LA-10809-SR
Status Report

UC-28
Issued: September 1986

LA--10809-SR

DE87 000792

Accelerator Technology Program

April—September 1985

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ACCELERATOR TECHNOLOGY PROGRAM

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ABSTRACT

This report presents highlights of major projects in the Accelerator Technology (AT) Division of the Los Alamos National Laboratory. The first section deals with radio-frequency and microwave technology. Following sections discuss the p-bar gravity experiment, accelerator theory and simulation activities, the Proton Storage Ring, and the Fusion Materials Irradiation Test accelerator. The last sections cover activities on the proposed LAMPF II accelerator, the BEAR (Beam Experiment Aboard Rocket) project, beam dynamics, the National Bureau of Standards racetrack microtron, and the University of Illinois racetrack microtron. The report concludes with a listing of papers published by AT-Division personnel during this reporting period.

RF AND MICROWAVE TECHNOLOGY

The Very High Power Section was formed two years ago to address the development of a new generation of very high power microwave sources, with power levels of several hundred megawatts and above. The recurring interest in very high current, compact linacs and evolving requirements for directed-energy systems has stimulated this effort. Several program areas are now being studied in support of DOE and DoD missions.

MICROWAVE VULNERABILITY, LETHALITY, AND EFFECTS (VLE)

One fundamental issue with directed-energy microwave systems is the development of credible vulnerability levels. Our microwave diagnostics capability has already had significant success in producing and measuring high-power microwave fields. This diagnostics expertise and the availability of well-developed high-power microwave sources has resulted in a joint effort with DoD to establish realistic microwave-effect thresholds for particularly critical electronic devices and to identify the significance of various microwave pulse parameters. Very fast data-digitization equipment has now been field tested and is available to capture high-frequency signals.

DESIGN AND TEST OF VERY HIGH POWER MICROWAVE SOURCES

This effort is focused on the development of multigigawatt microwave sources and on understanding the limiting mechanisms inside high-power sources. Under this program, two new microwave sources have been developed that are being theoretically and experimentally investigated to explore the practical limits of microwave sources. This is a three-division, multidisciplinary effort with continuing Air Force support. Final designs of both devices are complete, and some experimental work has been initiated.

EXPLOSIVELY DRIVEN DIODE SYSTEMS

The use of explosively driven diode systems (EDDS) is a new area of effort, and we have started a conceptual design program that is intended to explore the practical limits of these systems. This is a joint effort with the DoD and involves Laboratory-wide participation. The final design has been presented, and the key technology issues are being experimentally addressed.

MICROWAVE SOURCE DEVELOPMENT

Much of the current microwave-source research is concerned with the collective effects of beam-field interactions. To address the use of these systems for present microwave source needs (acceleration, plasma heating, neutron sources, space communications), better understanding of the interaction time scale is required. To reach this understanding, we must develop long-pulse (tens of microseconds), high-current electron guns. The effects of plasma formation in gun designs is now being studied experimentally to establish the feasibility of long-pulse current, field-emission diodes.

PORTABLE ACCELERATOR PROJECT

A small project to complete the documentation and make the subsystems operational was started in August. All cables have been labeled, and the documentation upgrade is 90% complete. Very good results were obtained from the system tests. The project should be finished on schedule, by mid-October.

THE P-BAR GRAVITY EXPERIMENT

The Accelerator Technology (AT) Division has joined a Laboratory-wide collaboration to measure the gravitational force on antiprotons (p-bars). The experiment is designed to decelerate and capture 5-MeV p-bars produced by the CERN proton synchrotron (PS) and stored in the low-energy accumulator ring (LEAR). After capture, the p-bars will be cooled and then released vertically. Time-of-flight methods will be used to determine the effect of gravitational forces on the p-bars.¹

The Linac Technology Group, AT-1, is designing the RFQ decelerator and sophisticated transport lines needed to reduce the p-bar energy to 20 keV so that they can be captured in a Penning trap. The geometry of the Penning trap is shown in Fig. 1. Longitudinal confinement is provided by the parabolic electric potential along the z-axis. Transverse confinement is provided by a

Fig. 1. Geometrical arrangement for the proposed Penning trap. The 20-keV p-bars enter the bottom electrode when there is no electric field present. The electric field must rise in less than 40 ns according to present plans. This system will trap about 10 electrons and 9 p-bars. Radial confinement is provided by a 6-T solenoidal magnetic field. To measure the gravitational force, p-bars are later released vertically into the compensated measurement trap.

6-T solenoidal magnetic field. To simulate the capture process, we have calculated the exact field of a solenoid similar to the one that will be used in the experiment and have followed the trajectory of several particles in this field. Figures 2 and 3 show the trajectories projected on the rz - and xy -planes. The next step will be to introduce the time-dependent electric field that will provide longitudinal confinement.

Fig. 2. Trajectories of 10 different particles passing through the proposed solenoidal field of a Penning trap. Cylindrical coordinates are being used. The solenoid itself extends 16.7 cm on either side of the origin. The vertical scale has been exaggerated.

Fig. 3. The x-y plane projection of 3 of the 10 orbits of particles passing through the solenoidal field of a proposed Penning trap. It appears that none of the 10 orbits pass through the z-axis, which is perpendicular to the plane of the paper.

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ACCELERATOR THEORY AND SIMULATION

MAFIA, A 3-D RF CAVITY DESIGN CODE

As discussed in the previous status report, a comprehensive work plan has been prepared for all the 3-D code development effort in AT Division. The effort involves design codes for rf cavities, magnets, and (perhaps) klystrons. The initial emphasis is on the rf-cavity code, MAFIA, being developed by an international collaboration consisting of DESY, KFA Jülich, and Los Alamos. The code consists of a mesh generator M3, a resonator eigenvalue matrix generator R3, two types of eigenvalue solvers E31 and E32, and a postprocessor called P3. During this reporting period, the code has been completed and is currently undergoing tests on idealized 3-D cavity designs that can be calculated analytically and with other codes. We are also testing it on realistic cavities, such as the one suggested for the LAMPF II Booster. The code has been made available to friendly users.

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. Recently, we have received support from the DOE for better documentation and minor improvements in the codes. During this reporting period we have established user working groups for POISSON and SUPERFISH. The purpose of the working groups is to recommend and approve changes in programs, to promote the use of the codes among the accelerator community, and to evaluate the performance of the maintenance and distributing activities.

PROTON STORAGE RING

SUMMARY

This period encompassed completion of the Proton Storage Ring (PSR) construction phase and beginning of the commissioning period. First beam was circulated in the PSR on April 26, within 6 hours of the day scheduled many months before. Hundreds of turns were observed on the strip-line detectors at initial injection, and horizontal and vertical betatron oscillations were recorded with the beam-position monitor (BPM) system. Less than 1 month later, on May 24, first beam was extracted from PSR to the tune-up beamstop at 1×10^{12} protons/pulse.

The following discussion is organized in three parts. The first part is a chronology of commissioning events during the first LAMPF run cycle (3 months of operation). This period concentrated on initial operation of many PSR components and was a time of rapid progress to achieve commissioning goals. Several serious problems were solved along the way, such as complete replacement of a flawed septum magnet downstream of the switchyard kicker magnet. The second part of the discussion deals with specific equipment operation and characteristics of PSR component performance observed during the first 6 months of operation. The final part discusses what we have learned so far and PSR commissioning plans for the near future.

CHRONOLOGY OF FIRST THREE-MONTHS OPERATION

- April 16 First H^- beam into Line-D. Operation of H^- chopper, switchyard kicker magnet, switchyard septum magnet, BPM system. Observe chopping and modulation patterns on wide-band monitor in switchyard.
- April 17 First Line-D wire scans, observe chopping pattern with strip line monitors.
- April 23 First problem with overtemperature on switchyard septum magnet.
- April 24 First beam in PSR injection line, beam steered to halo beamstop.
- April 25 First harp data (local mode). The BPM display facilitates steering of transport lines.
Beam steered to H-zero beamstop; phosphor operation.

April 26 First beam circulated in PSR.
 Observe betatron oscillations, horizontal and vertical tunes,
 50 turns register on BPM position, >160 turns on intensity
 signal.

April 27 Observed initial closed orbit.
 First operation of bump magnets.
 Intensity observed on ring toroid, 20- μ s injection, coast-
 ing beam for over 1000 μ s.

May 1-5 Improvement in diagnostics while working around frequent
 failures in switchyard septum magnet.

May 6-17 Long maintenance period.

May 22 Harps interfaced to computer. On-line beam profiles in
 injection line.

May 24 First extracted beam from PSR, steered to tune-up beamstop:
 100- μ s injection
 0.5- μ A average current
 1×10^{12} protons/pulse
 >90% extraction/injection

May 28 Observe coasting beam and longitudinal spreading (out to
 750 μ s) with wall-current monitor.

May 29 Operation of injection halo scrapers.

June 2 Investigate stability, cross integer resonances, reach
 transition.

June 10 Correct horizontal closed orbit from 3- to 0.6-mm rms by
 adjusting shunts.

June 14 Adjust vertical closed orbit to 0.6-mm rms by moving quadru-
 poles.

June 15 Begin looking at loss monitors (LMs) on scope to observe beam
 losses as function of time.

June 16 Initial tests of beam with 2.8-MHz buncher; see bunching
 effect on beam.

June 19 New switchyard septum magnet installed.

June 21 $\Delta E/E$ signal observed and calibrated; fluctuations compared
 with BPM data.

June 22 Tune Line-D and ring injection for reasonably high current.

- Using wire scanners and harps to improve understanding of optics in line.
- Beam energy stabilized by inhibiting H^+ beam during H^- macropulse.
- 10 μA on halo beamstop, reach 200° C.
- 10 μA on H-zero beamstop, (14 μA , briefly).
- June 25 Investigate beam energy versus time between H^+ and H^- beams within macropulse using $\Delta E/E$ system; 20 μs is minimum for H^- stability.
- June 26 Comparison of energy variation with and without pulse-width-modulation (PWM) at start of macropulse.
- June 23-27 Steer beam down Line-D and injection line to minimize quad steering. Apply offset table to BPMs.
- June 27 Further PWM investigations, pattern cycles, beam trigger receiver (BTR) confirmation.
- June 28 Investigate LMs around the ring for several turns.
- June 29 Begin looking at profiles of beam in ring using halo scanners in Ring Section 4.
- June 30 Comparison of coasting beam losses with and without bump magnets.
- July 1 Series connection of two water circuits in new switchyard septum to reduce flow velocity.
- July 3 Moved activation protect detectors closer to beamline to pinpoint losses.
- July 2-6 Focusing in Line-D and injection line to increase transmission and attain theoretical ring match.
- July 6 Set up for single-turn, dc extraction.
- July 7-12 Investigate beam profiles in ring for single-turn injection and effect of injection-line halo scraping.
- July 12-13 More tuning in Line-D and injection line, particularly trying to achromatize the optics.
- July 14-15 Beam profiles in ring again, single-pass, observation of tails of distribution with halo scanners in ring.
- July 19 Put 5 mA through ring to tune up beam dump in single-pass mode.
- July 21 Further investigations of beam distribution tails in ring.
- July 22-31 Ten-day shutdown between LAMPF run cycles.

EQUIPMENT AND OPERATION HIGHLIGHTS

Beam Chopper

The traveling-wave H^- beam chopper, located in the 750-keV transport line between the injector and linac, must chop the beam intended for PSR into bunches at a 2.8-MHz rate during the LAMPF macropulse. Figure 4 shows a beam-intensity signal observed in the PSR injection line during one 100-ns-long bunch, and Fig. 5 shows a succession of 200-ns-long bunches on a longer time scale. Variable bunch lengths up to the full revolution period of the ring (360 ns) have been used during the ring commissioning studies.

Fig. 4. Single, 100-ns-long bunch observed on a strip-line detector in the PSR injection line. The bunch was chopped in the 750-keV linac injection line by the 5-ns rise time traveling-wave chopper. The bunch contains about 17 micro-pulses at 200 MHz.

Fig. 5. A succession of 200-ns chopped bunches entering the PSR injection line. The 360-ns spacing of the bunches coincides with the revolution frequency of the protons in the storage ring.

Operation of the chopper has met all expectations, and the flexibility of the pattern generator that drives the amplifiers has been invaluable for ring tuning studies.

Switchyard Kicker Magnet

The switchyard kicker magnet deflects H^- beam into Line-D. Signals from the two kicker modulators are shown in Fig. 6, along with a 200- μ s-long beam gate representing the time beam is delivered to PSR. The 40- μ s rise

Fig. 6. A 200- μ s-long PSR beam gate (bottom) is shown at the beginning of the flat-top portion of the 1-ms-long switchyard kicker current pulse (pulses from both modulators, one offset). The kicker rise time is 40 μ s. Full injection of PSR will utilize a beam gate about 800- μ s long.

time and 0.1% flat-top regulation for 1 ms obtained by these kicker systems meet all requirements, and operation has been very reliable. The pulses shown represent 1750 A through each magnet.

Switchyard Septum Magnet

The first magnet installed in the switchyard began overheating within one week of initial operation and, in spite of many attempts to improve cooling, became steadily worse. By the middle of May, it was clear that the magnet cooling was seriously flawed, and a crash effort was made to finish a replacement magnet with better water cooling. The second version was installed on June 19 and has performed satisfactorily since then. Post-mortem on switchyard septum No. 1 showed the presence of deionizing resin and copper oxide build-up in the conductor cooling channels, caused by high temperatures in the series water circuits.

Momentum Detector

The momentum detector is part of the beam-energy regulation system described in the previous status report. Figure 7 (top) shows the output of the momentum detector ($\Delta E/E$) during the first part of an H^- macropulse. The bottom trace is from the Beam Trigger Receiver, a strip-line detector located at the head of the PSR injection line. During the first 10 μ s of the pulse, when the pulse-width modulator in the LAMPF injection line operates to cause a gradual turn-on of the H^- beam intensity, the momentum detector is gated off. Energy variations seen during most of the pulse are approximately 0.4 MeV.

Fig. 7 The bottom trace shows the pulse-width-modulation pattern during the first 30 μ s of an injected beam pulse, providing a slow rise of the average beam intensity in the linac. The top trace shows the energy variation ($\Delta E/E$) of the macropulse. The time-of-flight/phase comparator is gated off during the first 10 μ s of width modulation because of reduced signal intensity. Subsequent variations observed are about 0.4 MeV.

Beam-Position Monitor (BPM) System

This system, described thoroughly in several previous reports, has performed nearly flawlessly and has been an invaluable tuning and diagnostic aid. Figure 8 shows the horizontal and vertical betatron oscillations at a single ring detector observed on the very first injection of beam into the PSR. Refinements since that time have produced even better results for longer circulation times. The data are input to a Fourier transform code that gives tune values. Intensity information from the strip-line signal processor is

Fig. 8. Horizontal and vertical betatron oscillations observed on a PSR position monitor during the first injection of beam into the ring. The fractional vertical tune can be easily calculated from these data and was as predicted from the lattice design.

now amplified with a logarithmic amplifier, digitized, and displayed by the control system along with the position information. In addition to observing betatron oscillations and closed orbits in the ring, the system has been used extensively to tune the transport lines to and from the PSR.

Harps

The harps are multiwire secondary-emission monitors used to measure beam profiles in the ring injection and extraction transport lines. They have an advantage over the wire scanners used in Line-D in that readings can be taken rather quickly, allowing the operator to immediately see the effect of changes in the focusing. The system we have implemented consists of units with both x- and y-wires in each package, insertable into the beam with a pneumatic actuator. There are eight units in the ring injection line, most with 1-mm-wire spacing, and eight in the extraction line with 2-mm-wire spacing.

The injection-line harps have proved to be quite unreliable for accurate measurements on the H^- beam. We observed significant wire-to-wire fluctuations and negative undershoot, making precision width determination impossible. An attempt to understand and correct these deficiencies has produced some improvements. The negative beam apparently carries with it, or produces when it impinges on bias wires in the harp assembly, energetic electrons that interfere with the secondary emission current from the harp wires. The wire-to-wire fluctuations were reduced by shielding the leads and solder connections on the upstream side of the pc boards holding the harp wires. The negative undershoot is being addressed by investigating the effect of higher bias voltages and different wire configurations. Further changes, such as using metal strips instead of wires or separating the x- and y-measurements to reduce interference are also being considered. In the meantime, a Gaussian fitting program has been brought on-line that allows operator setting of the base line for the width calculation.

Closed-Orbit Correction

The circulating beam closed orbit in PSR is obtained by averaging the position monitor readings at each detector over enough turns to average the betatron oscillations (~20 turns). The initial closed orbit was within 7 mm at all 17 detector locations, indicating excellent alignment of ring magnets and careful matching of the optical properties. A computer program calculated

(from the position-monitor readings) the dipole shunt settings and magnet movements necessary to correct the horizontal and vertical orbits. After six shunt setting iterations, the horizontal closed orbit was corrected to within 1 mm. One iteration of the vertical corrections (vertical movement of quadrupoles and yawing of dipoles) achieved a vertical closed orbit within 1 mm of the design value. Figures 9 and 10 show the position-monitor readings before and after the corrections.

Extraction Kicker Magnet

The extraction kicker produces a 10-cm deflection of the beam at the entrance to the PSR extraction septum magnet. The modulators produce ± 45 -kV pulses with rise times of 70 ns and widths of 300 ns to drive two 4-m-long deflectors occupying Sections 7 and 8 of the ring. Figure 11 shows the positive and (inverted) negative pulses from one of the modulators.

The firing circuit for these kickers allows the operator to vary the desired time of extraction in 1- μ s steps. A 1-ns-resolution circuit then produces a beam-associated rotation delay that synchronizes the actual firing

Fig. 9. Initial closed orbit in both horizontal and vertical planes was within about 5 mm of the center of the quadrupoles. This figure shows the average of 20 successive position-monitor readings at each of the 17 detector locations in the ring. The bar graphs indicate the positions for the last five samples (averages) to give an indication of the stability of the measurements.

Fig. 10. The same closed-orbit data of Fig. 9 taken after adjustment of the dipole shunts and quadrupole positions. The final closed orbit obtained is within 1 mm at all locations measured.

Fig. 11. Extraction kicker pulses (+45 and -45 kV, inverted) for one of the modulators. The horizontal scale is 50 ns per division. The 70-ns rise time and 300-ns flat top can extract a 250-ns-long bunch in PSR in a single turn.

with the longitudinal position of the beam in the ring, determined from the 2.8-MHz low-level rf signal. Pickups on the cables check this nanosecond timing delay with respect to the set value through a microprocessor-controlled time-to-digital converter. If the synchronization varies, perhaps because of aging of the modulator thyatron tubes, the microprocessor makes corrections to the delay units and reports mean jitter values to the operator. Correct delays have been determined experimentally by observing the disappearance of the circulating beam on a ring current monitor and appearance of the pulse on

the extraction current monitor. Figure 12 shows oscilloscope traces of the injection and extraction as observed by beam transformers.

Fig. 12. Injection and extraction of PSR beam as measured by a current transformer. Trace (a) shows an injection cycle of 200 μ s, consisting of 560 bunches that are 200-ns-long, stacked in the ring, followed by 30 μ s of coasting beam before extraction. Trace (b) shows the last four revolutions of the bunch in the ring, consisting of 2×10^{12} protons per bunch, just before extraction. Trace (c) shows this bunch in the extraction line on the way to the LANSCE target.

Computer Control System

A vital prerequisite to achieving PSR commissioning goals was the operation of the control system. Consisting of a central VAX computer, a console with 6 color-graphics/touch-panel displays, 6 LSI-11 subsystems, 32 CAMAC crates, and 2500 channels, the control system was fully operational in time for first beam. Subsequent additions to the software have responded to requirements arising from operating experience. These improvements, as well as others planned for the upcoming shutdown, continue to add to a powerful and efficient control system that has been widely applauded for its efficient, functional design.

DISCUSSION OF PRESENT PSR STATUS

At the present time the PSR has extracted beam to the Los Alamos Neutron Scattering Center (LANSCE) target at the 1- to 2- μ A level with the following parameters:

4 Hz

200- μ s injection at 6-mA peak H^-

200-ns-long bunch length

2×10^{12} protons per extracted pulse

Activation levels are highest at the extraction septum magnet (ring aperture side), the injection stripper magnet, and the first focusing quadrupole in Ring Section 1. Several rem/hour on contact are observed at the highest activated locations immediately after shutdown of the beam.

Losses in beam injection are caused by small apertures at the stripper magnet and the beamline entering the ring. We believe these losses can be eliminated by improved tuning of the injection line and enlarging the hole through the yoke of the first ring-bending magnet.

Study of the ring losses on a turn-by-turn basis has shown that they arise from two major sources: (1) First-turn losses from the injected beam account for part of the beam loss and are constant during the time of injection. (2) Circulating losses grow with number of protons in the ring and continue during the storage time, suggesting a loss mechanism that continually moves protons out of the ring aperture. These latter losses continue after injection at a relatively constant rate until observed to exponentially decay with loss of beam at long storage times. They can be substantially increased by inserting a thicker stripping foil and can be reduced by bumping the closed orbit off the foil after injection, implicating multiple scattering of the beam in the process. However, computer simulations have so far failed to confirm that emittance increase from foil scattering is at fault. Figure 13 is a photograph of losses in Ring Section 1 for a condition in which beam is injected every other ring cycle, allowing one to visually separate the two loss sources discussed above.

Recent commissioning activities have concentrated on defining and understanding beam optics in Line-D and the PSR injection line, matching into the storage ring, and studying the beam losses. Elements of this investigation included the following.

Fig. 13. Loss pattern observed at a scintillator in Section 1 of the PSR during an injection cycle, lasting 50 μ s. The chopper-pattern countdown has been set at two (injecting every other 2.8-MHz pulse into the ring) to see the difference between first-turn losses and circulating-beam losses during injection. These appear on the oscilloscope trace as two distinct intensities. Following injection, the beam coasts for 30 μ s before the bump magnets drop the closed orbit off the stripper foil. This decreases the loss by a large factor for subsequent turns. For this figure, the extraction has been set past the end of the trace.

- Installing a new stripper magnet in vertical-gap configuration and attempted matching to ring optics
- Reinstalling the original stripper magnet in horizontal-gap configuration
- Collimated beam experiments in switchyard and Line-D and attempt to study injection of this beam in PSR
- Full implementation of orbit bumpers and the effect of bumping on beam losses
- Theoretical studies of foil scattering and experimental characterization of losses versus time
- Installation and commissioning of wire scanners in Section 2 of the ring
- Preliminary look at scraping of circulating beam with halo scrapers in Ring Sections 4 and 5
- Development of a "nominal tune" for Line-D and the PSR injection line
- Trying to characterize and understand the source of losses in the ring, currently estimated at the 1-5% level

We still do not fully understand why losses are as high as they are. The picture that is emerging is a complicated synthesis of effects, including the following.

- Less-than-optimum match of injected beam into the ring in horizontal $x-x'$ phase space
- A larger-than-desirable radial beam distribution because of divergence introduced by the stripper magnet
- Off-momentum tails and anomalous halo accompanying the beam at times
- Scattering in the stripping foil that causes continued beam loss during circulation
- Smaller-than-optimum apertures in the ring, particularly at the extraction septum and foil holder

There is also an unknown correlation between losses as read by the AP detectors and actual beam loss. Adding to the inability to reach higher currents is a perhaps too unrealistic goal of keeping total losses below 100 nA. Runs at the 10- μ A level would be possible if we accepted greater activation of the ring.

The experiment to rotate the stripper magnet by 90° (to a vertical aperture) was instructive but did not lead to a permanent solution. With the narrow, 1-cm aperture, we could not focus the beam through the magnet and still match properly to the ring. Widening the gap to 2 cm gave more flexibility in the optics, but the increased divergence in the y -plane caused by inability to obtain the necessary field gradient led to vertical losses and reduced bumping efficiency. We have now returned to the original stripper-magnet configuration.

An experiment to move the foil stripping upstream of the first focusing quad in the ring is in progress. This should lead to an improved $x-x'$ match, but may degrade (significantly) the $y-y'$ match.

Theoretical tracking studies of beam scattering from repeated passes through the stripping foil do not predict a serious loss. However, the present simulations take into account only the core of the beam. It has been postulated that inelastic nuclear interactions in the foil could account for some of the losses near Ring Section 0 but fall short by a factor of 10 in accounting for a major portion of the scattering loss. Further theoretical and experimental studies are under way to illuminate the scattering mechanism.

FUTURE ACTIVITIES

The overall operation of PSR has been excellent, and we feel we are making good progress in understanding and controlling beam losses. The plans for the remainder of the LAMPF run cycle (through December 1985) concentrate our effort on performing machine experiments that will help determine improvements that need to be made during the following 6-month shutdown. These include measuring the ring chromaticity and a first look at high-intensity effects (at low repetition rate). We have also scheduled two periods of 3-4 days each to deliver 5-10 μ A at the LANSCE target for experimental equipment check-out. Plans being made for the shutdown include halo scraping in the ring, possible lattice changes to improve matching, increasing apertures in several locations, diagnostics to improve the linac tuning, and possibly a bunch rotator in Line-D to improve longitudinal matching and decrease sensitivity to momentum variations in the injected beam.

FMIT 2-MeV PROTOTYPE ACCELERATOR

The 2-MeV radio-frequency quadrupole (RFQ) has achieved more than 150 hours of cw operation without a major failure. This indicates that problems associated with cw operation have been solved. The remaining operational concerns are associated with one of the RFQ end walls, which became magnetic during fabrication, and an apparent position shift of one of the RFQ vanes as the rf is increased to full power. The magnetic end wall adversely affects the matching of the beam into the RFQ and may be at least partially responsible for the discrepancy between the theoretical and experimental output beam characteristics. The vane shift shows up as a change in the relative quadrant-to-quadrant rf power balance as measured by the monitor loops. This shift is probably responsible for the output beam being misaligned with the mechanical axis of the beam pipe by 0.5° .

Nearly all the data runs to date have used beam currents of about 20 mA to minimize equipment risks while characterizing the output beam. We discovered earlier that the orientation of the phase space of the output beam was substantially different from what the simulations had predicted, but only in one plane (Fig. 14). Transporting this different 2-MeV beam without melting the beam pipe proved to be difficult with the small-bore magnets that simulated the linac drift tubes. The characteristics of the beam were extremely difficult to measure without an adequate transport solution. Therefore, we replaced the small-bore system with a larger bore system to provide a much-needed safety margin. The new transport line proved to be extremely rugged and has withstood numerous beam spills that would have quickly destroyed the old line. When the beam characteristics are better understood, we will reinstall the small-bore system and investigate RFQ-DTL matching.

Using the new transport line has allowed us to make studies of beam characteristics under a variety of different operating conditions. The focus of our studies is directed toward understanding the characteristics of the RFQ output beam. The significant difference between the phase-space orientations of the theoretical and experimental beams is puzzling and needs clarification. The primary limitation to our studies has been the diagnostic instrumentation and the associated software algorithms. Beam profiles are obtained by measuring the light from the residual gas atoms and molecules ionized by interactions with the ion beam. This technique is very well suited to injector beams (less

Fig. 14. Comparison of the measured emittance orientations (solid ellipses) with the results of PARMTEQ, which utilized the measured injector beam (dashed ellipses). The agreement with the theory is good in the x - x' plane but substantial disagreement with the theory is evident in the y - y' plane.

than 100 keV) where the ionization cross sections are quite large. However, the cross sections decrease rapidly with increasing energy and, at 2 MeV, are at least an order of magnitude smaller. Because the absolute light intensity

is much smaller, the 2-MeV system is much more sensitive to noisy electronics, scattered light, detector dark current, and beam halo. At 75 keV, signal-to-noise ratios of greater than 5 to 1 are not uncommon, but at 2 MeV, the best ratio achieved is 1 to 1 with typical data having less than 1 to 2 signal-to-noise ratio (Fig. 15). This small ratio makes the data analysis and emittance reconstruction very sensitive to the background subtraction method used to derive beam profiles from the combined signals. During this reporting period, we also discovered that the emittance analysis routine produced results that did not always adequately represent the beam, especially when more complicated nonelliptical shapes were evident (either from aberrations caused by the solenoids or by the RFQ fields). For example, Fig. 16 shows a comparison of the idealized emittance ellipses derived by the analysis routine from a particular data set. These data were chosen to illustrate some of the problems with the analysis routines. The complicated shape is not typical of most emittance data. The three contours (solid lines) represent the 99.4%, 85.8%, and rms beam-fraction contours. The three ellipses (dashed lines) show the analysis routine's idealized representation of that data.

Fig. 15. Beam profile of the 2-MeV beam. The beam-profile data are represented by the very broad peak beginning about Channel 30 and ending about Channel 225. The sharp peak at Channel 160 is due to beam heating of a spot on the beam-pipe wall. The data shown have been color filtered to reduce the thermal red and orange light by about a factor of 1000.

Fig. 16. Comparison of idealized emittance ellipses (derived with the current-weighted analysis routine, dashed lines) with a particular set of data, solid lines. The three contours shown represent, respectively, the 99, 86%, and rms beam fractions. The three ellipses were derived from data contained within each of these three contours. The current weighting in the analysis biased all three ellipses toward the center of the distribution. It is evident from this figure that beam-transport solutions based on these idealized ellipses may not transport all of the beam because a substantial percentage of the beam data is outside the ellipse boundaries. The data shown were chosen to illustrate the differences between the data and the derived ellipses. The shape is peculiar to this particular measurement and is not typical of the normal FMIT 2-MeV beam.

It is obvious from Fig. 16 that the three ellipses are poor representations of the data in this case. This effect is likely responsible for the apparent inconsistency of previous emittance measurements. It is also evident from this figure that any beam-transport solution based on the outside ellipse (99% beam fraction) will not necessarily transport all of the beam because a substantial portion of the data is outside the idealized ellipse boundaries. We discovered that the analysis routine used a current-weighting scheme that multiplied each data point in the beam profile by the relative current it carried in deriving an emittance ellipse. This current weighting overemphasized the importance of the central portion of the beam, which tended to pull the emittance ellipse boundaries in toward smaller values. Hence, the idealized

ellipses were always smaller than the actual data distribution and also tended to be oriented more along the rms contour than along the actual data distribution. Eliminating current weighting from the analysis produced idealized ellipses that more closely represented the data (Fig. 17).

As a final exercise, we adapted a routine¹ that computed the minimum emittance ellipse that enclosed 100% of the emittance data. This modified routine was used to define beam ellipses subsequently used in deriving beam-transport solutions. The transport solutions derived from these ellipses should minimize any equipment risk from beam halo. Figure 18 shows the MINIEL emittance ellipses derived from the same data as Figs. 16 and 17. In the future, we will derive beam-transport solutions based on the MINIEL ellipses and will use the improved analysis results for comparison purposes, such as emittance growth factors and ellipse orientations.

Using the improved analysis routine, we have derived emittances of RFQ beams under various operational conditions. Reanalysis of old data using the

Fig. 17. Comparison of the same data, as in Fig. 16, with results of an analysis without current weighting. The agreement with the data is much improved. Some of the beam data still lie outside the ellipse boundaries, which poses a potential problem with beam-transport solutions based on these ellipses.

Fig. 18. Comparison of the data in Fig. 16 with the results of MINIEL. This routine was designed so that the ellipses encompass all of the beam. These ellipses will be used in deriving beam-transport solutions to minimize potential problems caused by beam impingement on the beam pipes.

new routine has produced results that are more self-consistent than before. Comparison of these 2-MeV emittances with reanalyzed injector data led to an emittance growth factor of 3.36 ± 0.62 . This factor is somewhat larger than the theoretical factor of 2.7 but is not unreasonable considering that the injector beam emittance is about 50% larger than the RFQ design value.

Before installation of the RFQ, the injector beam was analyzed at the position of the RFQ match point, using a viewport in a temporary beamline. At that time, we derived Twiss parameters for the beam as a function of solenoid magnet currents and injector beam current. A plot of both alpha and beta as a function of solenoid current in the second solenoid (Fig. 19) (dashed lines) shows what one would expect of a focusing system, both parameters decreasing with increasing solenoid current.

With the RFQ installed, we can observe the beam with a TV camera and actually obtain beam profiles inside the RFQ in the space between the low-energy end wall and the vanes. From these profiles, we can derive emittances on the assumption that this space can be approximated by a drift. Although there are some rf fields in this region, they are directed primarily along the

Fig. 19. Comparison of Twiss parameters measured prior to installation of the RFQ (dashed lines) with measurements made after installation of the RFQ (solid lines). It is obvious that the magnetic end wall is greatly affecting the matching of the beam into the RFQ.

direction of ion motion and cannot significantly affect the transverse beam profiles. The emittance reconstruction uses three transverse profiles obtained well away from the vanes. Hence, approximating this region by a drift is not unreasonable. Emittances derived from these profiles have Twiss parameters

significantly different from our previous measurements. In searching for a cause, we discovered that the low-energy end wall of the RFQ had become magnetic during fabrication. Because the entrance aperture of the RFQ is only half the size of the magnet bore, the effective fields of the solenoid are greatly distorted by a magnetic end wall. This change in magnetic susceptibility is easily demonstrated by touching a permanent magnet to the end wall: When the solenoid is on, the magnet sticks to the end wall; when the solenoid is off, the magnet will not stick.

We also discovered that the vacuum pipe had been attached to the RFQ using steel, rather than stainless steel, nuts. Because of the bolt pattern, this would induce an effective octupole component at the RFQ end of the solenoid. It was expected that this effect would be small, but when the steel nuts were replaced with brass nuts, the measured Twiss parameters took on values between the previous two measurements illustrated in Fig. 19. If RFQ match parameters are sensitive to effects in the vicinity of the low-energy end wall, then we need to be careful in future designs to ensure that beam characteristics at the match point are stable.

One of the major uncertainties in this critical region is the beam's effective space charge and how it changes from being nearly completely neutralized outside the RFQ to being nearly completely unneutralized in the high electric-field region between the vanes. Current RFQ designs have assumed full space-charge current once inside the RFQ walls. However, we have evidence that the beam remains well neutralized right up to the vane ends. This condition should be particularly true for negative ion beams where the low mobility of the positive ions prevents the rapidly changing rf fields from clearing the ions from between the vanes in one rf cycle. Negative ion beams may remain significantly neutralized because of trapped positive ions, even between the RFQ vanes. This effect significantly affects the parameters of the beam at the RFQ match point. Because the FMIT RFQ is ideally suited to study the region between the end wall and the vanes, the data we have can perhaps shed some light on this question as well.

COMPUTER CONTROL SYSTEM

The computer control system has been upgraded to incorporate a faster local area network (Ethernet). The conversion of all the operating programs has been completed, and the accelerator has been operated for the last 4 months

using the upgraded control system. Operator response is much better than with the previous system. A second console position has been added and is operating well. This feature allows the operator to work with two subsystems at the same time and results in improved tuning of the accelerator.

The performance of Ethernet has proved to be completely satisfactory for the FMIT RFQ accelerator. The response time of the software-connected control knob has been increased from 4 to 15 messages per second by the Ethernet system. This fast response gives the operator "real time" control of the accelerator.

Ground-Support System

The Engineering Prototype is the system to support the flight experiments. It will use many of the designs that were conceived for the accelerator test stand upgrade (ATSU) that was designed at 50 MeV and at a 5% duty factor. Through effective choice of materials, we found that high duty-factor capability could be retained in a lighter weight structure. In particular, the front end of the designs did not change in concept. Heavy-gauge copper-plated aluminum was retained for the tanks and OFHC for the drift tubes.

Especially important were the concepts advanced for the drift-tube bodies and quadrupoles. First, we know that rare-earth cobalt (REC) quadrupoles require care in fabrication and that welding heat at final assembly degrades the material; therefore, a technique of "cold" assembly was developed that placed the quadrupole in hard vacuum inside the drift-tube body (see Fig. 20). Secondly, by providing a substantial gap in the bore tube while effectively cooling the outer periphery of the drift-tube shell, the gap closes during beam-loss heating and thus reduces detuning effects on the tank. Thirdly, the gap provides a useful aperture for noninterceptive diagnostic circuitry to measure beam parameters, principally position, profile, and energy. Full implementation of the diagnostic potential of this concept requires that the quadrupole be a "split-singlet" to provide center space for the diagnostic strip-line probe; this is only feasible beyond 4 MeV so the concept will probably not be used in the first tank, the ramped-gradient DTL. However, other features of the concept such as cold assembly and the compensation gap, as well as the high thermal capacity can be used to advantage in all drift tubes.

Fig. 20. Split-quadrupole concept.

The quadrupoles were reconfigured to better anchor the pole pieces and provide captive screws for accurate and controllable shimming (see Fig. 21). These quadrupoles can be sliced in half to provide the split singlets required in the instrumented drift tubes at higher energy. Those same designs are adaptable to other focusing methods, such as doublet and triplet focusing, that have been proposed and are being considered for advanced linac concepts.

Fig. 21. Permanent-magnet quadrupole concept.

Doublet focusing reduces by a large degree the sensitivity of beam steering to drift-tube misalignments but is very sensitive to misalignments of the doublets within the drift-tube body itself. Triplet focusing is insensitive to all misalignments. Only in the higher energy drift tubes would triplet focusing be possible because of the space required in the drift-tube body.

An additional application of the new drift-tube concept is to provide steering magnets in place of the diagnostic ring, although the impulse available will be quite small.

Other developments on the Engineering Prototypes during this quarter are listed below.

- **Beamstop Graphite Cladding:** Two different methods of cladding 6-mm-thick graphite tiles on water-cooled copper were developed by outside industry. One uses a direct braze onto a molybdenum sheet. The other

uses a complaint mesh (see Fig. 22). A third method, using refractory cements has also been developed. All three of those methods await testing in the FMIT prototype beam at power densities of 500-800 W/cm².

Fig. 22. Graphite cladding on beamstop.

- **Mechanically Isolated Beam Tube:** A method of isolating beam-transport lines from outside floor and vacuum-pump vibrations was developed and tested (see Fig. 23). The method simply uses equal-sized, diametrically opposed, very flexible welded bellows to provide balanced vacuum forces on the beam tube, thus permitting the tube to "float" with a minimum of mechanical coupling from outside vibrations. This technique, along with isolation pads, was invented for the ATSU project.
- **Precision Alignment:** The old Brookhaven National Laboratory (BNL) method of drift-tube alignment using a current pulse down a taut tungsten wire has been resurrected. The system was reconfigured with the wire vertical through a single drift tube at a time. Tests have indicated ± 0.004 -mm reproducibility and promise the potential for overall drift-tube alignment in a tank of ± 0.05 mm. The laboratory setup is shown in Fig. 24. It has been used to measure the offset of the magnetic and geometrical axes on several of the accelerator test stand (ATS)-DTL drift tubes.

Fig. 23. HEBT vacuum-system details.

Fig. 24. Laboratory setup of drift-tube alignment.

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LAMPF II

THE 50- to 60-MHz FERRITE-TUNED CAVITY

The proposed LAMPF II accelerator will require an accelerating cavity tunable over a range of 50 to 60 MHz. The cavity chosen consists of a modified quarter-wave coaxial resonator loaded with microwave ferrites. The rf permeability of the ferrites (and therefore the cavity frequency) is varied by applying an external bias magnetic field perpendicular to the rf magnetic field.¹ We have fabricated and vacuum tested an aluminum prototype of this cavity and have made some mechanical modifications to the cavity to make assembly easier. We have received the accurately ground disks of beryllium oxide that will transfer heat from the ferrite to a water-cooling jacket. A coaxial capacitor, which will couple the rf amplifier to the cavity, has also been fabricated. The cavity is now ready for initial electrical tests.

MEASUREMENTS OF BEAM-COUPLING IMPEDANCE EFFECTS

The LAMPF II accelerator will use ceramic vacuum chambers in the gaps of the rapid cycling dipole magnets of the lattice. To provide a conducting path for the beam-image currents and yet prevent large eddy currents caused by the varying dipole magnetic field, the ceramic will be coated with narrow silver-plated conductor strips. A system has been set up for measuring the longitudinal and transverse beam-coupling impedance of sample ceramic chambers. Preliminary results indicate that longitudinal and transverse coupling impedances of 1 Ω and 100 Ω/m , respectively, can be measured.

We have performed calculations to evaluate methods and to determine specifications of equipment needed to measure the expected LAMPF II impedances, which will be two orders of magnitude smaller.

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BEAR

AN RFQ BEAM-DYNAMICS DESIGN STUDY

A study of RFQ beam-dynamics designs for the BEAR (Beam Experiment Aboard Rocket) project, based on the ideal two-term potential function, has been completed. In the initial part of the study, the synchronous phase (at the end of the bunching section) and peak surface-field values were varied, and a standard RFQ design procedure was used for obtaining good first-order designs. We chose the synchronous phase and peak surface-field strength as a compromise that allowed us to approximately minimize both power and length and yet maintain reliable operation with respect to unwanted electric breakdown.

We have modified the standard design approach to reduce the transverse and longitudinal current limits to the same value as those at the end of the gentle-buncher section. This new procedure lowers the length and power with almost no cost in beam performance. The resulting design parameters are shown in Table I.

TABLE I
BEAR RFQ DESIGN PARAMETERS

The rf frequency	425 MHz
Ion type	H ⁻
Nominal output current	25 mA
Output rms normalized emittance	0.01 π •cm•mrad
Injection energy	0.03 MeV
Final energy	1.0 MeV
Peak surface field	37 MV/m
Minimum radial aperture	1.2 mm
Length	1.0 m
Power (at 30 mA)	67 kW

BEAM-TRANSPORT DESIGN STUDIES FOR BEAR

Low-Energy Beam-Transport (LEBT) Line

The purpose of the LEBT is to match the beam from the ion source to the RFQ. Because of the asymmetric beam emitted by the ion source, permanent-magnet quadrupoles (PMQs) are the logical choice for focusing elements. We assume the beam to be neutralized (or nearly so), and quadrupole magnets should not interfere with this neutralization.

The design of the LEBT was accomplished using the program TRACE. Starting with three quadrupoles within a specified distance between the ion source and the RFQ, TRACE can determine the gradients of the three quadrupoles and the location of the center quadrupole so that the beam is matched to the RFQ. After finding a solution, one can set all three quadrupole gradients to the same absolute value and adjust their lengths in a reasonable way to achieve an approximate match.

In this case, the length of the center quadrupole was set to 3.81 cm, and the lengths of the outer two quadrupoles were set to 2.54 cm. TRACE can then adjust the drift distances between the ion-source slit, the quadrupoles, and the RFQ to obtain a match.

We found solutions for a neutralized beam when we varied the quadrupole gradients between 2.2 and 2.7 kG/cm. The distance between the ion-source slit and the RFQ was between 30.8 and 35.1 cm. Similar solutions were found when the beam was assumed to be underneutralized by 5 mA or overneutralized by 5 mA. The overneutralized beam requires quadrupole gradients of 1.6 or 1.7 kG/cm to satisfy the constraint of having at least 5 cm between the ion-source slit and the first quadrupole.

High-Energy Beam-Transport (HEBT) Line

The beam emerging from the RFQ is small in size and large in divergence. At the neutralizer, the beam should be relatively large with a small divergence. The purpose of the HEBT is to perform this beam transformation over a reasonable distance.

The program TRACE 3-D was used to find the proper positions of four large-aperture PMQs to bring the 25-mA beam to a 2.54-cm-diam circular waist at the neutralizer. Using 5.08-cm-long quadrupoles, solutions can be found

for quad gradients of approximately 1.2 kG/cm. The inner radius of the quadrupoles must be 2.5 or 3 cm. The distance between the RFQ and the neutralizer is approximately 60 cm.

BEAM DYNAMICS

SCHEME TO FUNNEL ION BEAMS WITH A RADIO-FREQUENCY QUADRUPOLE

Although considerable progress has been made in the generation of low-energy, high-brightness beams, beams with even greater brightness and higher energy are needed for a variety of applications. In principle, one can generate higher brightness, higher energy beams by starting with multiple beams from ion sources. After the multiple beams are bunched and accelerated in RFQ accelerators, they can be combined in pairs by a process called funneling. This process can be repeated, with each funnel followed by a linear accelerator to increase the energy. In such a funneling "tree," if emittance growth and beam loss are carefully controlled, the final beam will have increased brightness as well as a higher energy. Figure 25 shows how a single funnel combines two bunched beams into a single beam with interlaced beam pulses. In practice, the use of funneling to increase beam brightness has proved to be a challenging design problem and has yet to be investigated experimentally. To prevent beam loss and irreversible emittance growth, the two beams to be funneled must be carefully focused during the funneling process. Because low-energy beams are difficult to transport and focus, it is a special challenge to funnel beams after their initial acceleration to a few million electron volts in RFQ accelerators.

Fig. 25. Diagram showing two bunched particle beams being combined into a single beam with interlaced bunches. This process is called funneling.

In the previous status report (October 1984–March 1985), we discussed a novel method to deflect ion beams within a periodic focusing beam channel. Continued work in this area has allowed this deflection technique to be used

in the development of a new type of RFQ structure^{1,2} that is suitable for funneling two low-energy beams. The properties of the RFQ linear accelerator have been extended to include programmed transverse deflections of the RFQ ion beam. In a standard RFQ accelerator, the focusing system consists of a series of electric-quadrupole, time-varying, focusing and defocusing lenses. If these lenses are given alternating transverse displacements, we can generate the deflection forces needed to funnel. In Fig. 26, we show a series of focusing and defocusing lenses that have such alternating transverse displacements. For any particle entering these lenses from the left, the alternating displacements shown produce an upward impulse at each lens that is added to the usual focusing effects. By programming the magnitude and sign of the lens displacement α , we have the flexibility needed to produce funneling trajectories.

Fig. 26. Schematic illustration of the method used to deflect an ion beam in a strong-focusing lens array. Introduction of the transverse lens displacements α gives an upward impulse to the beam at each lens. In addition, the usual strong-focusing effects are maintained. The magnitude and sign of α can be programmed to produce the trajectories needed to combine beams by the funneling process.

The basis for this scheme is a newly invented potential function from which electric fields and pole geometry can be derived for the RFQ funnel. Because the electric fields of the RFQ are time dependent, the sign of the transverse forces depends upon the phase (arrival time) of the beam pulses. Suppose we introduce two parallel off-axis beams into the bore of this new type of RFQ, with the pulses of the two beams differing in phase by 180° . If the beams initially have $\pm x$ -displacement from the z -axis, both can be deflected toward the axis because they experience opposite polarity fields. At an appropriate point, the deflection forces can be reversed, by reversing the sign of α , so

that both beams reach the z-axis with zero slope. During this process, both beams are contained transversely by the usual alternating-gradient focusing forces of the RFQ structure. The transverse motion of a particle in an RFQ funnel is described by an equation of the form

$$\frac{d^2x}{dt^2} + A [x + B(\alpha) \cosh kx \cos kz] \sin(\omega t + \phi) = 0 \quad .$$

If the coefficient $B = 0$, this is the Mathieu equation that describes the well-known effects of alternating-gradient focusing. However, B (which is a function of the displacement parameter α) can be programmed to vary with z to produce appropriate funneling trajectories. Figures 27a and b show a computer simulation of two 2-MeV proton trajectories being combined in a 100-MHz

Fig. 27. Computer simulation of two 2-MeV proton trajectories being combined into a single beam by an RFQ funnel.

RFQ funnel that is 1.5 m long. In Fig. 27a, the x-displacement from the z-axis is plotted versus distance along the z-axis, in dimensionless units. On the left, two particles are introduced, equally displaced on either side of the z-axis and with phases that differ by 180° . The shapes of the RFQ-funnel electric poles in the x-z plane are shown crosshatched. The funneling trajectories are produced by the variations of the lens deflection parameter α (shown in Fig. 27b). The funneled beam is then suitable for acceleration to a higher energy in an rf accelerator having twice the frequency of the RFQ funnel. This method of increasing the brightness of ion beams may have important future applications in neutral-particle-beam technology and in the rf-linac approach to heavy-ion fusion.

COMPACT, LOW-EMITTANCE FUNNELING LINE

To obtain high-current beams, it may be advantageous to use funneling lines in which two bunched beams of current I and longitudinal bunch separation $\beta\lambda$ are merged into a single beam of current $2I$ and bunch separation $\beta\lambda/2$. In most cases, emittance growth must be kept to a minimum. A theoretical design study³ has resulted in a conceptual funneling-line design that has a transverse emittance growth limited to less than 15%, based on beam-dynamics calculations. Two 2-MeV, 100-mA proton beams are funneled from a two-channel, 212.5-MHz RFQ to a single beam suitable for injection into a 425-MHz linac. The design uses PMQs, dipoles, and combined-function elements. A schematic drawing is shown in Fig. 28.

Beam-dynamics calculations were performed using the particle-tracking code PARMILA. A plot of X-, Y-, and Z-emittances along the funneling line is shown in Fig. 29. The low emittance growth is obtained by arranging the focusing strength, the periodic structure, and the bending elements so as to minimize abrupt changes in the beam environment that lead to charge redistribution and unwanted space-charge-caused emittance growth.

This design has not been optimized, and more detail (such as the inclusion of image charges where the beam is off-center in the beamline) is needed in the calculations. Nevertheless, the calculational results have confirmed some ideas about the control of emittance growth, and indicate that similar designs may be useful in generating and transporting high-current, low-emittance ion beams.

Fig. 28. Schematic of conceptual funneling-line design.

Fig. 29. Plot of X-, Y-, and Z-emittances along funneling line.

GENERALIZED EQUATION FOR EMITTANCE AND FIELD ENERGY

Recently, an equation has been presented by Wangler et al.^{4,5} relating the rms emittance of a beam to its electric field energy in the case of an azimuthally symmetric charge distribution and a continuous focusing force. This equation has been found useful for interpreting the change of rms emittance under extreme space-charge conditions. In this limiting case, it has been possible to predict final emittance growth from the field energy stored in an initially nonuniform charge distribution.⁴

Real beams are focused in periodic quadrupole channels and thus deviate from azimuthal symmetry. Moreover, in linacs they are bunched longitudinally and can transfer emittance between the longitudinal and transverse directions. The question has been raised as to whether it is possible to generalize the equation to a multidimensional case with periodic focusing and thus obtain relatively simple equations for emittance growth that can be useful for practical design and can enhance our general understanding of emittance growth.

I. Hofmann (GSI Laboratory, West Germany), a visitor to Los Alamos last summer, succeeded in generalizing these results. He found that the equation is valid in constant or periodic focusing and for 1-D, 2-D, or 3-D; thus, it provides a general framework for the study of emittance growth. It allows an estimate of the expected total emittance growth if the change of nonlinear field energy can be predicted from general principles, like the homogenization of charge density in space-charge-dominated beams. Structure resonances in periodic focusing can be identified as a resonance between the envelope modulation and the oscillating nonlinear field energy term. The equation leads to estimates for the maximum longitudinal/transverse emittance transfer in situations where equipartitioning occurs. A comparison with results from computer simulation will be the subject of current work.

DOCUMENTATION OF THE BEAM-DYNAMICS CODE TRACE 3-D

TRACE 3-D is an interactive program that calculates the envelopes of a bunched beam, including linear space-charge forces, through a user-defined transport system. It is extremely useful for designing transport systems and matching sections. The documentation describes how the program works, how to

use it, and includes several examples. The documentation has been completed through the second draft and is awaiting final editing.

In addition to the documentation, TRACE 3-D has used comment statements extensively and has been structured to allow easy modification.

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NBS RACETRACK MICROTRON

Los Alamos has now completed all of its design and construction activities in a continuing collaboration with the National Bureau of Standards (NBS) to build a room-temperature cw racetrack microtron. During the first half of FY 85, Los Alamos delivered and installed the 5-MeV injector linacs, the rf power and distribution system, and the microprocessor-based accelerator control system. During the second half of the fiscal year, each of these systems was exercised and integrated into the facility. In September, the first beam was accelerated to 5 MeV.

The rf power system consists of a 65-kV dc power supply and a 450-kW cw klystron and crowbar unit. The power distribution system includes an rf circulator to protect the klystron from reflected power, waveguide phase shifters and power splitters (one each for the injector linac) and their associated controls, and tens of meters of water-cooled waveguide. The Los Alamos personnel assisted extensively in bringing this system into operation and in training NBS personnel in its use. The operating klystron, circulator, and crowbar are shown in Fig. 30.

The injector linacs consist of a 1.3-MeV capture section, the 5-MeV pre-accelerator, their support and alignment systems, vacuum, cooling, temperature- and resonance-control systems, and magnetic shields. The injector linac is shown connected to the rf distribution system in Fig. 31. All subsystems were thoroughly conditioned in Los Alamos before delivery to NBS. After their connection to the rf power system at NBS, the linac tanks were commissioned with the assistance of Los Alamos personnel.

The configuration of the microprocessor-based distributed control system is shown in Fig. 32. This system includes a primary-station console, now installed in the main control room, which allows the operators to monitor and control all of the accelerator's parameters. This control is effected through hardware and software located in secondary- and tertiary-control stations that are physically distributed close to the equipment they control. The control system was used at the secondary-station level to debug and exercise the rf power system, to condition the injector linacs, and was subsequently used to achieve the first accelerated beam. Los Alamos continues to improve the performance of the control system as we acquire more experience with it in

Fig. 30. The installed rf power system. The crowbar is in the open cabinet at the extreme right. The klystron is located in the right center of the photograph with the large water hoses. The circulator is mounted horizontally above the klystron and control racks, partially obstructed here by its cooling-water system.

Fig. 31. Injector system and associated rf power distribution system.

Fig. 32. Control system configuration.

actual operation. It already operates at close to the full potential of its original design.

The 12-MeV main microtron structure is now complete. The final field distribution has been measured, and the vacuum system and the operation of the temperature-control system have been tested. The residual magnetic field on the beam axis has been measured with magnetic fields in place and found to be well within specification. This linac, shown in Fig. 33, has now been packed and is ready for delivery and installation at the NBS where it will be operated at full power.

Fig. 33. The NBS/Los Alamos racetrack microtron 8-m-long main microtron assemblies with support structures and cooling systems.

UNIVERSITY OF ILLINOIS RACETRACK MICROTRON

Los Alamos is collaborating with the Nuclear Physics Department of the University of Illinois to construct a cascade racetrack microtron at the University in Champaign-Urbana. During FY 84, Los Alamos delivered the Stage I microtron linac. During the first half of FY 85, the chopper and buncher cavities and associated chopping slits were completed and delivered to Illinois for installation on the injection beamline. Los Alamos has since completed and delivered a temperature-control system for these three resonant cavities.

The injector linac consists of a 1.7-MeV capture section followed by a 5-MeV preaccelerator. The engineering design for these two sections has been completed, and detailed engineering drawings have been prepared. All copper and all braze alloy for both sections have been procured. Fabrication of the capture section was over 50% complete by the end of September. In addition, the temperature-control system for this section has been constructed and tested.

Los Alamos is also collaborating with the University of Illinois on the design of a distributed microprocessor-based accelerator control system. Progress on this project has been slow; however, four Intel 310 computers have been procured. An initial design has been prepared that takes advantage of some of the unique capabilities of the Intel machine and its iRMX-286 operating system. Other features of the design are borrowed from the control system developed for the Los Alamos Proton Storage Ring and include the following features:

- Applications codes access the system using equipment and channel identifiers
- The system is implemented with multiple tasks that communicate through a run-time database
- Tasks have direct access to the run-time database that resides in shared memory
- The design employs the "equipment-module" concept that allows control algorithms to be contained within the I/O subsystem

Some other aspects of the design are (1) equipment and channel identifiers used by application codes are character strings so that most programs need not be recompiled or linked when the database is altered and (2) the database is dynamically configurable. We are now proceeding with the detailed design of the software.

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P. J. Channell	Theoretical Support of a High Brightness Negative Ion Linac	AT-6:ATN-85-3	8/85
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G. P. Boicourt M. C. Vasquez	EFFECTS OF SOFT EDGED QUADS WITH HARMONICS	AT-6:85-62	4/10/85
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G. P. Boicourt M. C. Vasquez	EFFECT OF BORE RADIUS ON TRANSIT TIME FACTOR AND CELL POWER IN THE ATS U DTL	AT-6:85-86	5/24/85
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G. P. Boicourt	EFFECTS OF 2mm DISPLACED BEAM IN THE PBAR SOLENOID, (memo)	AT-6:85-137	9/9/85
G. P. Boicourt M. C. Vasquez	TRANSMISSION THROUGH THE ATS REQ USING DATA FROM SCANNER RUNS 363 AND 362	AT-6:85-143	9/16/85

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D. McMurry	Matching Bridge Couplers to Accelerator/Decelerator Systems	AT-1:85-224	6/18/85
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