken with the accelerator tank at reduced energy on the desired accelerator center line and in the following positions:

- At two positions horizontally and vertically displaced from the accelerator center line
- At one position both horizontally and vertically displaced

The displaced position and reduced energy should enhance the chances of observing BBU. Data were recorded on polaroid film, photographed from oscilloscope traces, and have been digitized and partially analyzed. Calibration

of the beam-position monitors still has to be folded into the data. The only conclusion that can be drawn from the data so far is that the beam from accelerator tank A is moving between successive microbunches; however, the source of this noisy movement is unknown. It may be impossible to separate the BBU signal from this background noise, but analysis of the data is continuing. Beam-position monitors are being installed on the ERX, and the BBU experiment will be repeated when the ERX is commissioned. The chances of seeing BBU in ERX are better than seeing them in the oscillator experiment.

ADVANCED INJECTOR DEVELOPMENT

In the development of an optically chopped photoemitter electron injector for FELs, the selection of good semiconductor wafers is an important step. This work on semiconductor photoemitters is being done in the Materials Science and Technology Division at Los Alamos. In the current reporting period, it has been shown that a good quantum efficiency depends not only on the surface preparation procedure but more critically on the bulk properties. For example, it is essential for the charge carriers produced by the photoelectric effect to have a long lifetime and, thus, to have a high probability of emerging from the surface into the vacuum. In addition, the wafer must have a low density of intrinsic defects (such as would be revealed in etch-pit-density studies), a high purity, and a suitable doping level.

In the preparation of the photoemitting surface, argon ion bombardment followed by a heat-cleaning cycle produced a reproducibly good surface. Anodic oxidation, a process used earlier in these studies, was not beneficial.

Ohmic contacts are also being developed to provide low-resistance contact to the wall of the rf-gun cavity when large average currents are required in the electron injector. Silver manganese contacts were tested but were found to separate into two layers when heated. Later tests with nickel silicon contacts were successful.

As part of the foregoing experiments, quantum efficiency measurements have been made on a few gallium arsenide samples. In one series of tests, quantum efficiencies of over 15% (at a wavelength of 532 nm) were obtained repeatedly on a single sample. Further tests on a variety of samples are needed to test the selection criteria for good photoemitter wafers.

High peak currents have been obtained in experiments on Cs_3Sb illuminated by a Q-switched Nd:glass laser. These experiments are being carried out under a contract with the Thermo Electron Corporation in Waltham, Massachusetts. The diagnostics is being improved in preparation for a demonstration of 200-A peak currents from a 1-cm^2 emitter.

Simulation calculations of short, intense electron bunches in the rf gun are being performed in collaboration with the Applied Theoretical Division at Los Alamos and with the Stanford Linear Accelerator Laboratory. Preliminary results show that the conventional (Pierce) cathode shapes for dc beams would overfocus the short bunches; a flat cathode is preferred. The large transient forces of the very rapidly changing current make a significant reduction in the energy spread produced by the space-charge force. These forces, which are non-linear both in time and in space, lead to some emittance growth. Work continues on the rf gun cavity to minimize not only the emittance growth in the pulse formation but also in its acceleration.

Electron-Gun Cavity Tests

An aluminum low-power model of the electron-gun cavity has been constructed. The model was used for the following:

- Measure the on- and off-axis electric fields and compare them to fields calculated using the SUPERFISH cavity computer code before a waveguide coupling slot was cut in the cavity
- Measure the effect of the waveguide iris slot on the uniformity of the cavity fields near the photocathode and near the electron beam's trajectory
- Measure the standing-wave pattern in a tapered waveguide coupled to the cavity and determine the optimum location for the waveguide vacuum window (so as to allow room for vacuum pumping slots in the waveguide wall, thus minimizing the electrical stresses on the vacuum window)

The cavity field measurements were made by the field-perturbation method using a conducting bead as the perturbing object. These measurements showed that the measured cavity fields agreed (to better than a per cent) with the fields calculated with the SUPERFISH cavity code, even after the waveguide coupling slot was cut into the cavity. The only disagreement between the calculated and measured fields occurred near the photocathode. There the size of

FUSION MATERIALS IRRADIATION TEST FACILITY (FMIT)

SUMMARY

Adequate funding was received to allow a small but meaningful development program for the 2-MeV accelerator. However, the Office of Fusion Energy of the Department of Energy will terminate all funding of FMIT activities on September 30, 1985. Alternate funding for the cw accelerator program at Los Alamos is being sought from the Strategic Defense Initiatives Office because of the probable application of cw accelerators in its programs.

Considerable progress was made in characterizing all operational aspects of the 2-MeV accelerator. We installed copper sheets over the single-convolution bellows at the ends of the vanes, thus eliminating the last source of excessive rf heating of the RFQ structure. We now have several hundred hours of cw operation at the 325-kW rf-power level. The contractor fabricated the last of the Reticon-based, transverse beam-diagnostics systems that were required for the high-energy beam-transport system. These diagnostics units are operational and are providing the detailed measurements crucial to characterizing the beam from the radio-frequency quadrupole (RFQ). An improved communication network, Ethernet, was installed for use by the computer control system. Ethernet improves both the data and control-function rates and allows easy implementation of additional task-oriented microprocessors as required. Significant progress was made in understanding both one-quarter and three-quarter wavelength, post-coupler rf-tuning of drift-tube linac (DTL) structures.

ACCELERATOR

Operation

Except for a brief shutdown during November to eliminate the last area of excessive thermal overheating of the RFQ structure, we have had satisfactory cw operation. The RFQ is relatively easy to bring to full power. The time needed from a cold start can be as short as 30 min, but we usually take about an hour to minimize thermal-shock effects.

The area of thermal overheating was the single-convolution bellows that provides a flexible connection between the vane and the tank wall. At the ends of the vanes, this copper-plated stainless steel bellows suffered extreme thermal cycling causing deterioration of the adhesion of the copper plating. Once the steel was exposed to the rf, very severe heating would destroy the bellows. We have installed copper patches over this bellows at each end of the four vanes. The improved electrical and thermal conductivity of these copper sheets has eliminated the overheating.

We have spent more than 100 hours measuring the characteristics of the beam from the RFQ. The transverse beam profiles were obtained at several locations along the high-energy beam-transport line. These profiles were obtained by digitizing the light-intensity profile emitted by the excited residual-gas atoms in the vacuum. Typical resolution was $130\text{ }\mu\text{m/channel}$, more than adequate for the tomographic techniques. A typical profile is shown in Fig. 17,

Fig. 17. Typical beam profile of the 2-MeV beam derived from the light emitted by the ionized residual-gas atoms in the beampipe. The three contours plotted enclose 99.9%, 95%, and 65% of the beam.

and an emittance reconstruction from three such profiles is shown in Fig. 18. The orientation of this emittance diagram in phase space differs from that predicted by the computer simulations of the RFQ beam dynamics (see Fig. 19). At the present time, we are investigating either the dependence of this orientation on machine operating parameters or the need for changes in the simulation programs.

Fig. 18. Typical RFQ 2-MeV beam emittances derived by tomographic reconstruction from three beam profiles such as those shown in Fig. 17.

Fig. 19. Comparison of measured x - x' and y - y' 95% beam fraction emittance ellipses with the theoretical predictions. The dashed ellipses show the expected beam emittances based on the measured injector beam and rf fields. The solid ellipses show the average x - x' and y - y' emittance values from several different measurements.

The 2-MeV beam current is measured using beamstop calorimetry and using an 80-MHz pulse-current transformer. Beam transmission efficiency can be determined from the ratio of this 2-MeV beam current to the injected beam current. Typically, we have measured transmission efficiencies ranging between 0.8 and 0.9 for a 20-mA 2-MeV beam.

Beam Diagnostics

The contractor, EG&G, delivered the last four transverse beam-diagnostics systems. Each of these units consists of a charge-coupled device (CCD) that is the light-sensitive element. This element is preceded by a microchannel-plate intensifier, a flexible fiber-optics cable, and an optical-imaging lens system. The associated electronics is designed to accommodate either a cw mode or pulsed mode of accelerator operation. These units are installed in the high-energy beam-transport line and are in routine use.

Signals from the three time-of-flight system capacitive pickups were used in an attempt to deconvolve from these signals the electric field distribution for a single beam bunch. By using this approach, we expect to be able to infer the longitudinal distribution of the particles in the bunch. The promising qualitative agreement we obtained for results by this analysis with the expected distributions will spur us to further improve this technique.

Computer Control System

We are progressing rapidly towards a full implementation of the local-area network Ethernet as the data and control-function communication system. Because Ethernet can accommodate up to 1024 independent nodes on the data link, we have been able to further distribute the intelligence we use. In particular, we have reduced the load on the prime computer by assigning the display tasks for the two control consoles to a microprocessor for each console. The prime computer is now free to perform the data-logging and data-processing functions it was originally intended to do. The remainder of the software drivers for the injector, cooling, rf, and beam-diagnostics nodes are in various stages of implementation. The conversion to Ethernet will be completed early in the next reporting period.

Early tests of the performance of the Ethernet system have demonstrated an increased speed of communication that overcomes previous limitations in providing responsive "real-time" control of the accelerator. Attempts to overload the Ethernet system have not been successful in degrading its performance significantly.

Operation of the accelerator from the control room is routine except for the rf node that is being integrated into the system. Continuous modification of the displays and application programs are being done to satisfy the needs of the machine developers.

POST-COUPLER DEVELOPMENT

The results from a recent experimental study of $3/4$ wavelength post couplers for the DTL are presented.¹ Although we had earlier succeeded in tuning the $3\lambda/4$ post couplers to approximately 368 MHz for the 16-cell 4.6:1 scale model of the FMIT first DTL tank, we were, nevertheless, unable to stabilize the on-axis field. The 40-cell aluminum model DTL for the neutral particle beam project provided an opportunity to test the stabilization properties of a $3\lambda/4$ post coupler in place of a conventional $\lambda/4$ post coupler. This machine operates at 550 MHz, and the $3\lambda/4$ coupler was indistinguishable from that of a $\lambda/4$ coupler. We, therefore, conclude that some other effect prevents stabilization in the 368-MHz scale model. We believe this effect is related to the TM_{01X} mode spacing, which depends upon the number of drift tubes (or the length of the tank). For a short tank, the first several TM_{01X} modes are far apart in frequency. It is thus difficult to mix the higher modes with the operating zero mode to produce an end-to-end tilt in the on-axis electric field. Because post couplers act to admix these higher order modes with the zero mode to correct for such a tilt, it is equally difficult to improve the tilt sensitivity of a short tank for the same reason it is difficult to tilt its fields in the first place.

It is somewhat fortuitous that post couplers only work in DTLs where they are needed and will not work where they are not required. We conclude that stabilization of DTLs is possible with $3\lambda/4$ post couplers, even in machines with a large drift-tube-to-wall spacing. They offer advantages over $\lambda/4$

couplers in that the coupling strength and resonant frequency may be adjusted independently, and one may take advantage of the higher shunt impedance afforded by very small drift tubes. The main disadvantage is a more complicated mechanical structure. The added shunt impedance may be partially offset by higher power losses on the post couplers if tuning errors become large.

THE RF SYSTEM

The FMIT rf system has operated for over 200 hours in support of rf quadrupole studies during this reporting interval. The rf power upon demand has been the guiding rule in this period, and the resulting data collected for the RFQ work have been extensive. Short periods of down time in the interval were caused by screen capacitor failure in the power amplifiers. These failures were remedied and it is believed the screen by-pass circuits are now reliable. Work continues in the operation of the FMIT transmitters as well as designs to permit two-loop drive for the RFQ to be initiated. Start-up studies associated with phase locking the two rf power amplifiers have begun during this reporting interval.

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G. P. Boicourt M. C. Vasquez	ATS BUNCHER CAVITY	AT-6:84-119	10/17/84
G. P. Boicourt	DISTRIBUTION OF ATS-RFQ BEAM AT NEUTRAL PARTICLE MEASURING CUP	AT-6:84-132	10/30/84
G. P. Boicourt M. C. Vasquez	EFFECTS OF QUADRUPOLE POSITION ERROR ON THE ATS DTL BEAM	AT-6:84-144	12/6/84
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G. P. Boicourt M. C. Vasquez	EFFECTS OF ALTERNATING SIGN AXIAL ROTATION OF QUADS IN THE ATS DTL	AT-6:85-28	2/13/85
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T. P. Wangler	ENERGY AND EMITTANCE RELATIONS FROM RMS EQUATIONS OF MOTION FOR A CONTINUOUS BEAM WITH AZIMUTHAL SYMMETRY	AT-1:84-323	10/15/84
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L. Young	RF BEAM-CURRENT, PHASE, AND POSITION MONITORS	AT-1:84-382	12/12/84
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