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Dr. 2615

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Accelerator Technology Program

January—June 1980

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

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January—June 1980

Compiled by

E. A. Knapp
R. A. Jameson

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ACCELERATOR TECHNOLOGY PROGRAM

Compiled by

E. A. Knapp and R. A. Jameson

ABSTRACT

The activities of Los Alamos Scientific Laboratory's (LASL) Accelerator Technology (AT) Division during the first six months of calendar 1980 are discussed. This report is organized around major projects of the Division, reflecting a wide variety of applications and sponsors.

The first section summarizes progress on the Proton Storage Ring to be located between LAMPF and the LASL Pulsed Neutron Research facility, followed by a section on the gyrocon, a new type of high-power, high-efficiency radio-frequency (rf) amplifier. The third section discusses the racetrack microtron being developed jointly by AT Division and the National Bureau of Standards; the fourth section concerns the free-electron studies. The fifth section covers the radio-frequency quadrupole linear accelerator, a new concept for the acceleration of low-velocity particles; this section is followed by a section discussing heavy ion fusion accelerator development. The next section reports activities in the Fusion Materials Irradiation Test program, a collaborative effort with the Hanford Engineering Development Laboratory. The final section deals first with development of H^- ion sources and injectors, then with accelerator instrumentation and beam dynamics.

SUMMARY

The people in the Accelerator Technology Division at the Los Alamos Scientific Laboratory have an important and exciting charter to make innovations and improvements in particle-accelerator technology, and to apply their results to actual devices for meeting a variety of needs. We have been working on a large accelerator for testing materials needed in fusion-energy systems,

a proton storage ring (PSR) that will extend the capabilities of the LAMPF facility for nuclear physics and materials research, and an electron microtron development program pointed toward high-intensity electron physics research. Other projects are in progress on free-electron lasers, heavy ion fusion, new types of radio-frequency (rf) amplifiers (the gyrocon), H^- ion sources, the development of improved instrumentation, and improved understanding of accelerator physics and beam dynamics. Preceding progress reports in this series, beginning in January 1978, are LA-8218-PR, LA-8350-PR, and LA-8592-PR.

A new type of accelerator structure, the radio-frequency quadrupole (RFQ), was successfully tested for the first time during this period. This concept for accelerating low-velocity particles is an extremely important breakthrough, and will influence, in one form or another, most future low-velocity machine designs. Our initial use emphasizes the RFQ's ability to convert a dc injected beam into an accelerating, bunched beam. The beam is handled in a sophisticated way, but so gently that superior current-carrying capability and beam quality result. Our first test accelerated up to 30 mA of protons from 0.100 to 0.640 MeV in a 425-MHz RFQ; the results were essentially as predicted. Although many details remain to be worked out, the proof-of-principle was convincingly demonstrated.

Cost estimates and Title-I work for the construction staging building were completed for the PSR project during this reporting period, and details of required modifications and timing interfaces to LAMPF were worked out. This report also covers in some detail the PSR injection system, main ring-magnet designs, and the extraction-system design progress, as well as progress on other subsystems. An experimental measurement of the field ionization rate of 800-MeV H^- ions through a magnetic field was successfully performed at LAMPF. Reporting of the theoretical effort includes progress on an orbit-tracking code, and discussion of the space-charge limit, accounting for tune shifts from perturbations in the focusing function.

In the gyrocon rf-amplifier project, fabrication of the majority of the many individual parts was completed, and considerable progress was made on the test stand; assembly will now begin. Theoretical work concentrated on the spherical gyrocon and several improvements to the computer simulation codes.

The NBS-LASL racetrack microtron (RTM) is a joint research project of the National Bureau of Standards (NBS) and LASL to develop high-energy, high-current, continuous-beam electron accelerators with room-temperature (that is, not cryogenic or super-conducting) rf accelerating structures. Conceptual design of their subsystems was completed during this period.

A great deal of progress was made on the free-electron laser project in the modification of the electron linac, wiggler design, and alignment techniques. This report concentrates on theoretical progress made with the two and one-half dimensioned, fully electromagnetic, relativistic particle-in-cell plasma-simulation code CCUBE. Waves propagating obliquely to the electron beam are shown to be always unstable with appreciable growth rates, so that mode competition must be a design consideration. Some of these waves can be absolutely unstable and disruptive, but we show that this can be avoided by careful design.

Heavy ion fusion accelerator development considered how to apply the RFQ accelerator to this application. Computational methods have been developed to predict the current-carrying capacity of linear accelerators, including the RFQ, and we have learned that the RFQ can carry more current than conventional linacs. We also participated in a number of national meetings and workshops on heavy ion fusion.

The Fusion Material Irradiation Test (FMIT) project being conducted jointly with the Hanford Engineering Development Laboratory (HEDL), stayed on its ambitious schedule. The prototype building moved toward completion, and testing of the injector system resumed. The RFQ proof-of-principle test showed the feasibility of using this device for FMIT. A major contract for the rf power systems was placed, and the control-system computers were also procured. Preliminary design activities for all subsystems made substantial progress.

This progress report concludes with a discussion of H^- ion-source research status and construction activities on a test accelerator to investigate the acceleration of high-quality H^- beams. Important theoretical contributions to the understanding of how beams must be matched in detail to the accelerator focusing systems, work on three-dimensional space-charge simulations, and a theory for the emittance growth caused by mismatch are outlined.

PROTON STORAGE RING

I. ENGINEERING AND CONSTRUCTION

A. Architect-Engineer Negotiations

The Architect-Engineer (AE) selected for the Proton Storage Ring (PSR) is Randy Holt and Associates of Albuquerque, New Mexico. The project is scheduled to be completed in two phases. Phase I will require completion of the staging building, to enable an early start on equipment development. Phase II will include the remainder of the facility. The schedule for Phase I is as follows:

Title II submitted	July 21, 1980
Title II review	August 21, 1980
Title II pick-up	August 29, 1980
Advertise for bids	September 2, 1980
Open bids	October 2, 1980

Construction should take approximately nine months, with beneficial occupancy after three months.

The schedule for Phase II is as follows:

Title I submitted	October 1, 1980
Title I review	November 1, 1980
Title II submitted	February 13, 1981
Title II review	March 16, 1981
Title II pick-up	March 31, 1981
Advertise for bids	April 6, 1981
Open for bids	May 7, 1981

Construction time for Phase II will be from 14 to 16 months.

B. PSR Special-Equipment Cost Estimate

William M. Brobeck and Associates of Berkeley, California, is doing a cost estimate for all the specialized equipment in the PSR. This estimate will include items such as 36° dipoles for the ring, rf systems, vacuum systems, injection and extraction lines, and modifications made to LAMPF to produce and transport the high-intensity H^- beam needed for the PSR.

The cost for engineering and design, fabrication, checkout, and installation will be included in the estimate. Research and development costs will not be included because R&D comes out of the operating, and not the construction, budget. This estimate, together with the cost estimate that the AE

will produce for the physical plant at the end of Title I, will give an independent comprehensive cost estimate of the PSR. Engineers from Brobeck have visited LASL and have talked to the staff members involved to gain a better understanding of the various system components that make up the special equipment hardware. Some equipment, for various reasons, cannot be defined well enough at this time for Brobeck to do a cost estimate. AT-Division personnel will estimate these systems by using rules of thumb that have proven over the years to be reasonably accurate. Brobeck is scheduled to deliver a rough-draft estimate by July 15. The draft will be studied to ensure inclusion of all the special equipment that can be estimated at this time and to ensure that the estimating is based on sound practices. The final report will be issued by the end of July.

C. Electrical Systems

1. Power System. A study of the power-system requirements has been completed. The power required for the staging building is approximately 1250 kVA connected; a 1000-kVA pad-mount transformer will serve this load. The power required for the combined storage ring and equipment building is approximately 3250 kVA connected; three 1000-kVA transformers and/or secondary substations will serve this load.

A study of the electrical power feeders has also been completed. It was recommended that the existing 350-MCM, XLP, 15-kV cable be reused where possible and new cable of the same size and similar type be used to separate LAMPF loads from Weapon Neutron Research (WNR) and PSR loads. The combined connected kilovolt amperage kVA of the PSR and WNR loads is 5500 kVA and allows for some expansion of either facility. The purpose of this study is to reduce the PSR construction cost by reuse of existing cable in lieu of larger new cable; approximately \$130 K will be saved.

2. Personnel Safety System (PSS). The design concept of the PSR PSS is ready for review. The operation of the system will be similar to the LAMPF PSS for reasons of standardization, maintenance, and fail-safe criteria. To minimize costs, this system will be contractor installed, with the majority of the equipment contractor purchased. For contractor installation ease and cost savings, the final design will be completed by the Wirex computer code.

3. WIREX.¹ The instrumentation and controls will, for the most part, use the WIREX system for specifying the complex wiring systems so that they may be contractor installed. The contractor, using WIREX, can install the majority of a system's wiring without any knowledge of what a system does. Project wiring costs will be lowered by use of this system.

D. PSR Alignment

PSR alignment will be accomplished by distance measurements, with respect to a central alignment reference monument, and wall monuments associated with each PSR straight section. Three independent and convenient distances repeat throughout the ring: the distances between the central monument to the wall monument, wall monument to second adjacent wall monument, and wall monument to dipole center fiducial. The monument locations are shown in Fig. 1.

Wall monuments will be accurately positioned radially through line-of-sight tubes from the central reference monument by measuring the distance to within ± 0.0007 in. (± 0.02 mm), using a CERN Distinvar or a Kern Distometer distance measuring system. Both systems are based on calibrated Invar wires. Distances between wall monuments will also be measured by one of these systems, thus eliminating the need to turn angles. The elevation of the wall monuments will be determined by a precision level mounted on the central reference monument. Each straight section will be aligned by sighting through a jig transit from one wall monument to a target on the second adjacent wall monument. Targets then will be located on the magnet fiducials, and the magnet targets will be aligned with the line of sight established between wall monuments.

The contour and orientation of the ring in relation to line D will be defined by monuments SM-1, SM-2, and SM-3 (see Fig. 1). These monuments are located with respect to line D by traversing the loop through the vertical breakouts, line D, the three SM monuments, and back to line D.

Requests for quotes have been sent out for both the Distinvar and Distometer measuring systems.

We have received a commitment from the Medium Energy Physics (MP) Division for use of their tooling dock on a schedule-in-advance basis. The details have yet to be worked out, but this could result in a substantial cost savings for the PSR.

Fig. 1.
PSR alignment reference designations.

II. BEAM PREPARATION

A. Magnitude of LAMPF Modifications

A series of meetings was held with LAMPF and WNR personnel to define the modifications to LAMPF that will be necessary to provide an adequate beam for PSR-WNR operation. It was concluded that new LAMPF operating modes will have to be established to meet future requirements. A reference scenario for average H^+ currents up to 1 mA is shown in Table I. Off-energy operation (as low as 400 MeV) of the H^- beam to line X will require time-shared acceleration with the H^+ beam, as will the intense beam to the PSR.

A new ion source to produce the 100- μA H^- beam for the PSR will be constructed and the 750-keV beam-transport line will be modified. The hardware costs for these two items are estimated to be \$490 K and \$590 K, respectively. Switchyard modifications also will be necessary because the polarity and intensity of the beam to the present WNR transport system, line D, will have been changed. The hardware cost for switchyard modifications is estimated to be \$750 K. Additionally, steering modifications (\$70 K) and a provision for linac energy regulation (\$10 K) will be installed. The total effort will require approximately 19 FTE years of technician manpower and 10 FTE staff

TABLE I
PROPOSED LAMPF BEAM STRUCTURE DURING PSR OPERATION

800-MeV Operation		LAMPF Operation with PSR/WNR Complex H ⁺ Operation							9% Duty Factor Simultaneous SBHF Mode Sequential LBLF Mode On Energy Operation Time Structure		
PSR/WNR Mode	Beam Type	Repetition Rate	Pulse Length	Duty factor	600- μ A _p Beam Current	800- μ A _p Beam Current	1.0- μ A _p Beam Current	H ⁻ Chopping	WNR/PSR Time Usage	% Macropulse Usage	% Total Usage
PSR on SBHF Mode	H ⁺ beam to area A	120 Hz	750 μ s	9%	6.66 mA _p	8.89 mA _p	11.1 mA _p				
	H ⁻ beam to line X	120 Hz	630 μ s	7.56%	{ 0 - 130 μ A _p > 0 - 10 μ A _d 0 - 0.5 μ A _p > 0 - 35 nA _d }						
	H ⁻ beam to PSR	120 Hz	100 μ s +20- μ s windows	1.20%	$80 \times \frac{1}{12}$	$106 \times \frac{1}{12}$	$133 \times \frac{1}{12}$	60 ns H ⁻ chopping			
	(Assumes peak H ⁻ current equals peak H ⁺ current) = 6.6 μ A _d = 8.8 μ A _d = 11.1 μ A _d										
PSR on LBLF Mode	H ⁺ beam to area A	108 Hz	750 μ s	8.10%	7.41 mA _p	9.87 mA _p	12.3 mA _p				
	H ⁻ beam to line X	108 Hz	750 μ s	8.10%	{ 0 - 120 μ A _p > 0 - 10 μ A _d 0 - 0.5 μ A _p > 0 - 40 nA _d }						
	H ⁻ beam to PSR	12 Hz	750 μ s	0.90%	66.7 μ A _d	88.8 μ A _d	111.1 μ A _d	270 360 chopping			
	(Assumes H ⁻ peak currents 25% larger than H ⁺ peak current)										
Off-Energy Operation											
PSR on SBHF Mode	H ⁺ beam to area A	80 Hz	750 μ s	6.00%	10.0 mA _p	13.3 mA _p	16.6 mA _p *				
	H ⁻ beam to line X	40 Hz	750 μ s	3.00%	{ 0 - 330 μ A _p > 0 - 10 μ A _d 0 - 0.5 μ A _p > 0 - 15 nA _d }						
	H ⁻ beam to PSR	80 Hz	180 μ s	1.44%	$144 \times \frac{1}{12}$	$144 \times \frac{1}{12}$	$144 \times \frac{1}{12}$	50 ns chopping			
		80 Hz	135 μ s	1.08%	$144 \times \frac{1}{12}$	$144 \times \frac{1}{12}$	$144 \times \frac{1}{12}$	"			
PSR on LBLF Mode	H ⁺ beam to area A	70 Hz	750 μ s	5.25%	11.4 mA _p	15.2 mA _p *	19.0 mA _p *				
	H ⁻ beam to line X	40 Hz	750 μ s	3.00%	{ 0 - 330 μ A _p > 0 - 10 μ A _d 0 - 0.5 μ A _p > 0 - 15 nA _d }						
	H ⁻ beam to PSR	10 Hz	750 μ s	0.75%	97.5 μ A _d	134 μ A _d	142.5 μ A _d	270 360 chopping			
	(Assumes H ⁻ peak current is 25% larger than H ⁺ peak current)										

* Exceeds 14 mA_p peak current limitation.

Fig. 3.
New configuration proposed for the LAMPF switchyard.

III. INJECTION

A. Injection-Line Optics

A scheme for transport of H^- beam from line D to the ring is shown schematically in Fig 4. This solution simplifies and extends a previous design.⁵ A kicker located downstream of line-D quadrupole QD-14 deflects beam into a transport plane skewed 24.4° from the horizontal. The skew configuration consists of a 13.5° bend magnet, three quadrupoles, and a 15° bend magnet that serve to transport beam to a trajectory, collinear with the ring injection section. Quadrupole QHF1 and QHF2 provide a dispersion crossover at quadrupole QVF, and complete cancellation of dispersion at the 15° bend magnet. Fig. 5 shows the dispersion vector, and an illustrative beam envelope for the design emittance of 0.05π cm-mrad.

Quadrupoles QVF, Q1, Q2, and Q3, are adjustable, to provide beam parameters in accordance with the injection constraints; that is, the beam

- must pass through a small (1 cm) vertical aperture at the stripper magnet;
- emittance growth caused by the stripping process is to be minimal;

Fig. 4.
Injection line configuration.

Fig. 5.

Plot of injection line beam envelope and dispersion vector along the beam line. The solid line in the beam-envelope plot shows the rms beam outline in the local x-direction (that is, horizontal or parallel to the skew plane) for a "small spot" focus on the foil, and the dashed line shows the same information in the local y-direction.

- phase-space characteristics at the stripper foil are tailored to one of three injection modes;
- must be within a given size range at the H^0 beam dump;
- should be insensitive to the beam wobble experienced by LAMPF.

These criteria conflict with each other to some extent, so that the system parameters are in fact overconstrained by them. Suitable compromises, however, have been found so that all constraints are nominally satisfied.

Injection procedure requires motion of the injection spot relative to the ring stored-beam orbit. This is accomplished in the vertical direction by pulsed steering magnets located in the skew plane. Horizontal motion is accomplished by moving the stored beam orbit across the foil by the bump-magnet system seen in Fig. 4.

The beam intensity profile, as received from LAMPF, is roughly Gaussian. The consequent halo will be removed by several foil strippers located in the injection line so that the beam orientations in phase space at the stripping points are favorable for nearly complete halo stripping, and so that transport of the stripped beam through the line apertures is possible. Stripping along a 3σ contour in phase space will result in approximately $1\ \mu\text{A}$ of protons, which will be deflected downward by the 15° bend magnet and disposed of in a long pipe embedded under the ring floor.

B. Injection-Line Magnet Design

Preliminary design calculations on the bend magnets of the PSR injection line were made during the reporting period. These magnets were sized on the premise that the injected beam would be transported from line D to the storage ring by bend magnets oriented in orthogonal planes. This arrangement was unduly complex and expensive and has since been replaced by a skew-magnet concept of more economical proportions. Further design on the dipole and quadrupole magnets of the system will be made upon completion of the optics-design activity now underway.

C. Bump-Magnet System

1. Bump-Magnet Optics. The bump-magnet system will be used to sweep the circulating beam orbit across the stripper foil in the horizontal direction during injection to (1) tailor the beam phase-space density distribution and (2) reduce the beam-foil interaction with respect to both beam intensity at the foil and total particle passage through the foil. The bump magnets will be located in three of the ring straight sections (see Fig. 4). In Fig. 6, a plot of the bumped orbit is shown for the case of maximum orbit distortion,

Fig. 6.
Ray trace of bumped ring orbit.

which occurs at the beginning of the injection cycle. The orbit distortion decreases with time and vanishes at the end of the injection cycle. The first bump magnet (B1), located near the second extraction septum, delivers a kick of approximately 2 mrad and, with the aid of the PSR quadrupoles, determines the position of the beam orbit at the stripper foil. The strength of magnet B2 determines the angle at which the beam strikes the foil, whereas B3 and B4 return the beam to the equilibrium orbit. The relationship between the angle and the position at which the bumped orbit intersects the foil, along with the corresponding quantities for the injected H^0 beam (ϕ and d in Fig. 5), fixes the trajectory in the phase space along which the beam is injected. The beam phase-space density is then determined by the time variation of the orbit distortion. Using a Green's function method, calculations of the bump-rate effect on beam density prescribe certain forms for the injection rate necessary to achieve a given desired beam profile (assuming ideal orbits). In particular, to preclude charge pileup at the origin of beam transverse coordinates, the bump rate must be large at the start of injection and must decrease monotonically with time.

2. Bump-Magnet Construction. A bump-magnet prototype has been designed and its construction is nearly complete; Fig. 7 shows a sketch of the design. The magnet consists of a single-turn rectangular loop with a 3-in. clear aperture. The interior faces of the loop have a circular cross section with radius such that moments (other than dipole) of the field are small over the beam extent. Because the field distribution is a function of frequency, a com-

Fig. 7.
Bump-magnet construction.

promise in field uniformity between the high-frequency (including the effect of the vacuum jacket) and the dc cases was obtained. The inductance of the magnet is calculated to be about $0.5 \mu H$, with an ac resistance (for the anticipated pulse frequency spectrum) of $10^{-5} \Omega$. For a 2-mrad beam deflection (~ 3000 -A loop current), the power dissipation in the magnet is ~ 2 -W at 120 Hz.

3. Bump-Magnet Pulse Power Supply. A prototype bump-magnet pulse power supply has been designed and the parts ordered. The prototype unit is designed to use a multiple breakpoint pulse decay-shaping network. The initial prototype system will be used to test the first bump magnet for mechanical and electrical integrity at a pulse repetition rate of 120 Hz. The second phase of the bump-magnet pulse power-supply program will involve design and development of an active pulse-decay control system. Prototype construction awaits delivery of components and the hiring of a pulse-power technician.

D. Pulsed Steering-Magnet Modulator

The magnetic fields of the injection line vertical steering magnets will have an amplitude-modulated series of parabolic-like programming cusps. The voltage waveform generator, within the amplitude modulator that will serve as the reference for these cusps, has been investigated. Two methods of using linear amplifiers and operational multipliers have been investigated to achieve this waveform. Both methods have been moderately successful. Valuable circuit techniques have been demonstrated at frequencies in the range of a few hundred kilohertz, the range of interest for the devices. A new and more stable way of generating the cusps is now underway and shows promise of meeting all PSR requirements. Work has also begun in specifying the 400-A-current source and low-inductance transmission line for this effort. Figure 8 shows the block diagram of the steering-magnet power supply.

IV. RING, PASSIVE

A. Main Ring Dipoles

During the reporting period the PSR main dipole magnets were redesigned for a 10.48-cm aperture at the original gap field of 1.2 T. Two coil-matrix configurations were investigated, from which a two-pancake 4-by-12 turn coil was chosen as the more compatible coil system for the dipole magnets. The aluminum coil conductor was sized to provide a coil-window-aspect ratio of 1.54, with a current density of just over 250 A/cm^2 . Pole-end and corner-chamfer designs were determined and the developed lengths of the aluminum coil conductors were calculated.

Fig. 8.
Block diagram of unipolar, programmable steering-magnet supply.

The results of the coil geometry and window analysis were used to define the coil power and cooling characteristics for the single cooling-hole aluminum conductor. The coil power and coolant characteristics are

Coil current	1067 A
Magnet voltage	47.65 V
Magnet power	50.8 kW
Coolant flow	8.67 gpm/magnet
Pressure drop	80 psid
Temperature rise	40°F

The magnetic-field ripple caused by power-supply current ripple was calculated for a phased-back SCR-type 12-pulse power supply. Results show that the rms-ripple magnetic field relative to the dc magnetic field is

$$\frac{\Delta B \text{ ripple}}{B} = 8 \times 10^{-6}.$$

Calculations (see Fig. 9) were performed, using the POISSON magnet-design computer code to estimate the mechanical tolerances allowable during manufacture of the dipole pole tip. For a field uniformity of 10^{-4} over a 10-cm-diam aperture, the magnetic-shim profile tolerance (relative to the flat portion of the pole tip) is ± 0.003 cm.

Effects of changing magnetic properties of the dipole-magnet steel on the field uniformity were calculated (see Fig. 10) and found to be small.

Field uniformity changes caused by dipole-coil position variations were calculated and found to be negligible for coil displacements as large as 0.6 cm.

B. Ring Magnet and Ancillary Equipment Design and Cost Estimates

1. Background. Detailed design for the PSR dipole and quadrupole magnets has been undertaken for nominal 15.5- and 10.5-cm (6- and 4-in.) aperture systems, using laminated-core and water-cooled aluminum conductor coil assemblies. Cost estimates for lamination stamping, coil fabrication, and ancillary equipment fabrication were obtained from commercial firms for

Fig. 9.
Effect of dipole shim tolerances
on field uniformity.

Fig. 10.
Effect of dipole material on field
uniformity.

the 15.5-cm aperture system. Additional cost estimates for magnet assembly at LASL were derived for this larger aperture system. Quadrupole fabrication costs were obtained and corresponding assembly cost estimates for these elements were derived.

2. Magnet Component and Ancillary Equipment Price Quotations. Detail drawings of the 15.5-cm (6-in.) aperture dipole and quadrupole magnet initially were submitted to interested manufacturers during trips taken earlier in the fiscal year. Feasibility and fabrication information obtained on these trips was summarized in trip reports⁶ written earlier this year.

Formal quotation requests were submitted to fabricators for the 15.5-cm aperture laminated-dipole and quadrupole designs. Cost quotations for these systems are summarized in Table II. Detailed cost estimates for the assembly and initial check-out of the laminated-core dipoles and quadrupole-magnet systems were derived within AT-Division. The estimates encompass considerable detail that is not readily summarized for this report. For reference, however, the total cost estimate for the assembly and check-out of the magnets is given below.

15.5 cm-dipole assembly and check-out (11 magnets, including fixtures and support systems)	\$1323 K
15.5-cm quadrupole assembly and check-out (22 magnets)	\$452 K

TABLE II
SIX-INCH DIPOLE VENDOR QUOTATIONS AND ASSEMBLY ESTIMATES

<u>Item</u>	<u>High Quote</u>	<u>Low Quote</u>
Dipole laminations	\$454 500	\$337 000
Dipole coils	435 403	204 366
Quadrupole laminations	85 600	17 256
Air bearing system for magnet assembly	48 200	34 000
Magnet girder systems	\$143 000	\$133 419

Recent funding considerations have necessitated resizing the system to a nominal 10.5-cm (4-in.) aperture for dipoles and quadrupoles. Preliminary cost estimates for the 10.5-cm aperture magnets indicate that significant savings in material and fabrication costs for essentially all elements can be realized.

3. Solid-Core Design Effort. Preliminary drawings of a solid-core 10.6-cm aperture dipole have been made. These drawings have been submitted to materials and manufacturing firms for feasibility and cost quotations to obtain cost comparisons with the laminated-core magnets. To date, these quotations have not been received.

C. Bend-Magnet Current Monitor

A current-monitor design capable of measuring currents to 2000 A has been developed. This device will measure the PSR bending-magnet current to 1 part in 10 000.

A paper design, evolved during this period, has been followed by a low-current working model. The model has been studied and, apart from several difficulties that were associated with nonmatched magnetic toroids, it appears that the evolved circuit will satisfy the requirements for the PSR current monitors. Exact characterization of these circuits was initiated during this period.

The current-monitor circuit is called a zero-flux dc current transformer. It has no mechanical connection to the high-current leads to be measured. The high-current conductor is threaded one time (single turn) through three toroids, each wound with many turns of magnet wire. One toroid senses the ac component of the current to be measured. The other two toroids together sense the dc component of the measured current. These two sets of components are combined, resulting in a device that has a bandwidth from dc to several hundred kilohertz. The measured current capability for the design is 2000 A, full scale. Figure 11 shows the block diagram of the current monitor.

D. Dipole-Conductor Bend Pressure-Drop Study

A series of pressure-drop tests were made on dipole-magnet coil-conductor bends considered to be indicative of the corner-bend radii desired for compact magnet-coil design. Comparative flow and pressure-drop measurements were made with straight and 90° curved sections of a representative aluminum coil conductor, at bend-radius to conductor-thickness ratios from 3 to 5.

- BIPOLAR CURRENT MEASURING ($\pm 2,000\text{AMP}$)
- NO MAGNETIZING CURRENT RIPPLE IN OUTPUT
- ZERO FLUX OPERATING POINT
- 50 P.P.M. RESOLUTION
- D.C. TO 200KHz BANDWIDTH

Fig. 11.
Noncontacting precision current monitor.

These ratios represented sharp corner bends considered to be tighter than normally used in the coil-winding industry, but desired for magnet-coil compactness.

Tests were conducted at selected and controlled coolant-flow rates of interest in the design of the aluminum conductor dipoles and quadrupoles to be used on the PSR. Pressure-drop measurements were made for both straight and curved-section conductor samples, using water manometry. The results were compared to the classic bend-resistance compilation done by the Crane Company decades ago. The results obtained in this experiment span a selectively small portion of the Crane presentation and are in qualitative agreement with the Crane results, but show that the total resistance, and resistance caused by or from curvature, are both lower than those described by Crane and currently are used to derive the developed length of magnet cooling coils.

E. Main Ring Quadrupole Design

The PSR main quadrupole magnets were redesigned for an 11.43-cm aperture, an effective length of 39 cm, and a gradient of 5.73 T/m. Coil geometry

was sized to provide a current-turn product of 6942 ampere-turns, with the aluminum conductor sized for a current density of 250 A/cm^2 .

The results of the coil-geometry analysis were used to define the total quadrupole power and cooling characteristics for the single-hole, square cross-sectioned aluminum conductor. The magnet power and cooling characteristics are tabulated below:

Conductor current	694 A
Magnet voltage	2.98 V
Magnet power	2068 W
Coolant flow	0.353 gpm, series flow
Pressure drop	80 psid
Total coolant temperature rise	40°F

F. Septum-Magnets Preliminary Design

Preliminary design and analysis of the PSR septum magnets required to deflect the proton beam 18° relative to the ring orbit, and into the PSR extraction line, were accomplished. Principal effort has been given to initial analysis and conceptual design of the first septum magnet intended to provide the initial 4.3° deflection of the extracted beam. The magnet and septum chamber were sized to provide a magnetic field of 0.5 T, an effective length of 73 cm, and a septum height of 5.5 cm. With the Septum 1 magnet current-turns product set at 22,330-A turns, the septum-conductor current was determined to be 2791 A for an 8-conductor septum. This high conductor current is being carried in a one-cooling-hole square copper conductor at a conductor-current density of just over $10\,000 \text{ A/cm}^2$.

The power density for the 8-conductor Septum 1 design prompted a fluid flow and convective heat-transfer analysis to define the adequacy of the cooling process for the septum conductor. The analysis shows that the coolant flow is fully turbulent in the 1/8-in.-diam passage and will produce a convective heat-transfer coefficient sufficiently large to maintain the film temperature gradient to about 20°F . This will maintain the copper conductors at a power level of about 6 kW per conductor in the septum leg and about 2 kW per conductor in the return leg.

Conceptual layouts of the Septum 1 design were made, using a septum conductor system contained entirely outside the vacuum chamber. Design and preliminary experimental effort on septum-conductor fabrication were also

undertaken. Methods for insulating the conductors and maintaining consistent spacing and flatness in the septum-conductor region are being developed experimentally.

The preliminary septum coil-design features are shown in Figs. 12 and 13.

Calculations were made of the effects of septum-conductor dimensional and position errors on the uniformity of the magnet's field, and the septum design was changed accordingly. It was found that magnetic-field errors at the septum, caused by periodic septum variations, decay to 5.4×10^{-4} of their value at the extracted beam's position. It was also concluded that for good magnetic-field uniformity:

- (a) septum conductor turn-to-turn insulation has to be kept as thin as possible,
- (b) septum conductor water-cooling channels have to be kept small, and
- (c) septum conductor corners should be as square as possible.

G. Tunnel Radiation Shielding

1. General. It is expected that during PSR operation, part of the 800-MeV proton beam will be stopped on the neutral-beam, injection-line halo scraper and tune-up beam stops. Also, some beam loss is expected in the

Fig. 12.
Septum coil configuration.

Fig. 13.
Septum vacuum jacket.

extraction septum magnet. These areas will be sources of high-energy neutrons, and therefore the ring has to be adequately shielded to permit personnel access to the equipment building, control room and vicinity of the ring.

In addition, the material of equipment struck directly by the proton beam and cascade neutrons will be activated; x-ray shielding will have to be placed around this equipment to permit personnel in the vicinity.

A consultant, Marcel Barbier, was hired to do preliminary estimates of needed shielding thicknesses, and of activation problems that will arise during PSR operation. Table III and Fig. 14 show the acceptable dose rates for personnel and the major beam-loss points (and loss intensities at these points), used in the shielding and activation estimates. Table IV summarizes the philosophy underlying the PSR shielding and activated-component handling design.

2. Shielding Calculations. The thickness of the radiation shielding for a device such as the PSR is normally calculated by assuming that all the neutrons have the same energy (800 MeV for the PSR). M. Barbier's report⁷

TABLE III
DOSE AND DOSE RATE LIMITS FOR VARIOUS
CATEGORIES OF PERSONNEL

(Used in design of PSR shielding)

<u>Personnel Category</u>	<u>ALAP* Yearly Dose Limit (mrem)</u>	<u>Dose Rate Limits in Accessible Areas (mrem/hr)</u>
General public	100	0.18
Nonoccupationally exposed employees	170	0.085
Radiation workers	1000	0.5

*"As Low As Practical"; present DOE limits are 5 times higher.

Fig. 14.

Major beam-loss points for shielding calculations. Loss intensities are assumed for purposes of calculation and, except for the foil stripper, do not represent irreducible losses.

TABLE IV
PSR SHIELDING DESIGN PHILOSOPHY

GENERAL DESIGN

Shield thickness and geometry designed (very conservatively) for "worst case", 4- μ A, localized beam loss.

Compacted volcanic tuff used as shielding material; neutron attenuation nearly that of concrete.

FEATURES FOR ACTIVATED COMPONENT HANDLING

Large tunnel to allow local shielding around activated devices.

Overhead bridge crane adaptable to remote-handling operations (manipulators).

Vacuum equipment in high beam-loss areas equipped with remotely removable flanges.

Magnet-transport vehicle adaptable for remote operation.

suggested that the shielding thickness could be reduced by taking into account the variation between the angle and the neutron energy spectrum in the calculations. These calculations were carried out in the manner described below.

The radiation dose rate (dD/dt) received by a worker placed at distance R from an 800-MeV proton-beam-spill current I and shielded by a shield of thickness X is given by

$$\frac{dD}{dt} = \frac{I}{e} \frac{1}{R^2} \int_0^{800 \text{ MeV}} \frac{1}{n(E)} \frac{dN}{d\Omega dE} e^{-\frac{x}{L(E)}} dE ,$$

where

- dD/dt = neutron dose rate in mrem/hr,
 I = proton beam-spill current in amperes,
 R = distance of worker from beam spill in centimeters,
 $n(E)$ = flux of neutrons (per cm^2/s) required to give a dose rate of one mrem/hr,
 $dN/d\Omega dE$ = number of neutrons produced per steradian per energy interval by a proton colliding with material at the beam-spill point,
 x = shielding thickness in centimeters,
 $L(E)$ = neutron mean free path in shielding material as a function of energy.

The neutron mean free path is given by

$$\frac{1}{L(E)} = \rho \frac{N_0}{A} \sigma(E) ,$$

where

- ρ = density of shielding material
 N_0 = Avogadro's number
 A = molecular weight of shielding material
 $\sigma(E)$ = neutron-absorption cross section of shielding material as a function of energy.

The qualitative energy dependence of $\sigma(E)$ is shown in Fig. 15. This energy dependence can be expressed, relative to the plateau value (σ_0 at >100 MeV), as

$$\sigma(E) = \sigma_0 \left(1 + \frac{\Delta\sigma(E)}{\sigma_0} \right) .$$

The dose-rate equation then becomes

$$\frac{dD}{dt} = \frac{I}{e} \frac{1}{R^2} e^{-x/L} \int_0^{800 \text{ MeV}} \frac{1}{n(E)} \frac{dN}{d\Omega dE} e^{-\frac{x}{L_0} \frac{\Delta\sigma}{\sigma_0}} .$$

Fig. 15.

A linear model for relative absorption cross section as a function of neutron energy. This model was used for shielding calculation and closely approximates experimental data.

calculated by the two methods differ by 46 cm, if volcanic tuff is used as the shielding material.

The PSR shielding has been calculated using the exact method, and the results have been incorporated into the architectural drawings for the PSR site.

V. RING, ACTIVE

A. 2.8-MHz Buncher

1. Progress Summary. The 2.8-MHz buncher to be developed for the PSR will consist of a 30-kW ferrite-loaded cavity, gap structure, low-level control electronics, and a high-level 30-kW transmitter. This report discusses progress in the area of the transmitter (Collins 205G), the load resistor developed for testing the device, and progress in determining the properties of the ferrite used to increase the inductance of the cavity structure.

2. Collins Transmitter. By January (1980) all primary power and air-supply installations to the Collins transmitter were complete. During this reporting period, final modifications were completed on the transmitter power amplifier and low-level section of the Collins. After initial power supply and stage-bias-level checks, the transmitter was powered up to the 7-kW level.

where L_0 is the mean free path of 800-MeV neutrons. This dose rate was calculated for different angles, relative to the proton-beam direction. It was found that, after the first mean free path in the shielding, the low-energy neutrons have been removed and only the high-energy part of the spectrum remains. Because the low-energy part of the spectrum contributes very little to the radiation dose, the shield thickness calculated by this exact method differs very little from that calculated assuming that all neutrons have an 800-MeV energy. At an angle of 90° , the needed shield thicknesses

This first test at 7 kW indicated the need to modify the output coupling network, and a requirement for 1000-pF, 20-kV vacuum-variable capacitors in the output stages was established. This work at the 7-kW level also tested the overcurrent and safety system within the Collins Transmitter. The safety systems functioned correctly for all failure modes investigated.

Some modifications of output-tank circuit values then allowed short-term tests of the Collins Transmitter at the 15-kW level, the level where it would normally function in the PSR. Linearity and distortion products have not yet been evaluated completely; however, they appear to be below 5%, an acceptable value.

3. Load-Resistor Tests. During the Collins-test series, the dummy load used in the test was a newly completed load-resistor assembly. Power was applied to this load at the 15-kW level for 2-6 hr periods, and heat dissipation characteristics of the load resistor were measured.

The load resistor is immersed in an oil bath for effective cooling. The dissipative element is a ceramic metal resistor about 1.3 m long. The resistor is surrounded by a tapered ground plane, and oil circulation for cooling is achieved by a pumping system and heat exchanger. The load presents a 50- Ω resistive impedance to the source, with better than 1.1:1 VSWR up to 20 MHz. The load resistor incorporates a built-in heat exchanger for water cooling that will provide a 40- to 50-kW rms load power capability.

4. Ferrite Evaluations. This reporting period also included completion of fundamental tests on the AGS ferrite rings. The technique used was similar to that described by M. Plotkin (Brookhaven National Laboratory), wherein several turns of conductor are placed around the sample toroid; the magnetic and loss parameters are then determined by excitation of the core with a power oscillator. Values obtained for the loss parameters were larger than expected, because of stray fields and leakage flux paths. Therefore, a decision was made to construct a small coaxial test cavity of high Q, thereby reducing the leakage flux problem. This test cavity was completed during the last part of the reporting period. Tests indicated that the ferrite's relative permeability at low field was 380, a value very close to that expected. The small cavity also provided high magnetic (B) fields so that the permeability-versus-B relationship could be established. These relationships are shown in Fig. 16.

Fig. 16.

Ferrite evaluation test. AGS (Ferroxcube 4L) ferrite evaluated at 2.795 MHz, Sample 1, May 1980.

A larger cavity, equal in diameter to that of the final device, but half as long, was constructed to measure gap impedance and to aid in establishing the ferrite-permeability value (μ) versus air-gapping distances for the ferrite material. Preliminary data indicate the final gap impedance will be in the range of 2 000 Ω , and permeability values in the range of 20 can be achieved easily. Ferrite permeability values of from 10 to 20 are acceptable for the 2.8-MHz buncher cavity.

B. Distributed Amplifier

In the long-bunch mode of the PSR operation, the resistive wall-instability growth time is only a fraction of a millisecond (0.1 ms). Therefore, the PSR will require an active damper system, incorporating a 5-kW high-speed distributed amplifier (D/A), to suppress the coherent betatron motion. This section discusses the progress in the design of the amplifier and related devices.

Comprehensive testing was done on a batch (25) of RCA 4636 tetrodes in a model 8-tube distributed amplifier configuration. This amplifier was designed to aid in the selection of tubes for the D/A and to aid in confirming line parameters for D/A designs. Figure 17 shows a block diagram of the system. The primary purpose of these tests was to determine the suitability of the RCA 4636 for the PSR transverse damper power amplifiers. Twenty-five tubes were tested. Two of the "as received" tubes were defective and unusable. Only one of the 25 tubes matched RCA "typical" tube characteristic curves; the other tubes required higher control-grid voltages to produce the desired dc plate currents. In the model distributed amplifier, it was possible to operate each tube at the optimum plate current by selecting the proper screen-grid voltage for each tube. These voltages were obtained from a series-connected string of 10-V zener diodes. Under the screen-optimized voltage conditions, the tubes have an average transconductance of 40 mmho, which meets the manufacturer's specifications. The 8-tube configuration had the following characteristics:

Rise time	4 ns
Overshoot	< 1
Bandwidth (3 dB)	> 100 MHz
Nonlinearity	small signal gain is 50x lower at minimum plate current than at maximum plate current.

Fig. 17.
Block diagram of damper-distributed amplifier system.

The bandwidth and gain meet most of our objectives, and work is continuing on the reliability aspects of the design. Reliability is very critical, because 8% of the tubes were defective, and only one tube agreed with the manufacturer's typical curves. An EIMAC 2226 planar tetrode tube is also under review for D/A service. Future tests will examine various aspects of this device.

The driver amplifier used in the 8-tube tests was designed and constructed at LASL by AT-Division personnel. The driver uses microwave power transistors and has the following characteristics:

Output swing	26 V p-p max
Risetime	~2 ns
Power gain	~30 dB

Tests of this device continue and are designed to determine if the drive can successfully meet objectives of dc stability, matching performance, cross-over distortion, cost, and low failure rates.

VI. EXTRACTION

A. PSR Beam-Extraction System

1. Extraction Requirements. Two PSR operating modes must be accommodated by a single extraction system. In the future, it may be necessary to interleave both operating modes in real time.

The short-pulse, high-frequency mode of PSR operation requires the extraction of single 1-ns proton bunches from up to six bunches circulating at 60-ns intervals in the ring. This requires the kicker magnet to turn on and off quickly and to turn off cleanly, without disturbing the remaining proton bunches. These requirements lead to the choice of a kicker "magnet" that is a carefully terminated parallel-plate stripline. The kicker-magnet pulse requirements are shown in Fig. 18. A detailed discussion of the kicker requirements has been given.⁸

The short-pulse high-frequency operating mode requires the kicker to operate at a rate of 720 pps (0.62×10^8 per day!), which limits the operating voltage to ± 50 kV, until experience has shown otherwise. In a 7.5-cm aperture, this corresponds to an 80-G kicking field (actually 40 G, accompanied by a similarly forceful electric field). The pulse-timing budget limits the kicker electrode length to 4 m.

Fig. 18.

Kicker pulse requirements. An identical negative pulse is also needed.

The long-pulse, low-frequency-mode beam extraction will be accomplished with the same deflection electrodes, but driven by longer (~ 380 ns) pulses. The same risetime is desired, but there are no restrictions on falltime. For the long-pulse low-frequency mode, the overriding consideration is minimum beam spill; less than 10 nA is desired and less than 100 nA is required.

Beam is to be delivered to a 50-mm-diam target. Although the beam from LAMPF has a nominal momentum spread $\Delta p/p \approx 1 \times 10^{-3}$, the space-charge forces and rf bunching systems in the PSR result in an extracted beam with $\Delta p/p \approx 3 \times 10^{-3}$. The PSR is dispersive; the closed-orbit radius energy dependence is given by $\Delta r/\Delta E = \eta\gamma/(\gamma + 1) E \approx 1.6$ mm/MeV. It is desirable to cancel this dispersion in the extraction line.

2. Extraction-Line Overview. Figure 19 shows the extraction line in schematic form. The section beginning with the septum magnets and ending with line D insertion magnets is antisymmetric in the horizontal projection. This symmetry suggests a design such as is shown in Fig. 19. A crossover in the vertical projection causes the dispersion of the vertical bends to cancel each other. No crossover is used in the horizontal plane, so that the dispersions of the bend magnets cancel each other. A quadrupole pair, after the second bend (line D insertion) magnet, is used to cancel the effect of the ring dispersion on target spot size. A small deviation from the symmetry of Fig. 18 is used in the design: the first septum magnet bends the beam only in the horizontal plane and the second septum is skewed so as to direct the beam to line D.

The beam will be kicked horizontally and extracted in a plane skewed 19° from the horizontal. A vertical-kick extraction scheme could use the same extraction-line tunnel. As the tunes of the PSR are split ($\nu_x = 3.25$, $\nu_y = 2.25$), little coupling of the horizontal and vertical betatron motions from space-charge effects is anticipated. Because the PSR is a separated-function machine, it is possible to explore other operating tunes. The extraction system designed for the nominal tune also should be suitable for machine studies at tunes of 2.25 or 2.75.

A 7.5-cm aperture is preserved by this extraction scheme. Should operating experience with the kicker pulse generator indicate that higher voltages are possible, the aperture will be increased. The voltage requirement is a quadratic function of the system aperture, because both the applied fields and the electrode separation must be increased with the aperture. For full aperture (10-cm) operation, 89-kV pulses are required.

Fig. 20.
Beam envelopes of stored and kicked beams.

Fig. 21.
Cross sections of the circulating and
kicked beams at the septum entrance plane.

4. Summary and Status. An overall extraction-system reference design now exists. The kicker-magnet drivers have been studied in some detail and test-stand studies are underway. Lattice studies have determined suitable kicker placement. Septum-magnet-design studies are complete and an optical design of an extraction line now exists.

More work is needed on the extraction-system beam optics to include cancellation of PSR dispersion and the extraction of beam, using other PSR tunes.

Space-charge effects need to be modeled and estimates of beam spill must be made. The question of beam profile measurements in the extraction line should be studied, with careful attention given to the effect of beam-induced potentials on secondary electrons from grids in the beam path. It is, however, safe to say that we now have a credible scheme for beam extraction and delivery to the WNR target.

B. Extraction-Line Magnet Design

Preliminary sizing of the dipole magnets for the extraction line has been completed. These magnets consist of the following: (a) The switching magnet immediately following the septum 2 magnet, designed to direct the beam either up the extraction line to line D in the normal operational mode or downward to a beam stop during tuneup and checkout of ring operation. This magnet has been sized to provide a bidirectional deflection of 6.73° at a field strength of 0.86 T, requiring 73 170 ampere-turns excitation. Power to this magnet will be 13 kW, with a coolant flow of 1 gpm through the aluminum conductor. (b) The upper skew magnet for the extraction line requires an excitation of 85 000 ampere-turns for the 19.18° bend, 1-T dipole. Calculations indicate this magnet will require 26 kW of dc power, with cooling at 2 gpm through the aluminum conductor.

Further work on these dipoles and the quadrupole magnets await more definitive beam-optics assessment of the extraction line.

C. Extraction-Kicker Modulator

1. Design and Reliability Considerations. A bunch-trajectory deflection of 6 mrad is required for extraction from the PSR. This requires a magnetic-field path of 300 Gm. Because of the requirement for fast risetime and good pulse fidelity, the "magnet" is a parallel-plate transmission line 4 m long, schematically illustrated in Fig. 22. The force on a proton moving between the plates is $F = q [E + v \times B] = qE(1 \pm \beta)$, where $\beta = v/c = 0.84$ is the proton velocity expressed as a fraction of the velocity of light, and $cB = E$ for TEM wave propagation in vacuum. The deflection pulse is propagated in the direction opposite that of the protons, to get additive effects of electric and magnetic forces.

The two sides of the transmission lines are driven with pulses of opposite polarity, resulting in a virtual ground at the midplane. The impedance seen by the pulse generator is 50 Ω for each plate, relative to ground.

Fig. 22.
PSR extraction-modulator schematic.

For a 10-cm aperture (separation between stripline elements), a voltage of ± 50 kV is required. The pulse parameters for the short- and long-bunch-mode modulators are listed in Table V.

A number of design requirements follow from the application of the modulators in a working accelerator facility. Because of the limited downtime acceptable to the user and the limited operating budgets, all of the modulator components must have a long lifetime. High reliability is essential, because the consequence of improper deflection is beam spillage, which makes the PSR radioactive. Thus the failure rate in the long-bunch mode should not exceed 10^{-4} .

TABLE V
PSR EXTRACTION MODULATOR
PULSE PARAMETERS

	Parameter and Purpose	
	Short-Bunch Mode (Remove Single 1-ns Proton Bunches)	Long-Bunch Mode (Remove Single 270 ns Proton Bunch)
Pulse Voltage	(+) & (-) 50 kV	(+) & (-) 50 kV
Pulse Current	(+) & (-) 1 kA	(+) & (-) 1 kA
Pulse Risetime	30 ns	30 ns
Pulse Falltime	30 ns	Not critical
Pulse Base Width	80 ns	360 ns
Percent after Pulse		
Ringout	2%	Not critical
Pulse Repetition Rate	720 Hz	12 - 120 Hz
Peak Power	100 MW	100 MW
Average Power	4.3 kW	0.43 - 4.3 kW

2. Pulse Generator Systems. The development of the short-bunch mode, fast-extraction modulator prototype is detailed in this report. Similar systems will be used for the long-bunch, fast-extraction modulator. The short-bunch-mode modulator presents the largest technological challenge; the long-bunch modulator problems are similar, but less demanding.

A symmetrical generator system is desired to reduce the deflection-voltage levels required, with respect to ground. In addition, it is desirable to use some type of voltage-multiplication system to reduce the required switch-operating voltage and thus increase reliability. Several pulse-forming-network (PFN)-type pulse-generator systems were evaluated because of the square pulse shape desired. The requirement for minimum prepulse favors a switched PFN that prevents charging transients in the load, as shown in Fig. 23a. However, the switch of Fig. 23a must operate at twice the desired output voltage, and some form of voltage inversion (transformer) or double, oppositely charged, system must be used to obtain the required push-pull output. The basic Blumlein system of Fig. 23b can be used to reduce the switch-operating voltage to that of the desired output-pulse voltage, but the line-charging current must flow through the load, causing a prepulse. A dual, oppositely charged, Blumlein-line scheme can be configured to provide push-pull outputs, as shown in Fig. 23c; but again, the switch must operate at twice the single output voltage and must be dc isolated with respect to ground for the charging potentials.

A new Ferrite-Isolated Blumlein (FIB)-line circuit was developed at LASL to alleviate the above problems and is shown in Fig. 24. This circuit used one element to switch two Blumlein lines in parallel (instead of in series, as in Fig. 23c) and ferrite inductive isolation to provide bipolar output pulses. Computer network analysis indicates that the sum of the output pulses is $< 0.01\%$ of the absolute value of each. The FIB-line circuit can also reduce the charging currents that flow through the loads. If the circuit is charged at two points from the same source, the prepulses can be reduced to $< 1\%$ of the output voltage.

The pulse-generator system of Fig. 24 was fabricated, using 45-ns (15-ft), 23- Ω coaxial cable (17/14) lines and 50- Ω output cables. Sixty Ferroxcube Type CX38, 2-in.-o.d. ferrite toroids per line provide sufficient inductive isolation for the short-bunch mode when the cable is threaded

(a) Switched PFN circuit.

(b) Basic Blumlein-line circuit.

(c) Plus-minus charged dual Blumlein-line circuit.

Fig. 23.

Pulse generator circuits.

Fig. 24.

Ferrite-isolated Blumlein (FIB) circuit.

Fig. 25.
Initial trigger circuit and pulse output.

Fig. 26.
Inverted trigger circuit and pulse output.

Fig. 27.
Double-pulse trigger circuit and pulse output.

through them. The assembly is switched with an EG&G HY-3024 gradient-grid thyatron for increased voltage hold-off reliability. The tube is mounted in a low-inductance shroud on an EG&G Tm-42HV isolation system. The switch tube rises to one-half the output voltage during the pulse. Initially, the tube was triggered with a 2.5-kV positive pulse (unloaded) from an SCR-switched PFN added to the negative bias at grid G2 and a positive bias on G1, as shown in Fig. 25a. The resulting pulse shape, shown in Fig. 25b, indicates an unacceptably long turn-on time for the tube. Several other trigger configurations were investigated and are shown with their resultant output pulses in Figs. 26 and 27. The jitter for the trigger arrangements of Figs. 21-23 was excessive, ranging from ± 10 to ± 200 ns. A trigger booster, consisting of an 8.5- Ω , 1- μ s PFN switched by an EG&G HY-6 thyatron in the cathode follower circuit of Fig. 28a, was inserted between the original trigger unit and the HY-3024. Three overlays of the resulting output-pulse shape are shown in Fig. 28b, indicating low total-system jitter

Fig. 28.
Trigger booster circuit and pulse output.

jitter, or output-pulse shape. Note that the after-pulse ringout is greater than that desired, but can be reduced by matching the pulse generator more closely to the load.

3. Charging System. The charging system is required to charge the Blumlein lines (~ 5 nF) to 50 kV. The desire for high reliability is manifest in the choice of a charging system that uses a combination of resonant and transformer pulse charging. The charging circuit is shown in Fig. 29. Ideally, a 10:1 voltage step-up transformer would be used to charge the Blumlein lines to 50 kV. However, the stray capacitances are a sizable fraction of the FIB line. Thus the intermediate energy-storage capacitor must be resonantly charged to 6.2 kV to charge the FIB line to 50 kV. The intermediate energy-storage capacitor must be resonantly charged in 250 μ s. Then the transformer system charges the Blumlein lines to 50 kV in ~ 4 μ s. The main Blumlein-line switch is triggered within 100 μ s after charging, so

Fig. 29.
Two-stage resonant and transformer charge circuit.

(1-2 ns) and very good circuit-limited pulse shape. The voltage on the trigger booster was reduced from 4 kV to 1 kV, with little deterioration in pulse rise and fall-time ($< 10\%$ increase). The delay time from booster-anode voltage fall to HY-3024 anode fall is about 55 ns. The trigger-booster pulse length was reduced from 1 μ s to 250 ns without any observable change in delay,

that the high-voltage system is energized for only a short time, reducing pre-fire probability. The transformer backswing also assists in turning off the charge thyatron (initially an EG&G HY-3002), so that both switches are not closed simultaneously, to reduce fault problems. The charge thyatron is a 25-kV unit, but it is operated at only 6.2 kV, to reduce prefires and to increase reliability. The voltage on the intermediate energy-storage capacitor is regulated with a reactive de"Q" circuit,⁹ also illustrated in Fig. 29. The voltage on the intermediate capacitor is monitored during the charging cycle and the de"Q" switch is closed when the voltage reaches the desired value. Closing the switch returns any residual energy stored in the charging choke to the low-impedance power-supply filter capacitor and thus prevents the intermediate energy-storage capacitor from charging further. The charge thyatron and blocking diodes require the largest average and rms currents.

The switch-tube and diode requirements are listed in Table VI. The charge thyatron will probably have to be a 5-in. EG&G tube (123 A-rms) to provide reliable long-life operation at the 43-A rms current required. A complete computer model of the charge system was used to check the thyatron performance and the charging efficiency of the transformer circuit. The system charging, excluding the power supply, is about 80% efficient for this particular circuit; most of the energy is lost to the transformer stray capacitance, which is close to 10% of the Blumlein-line capacitance. The remainder is lost in the charge thyatron, the diode snubber, the diode forward resistance, and the transformer magnetizing reactance.

TABLE VI
SHORT-BUNCH MODE
EXTRACTION MODULATOR SWITCH AND DIODE PARAMETERS

	Charging Switch	Output Switch	Charging Diode
Operating voltage	6.2 kV	50 kV	50 kV
Peak current	1.3 kA	4.3 kA	120 A
Repetition rate	720 Hz	720 Hz	720 Hz
Pulse width	3.5 μ s	50 ns	250 μ s
Average current	2.0 A	1.5 A	2.0 A
RMS current	43 A	18 A	6.0 A
Lifetime	10^4 H	10^4 H	10^4 H

Fig. 30.
Diode voltage and current waveforms.

4. Charging-Diode Tests.

The charging diodes for the fast (4- μ s) transformer charge system present several unusual requirements. First, the rms and average currents are large, as listed in Table VI. Second, the charging diodes must turn on in less than one-tenth of the current pulse time, to prevent energy from returning to the transformer primary-energy store. Several manufacturers' diodes were tested for I-V turn-on characteristics, and also life-tested singly at the current levels and repetition rates present in the actual circuit. The voltage and current waveforms for several diodes from different manufacturers are shown in Fig. 30.

5. System Considerations.

The entire modulator system is mounted on a hydraulic scissor-lift table inside a tank of transformer oil. The output cables are routed to the deflection structure within the proton storage ring and then to 50- Ω loads for dissipation. The lift table permits easy access to the components for modification and maintenance. Two separate kicker systems (short-bunch and long-bunch modes) will be used with the same deflection structure. The modulator system will be equipped with computer-programmable time-delay units and power supplies, to permit computer control. The time-delay units will be interfaced to the modulator system by LASL fiber-optic trigger links. Life tests of the prototype system and components at the desired operating conditions will provide reliability data for the final modulator systems.

6. Conclusion. The development of a short-bunch mode, fast-extraction modulator for the LASL PSR has made necessary the design and development of a resonant-transformer charging circuit, along with the design of a new FIB line

circuit, to provide bipolar pulse outputs with low prepulse, postpulse, and an optimum high-voltage switch environment. The systems are now being developed to operate reliably at the high average powers required. The short-bunch mode, fast-extraction modulator prototype is presently operating. The initial construction of the long-bunch mode, fast-extraction modulator prototype is underway, with results expected within the year.

VII. VACUUM

A. PSR Vacuum System

Calculations of the pressure profile in the 4-in. aperture PSR vacuum system were completed and are shown in Fig. 31. The 270-l/s ion pumps can keep the vacuum system pressures below 4×10^{-9} Torr, even if the vacuum chamber is outgassed at only a moderate 300°C temperature. Components such as vacuum gauges, pumps, valves, etc., were selected, and purchase requisitions for early purchasing have been written. The components of the vacuum system are shown in Fig. 32.

Fig. 31.

PSR vacuum system and pressure profile for a typical straight section.

Fig. 32.
Schematic of PSR vacuum system.

B. Sector Valves, Bellows, Belleville Seals

Because discontinuities in the electrical or physical properties of the vacuum chamber walls (that is, impedance changes) can produce beam instabilities, the following efforts were undertaken:

(1) A sector vacuum valve was designed with bore electrically smooth when the valve is open (Fig. 33). This design, and a similar one from Cornell University, were sent to the manufacturer to determine manufacturing costs. Verbal cost estimates of \$5000 per valve (for a total of 3 valves manufactured) were received.

(2) A tentative design for a vacuum bellows was sent to Stanford Linear Accelerator Center (SLAC) for evaluation of its electrical "smoothness", relative to the rf structure of the beam. A prototype has been built and is being evaluated by Time Dependent Reflectometry, to determine its electrical properties.

(3) Design for making the Belleville-type vacuum flanges rf smooth was initiated. Several designs for the rf gasketing of these flanges have been completed.

Fig. 33.
Six-inch rf shorting valve.

Fig. 34.
Section representation of a Belleville seal and flange system.

This work was a continuation of PSR Technical Note 36, dated November 5, 1979, entitled, "PSR Beam-Monitoring System and Initial Tune Up." An overall block diagram was completed showing the major components of the system, and final timing diagrams were developed to show the system operation. The principal rf components include a beam detector in the injection line, which generates pretriggers to initialize the system; 37 4-quadrant position monitors; and 20 rf switching units, which enable selection of any monitor. Signals from a selected monitor are fed to differential phase correlators, which extract the beam-position data and convert it to analog voltage levels. These voltages are converted to digital values, and then are arithmetically processed and stored

C. Remote Handling

It is expected that several components in the PSR vacuum system will become radioactive during operation. Several devices for remotely decoupling Belleville-type vacuum flanges (shown in Fig. 34) have been designed and are being tested. Two designs for a remote decoupling device are shown in Fig. 35.

D. Vacuum Feedthrough Connectors

Several feedthroughs were evaluated for applicability as impedance-matched coaxial seals. A specific device (EG&G NI64) modified for PSR use appears best suited for this service. The VSWR through 500 MHz was less than 1.1. Figure 36 shows a sketch of the device, connected to a vacuum pumping spool.

VIII. BEAM DIAGNOSTICS

A. Development of the Block

Diagram and Timing Diagrams of the PSR Beam-Monitor System

Fig. 35 a,b.
Two designs developed for flange quick-disconnect mechanisms.

Fig. 36.
PSR impedance-matched coaxial seal.

in memory. Evaluation and design of the digital aspects of the system will require a System Exerciser Module, the design of which was completed during this report period. By means of the System Exerciser, an operator can select the equipment operating mode, and the data display mode, as well as other critical system parameters. Beam-position information is displayed in the test mode by a Hewlett-Packard Model 1350A Graphics Translator and a Model 1304A X-Y cathode-ray tube display. Both of these components of the system were tested during this report period, with complete success.

B. Development of Beam-Position Displays

A digital processor was fabricated to provide means for generating and evaluating different signals for display. This equipment allowed certain signal and display formats to be simulated for use in the development program. The format proposed by PSR Technical Note 36 was evaluated and has been incorporated in the design of the System Exerciser as an initial design tool for work leading to establishment of the parameters for a data interface module.

C. Design and Fabrication of a System Trigger Simulator

A circuit was designed and constructed to simulate triggers that correspond to signals from the storage-ring beam-position monitors. This circuit was installed in a chassis, along with modular power supplies. It will become an integral part of the equipment required for a proof-of-principle experiment, to be conducted with various elements of the monitor systems during the fall of 1980.

D. PSR Beam-Monitor System Exerciser

Design of the System Exerciser was initiated during the latter part of March. This unit will be used during the design, fabrication, and testing phases of the system construction. It will enable signals to activate the data interface and processing channel of the beam monitor for various modes and signal conditions. It will serve as a test unit for defining the types of interface processing to take place in the monitor and will aid in the overall design effort.

E. Candidate Beam-Monitor Evaluation

Models of the injection-line detector were fabricated and tested with simulated beam signals; these evaluations indicated satisfactory performance. A prototype device has been installed in line D at WNR and is currently undergoing tests with real beams. The injection beam monitor has the following characteristics:

Beam mutual impedance	2.6 Ω
Impedance	50 Ω
Displacement sensitivity	2 dB change/cm displacement
Clipping time	2 ns
Risetime	< 1 ns

Other parameters are under investigation.

F. A Beam-Trigger-Receiver Model

The device, configured as a linlog amplifier chain, can easily detect 1 micropulse and has an intensity range of 40 dB, 100:1. This device provides a standard Schottky TTL pulse signal for monitor synchronization and timing purposes. Figure 37 shows a simplified functional diagram of the overall beam-monitor system.

Beam-detector devices have also been fabricated and tested during this interval. Electrical parameters are similar to the injection-line devices described above, but the electrical components are located interior to the ring pumping spools. Figure 38 shows the overall cross sections of these devices.

Fig. 37.
PSR beam-position monitor functional outline.

Fig. 38.
Typical PSR vacuum-system pumping spool and position monitor.

G. Impulse Generator

An avalanche transistor circuit has been built to simulate the beam signals in the PSR short-bunch mode. This circuit produces pulses 200 ps wide, with 9-V amplitude at 100-kHz rep rate, with very low jitter between trigger input and output pulses. This device will be very useful in testing and developing the necessary devices for the damper and choppers. The device will also be useful in developing and testing beam detectors and beam deflectors.

IX. INSTRUMENTATION AND CONTROL SYSTEM

Work on the Instrumentation and Control (IC) system has been slow to begin because of recruiting difficulties. However, in the period covered by this report, a start has been made.

A number of conclusions were reached, resulting from a study of the needs for efficiently operating the PSR.¹⁰ Unlike the position several years ago, the procurement of the hardware for nearly all the computer-related parts of the system is no longer a problem. International standards exist for the computer-equipment interface and components can be purchased from several manufacturers. Thus the decision to use CAMAC for the computer-equipment interface is an easy and obvious one.

The need to dedicate small processors to various aspects of the control of the PSR is recognized, and there are many implementations of microprocessors in CAMAC. Considerations of software support indicate that choosing processors from the same family for the central computer and the dedicated microprocessors will simplify and speed up the development of the system.

Graphics will play an important role in communication with the machine operator. However, the choice of system details for graphics is not so obvious as in other areas. Because of the complex information that needs to be presented, color graphics will have to be seriously considered for the operator's consoles. Also worthy of serious consideration are the input devices for the operator to use. The better presented the data on the machine performance is, and the more convenient the input devices are to use, the better will be the performance achieved with the PSR.

The FMIT prototype accelerator that is being built, under contract to Hanford Laboratory, will be a proton linear accelerator to provide neutron beams for irradiation tests. Although in many respects this is a quite different machine from the PSR, there is a lot of commonality in the IC requirements that must be exploited to the full for the benefit of both projects.

X. PHYSICS DATA

A. H⁻ Field Stripping

The experiment at LAMPF, which measured the field ionization rate of high energy H⁻ ions through a magnetic field, was successfully performed in late March 1980.¹¹ A preliminary run¹² in January was invaluable in evaluating instrumental performance, and contributed to the success of the

Fig. 39.

Schematic diagram of apparatus used to measure H⁻ field stripping rate.

March run. The apparatus is shown in Fig. 39. The 800-MeV H^- beam passed through a specially constructed stripper magnet (Gypsy), which alternatively presented a linearly increasing field (over a 20-cm distance) or a "hard"-edged field, transverse to the beam. The angular deflection undergone by a given particle in passage through Gypsy was a monotonic, calculable function of the distance traveled through the field by that particle. This distance was also measured by means of a retractable foil stripper, which was movable through the stripping region. Angular deflection was directly measured by a multiwire chamber counter located at the downstream end of the apparatus. The magnet Eros was used for separation of charge species.

The results of the experiment are plotted in Fig. 40, along with low-field data obtained by a previous experiment at TRIUMF. The data fit a first-order theoretical formula

$$\ell = \frac{A_1}{B} e^{A_2/B},$$

where ℓ is the stripping length in meters, B the magnetic field in Tesla, with A_1 and A_2 fitting parameters determined by the experiment to be

Fig. 40.
Measured stripping length for 800-MeV protons as a function of magnetic field.

$$A_1 = 2.47 (\pm 0.10) \times 10^{-6} \text{ Tesla} \cdot \text{M},$$

$$A_2 = 9.65 (\pm 0.05) \text{ Tesla}.$$

Conversion to a stripping time in seconds as a function of rest-frame electric field in volts/meter is accomplished by replacing B in the above relation with the electric field and multiplying A_2 by $\gamma\beta c$. The results of the experiment specify the PSR stripper-magnet design in terms of the field configuration necessary to obtain a given deflection and angular spread in the stripping process. A direct measurement of these quantities is shown in Fig. 41,

Fig. 41.

Direct measurement of the angular growth in field stripping by a dipole magnet with 1.5-cm gap.

in which relative beam intensity versus position (and hence angle) along the multiwire counter is plotted for passage through the hard edge of Gypsy (that is, a dipole magnet with 1.5-cm gap). The observed angular increase of 1.5 mr can be reduced by approximately a factor of two in the ring stripper magnet by special magnet design.

B. LAMPF Beam-Energy Measurements

The PSR will require that energy fluctuations in the incoming H^- beam be less than ~ 1.2 MeV.

A method was developed to determine the beam energy by measuring the phase difference between the beam

signals from two separated detectors to find the time of flight. Energy fluctuations of 0.2 MeV on a time scale of 0.25 μ s can be measured with absolute energy accuracy of ± 1.3 MeV. At WNR in March 1980, energy measurements were made of the LAMPF proton beam. The energy variation in the main micropulse was ~ 0.5 MeV, which indicates that the stability of the H^- macropulse for the long-bunch mode should be acceptable. The short-bunch mode will require a gap time within the H^- macropulse for the kicker magnet to turn on. Energy variations, as measured within a portion of beam separated from the main macropulse by a gap time, were between 2.2 MeV and 6.6 MeV, depending upon the gap time. These larger fluctuations were due to shock excitation of the rf cavities. If a gap is needed in both H^+ and H^- beams to allow beam separation, then cavity shock excitation and energy variation will be a problem. It may then be necessary to gradually turn on the beams following the gap time to avoid shock excitation, which would require a longer restored beam time for a given PSR proton bunch size. If beam separation can be produced without a gap in the H^+ beam, then the cavity loading will be smoother and the energy variations should be less. Further measurements will be required when a suitable H^- beam is available.

XI. THEORY

A. Chromaticity Calculation

The chromaticity of a storage ring or circular accelerator is a measure of the variation of the betatron oscillation frequency with momentum deviation from the design momentum. That is, if Q_x is the horizontal tune (the number of betatron oscillations per revolution), then the horizontal chromaticity ξ_x is defined by the equation

$$\frac{\Delta Q_x}{Q_x} = \xi_x \frac{\Delta p}{p} .$$

The head-tail instability in circular machines has a growth time that is inversely proportional to the chromaticity, so that a chromaticity value of zero yields an infinite growth time, a desirable state of affairs. Moreover, for machines (such as the PSR) operating below the transition energy, a negative value of the chromaticity (the normal case) avoids the instability altogether. Small circular accelerators such as the Rapid Cycling Synchrotron at Argonne National Laboratory (ANL) and the proposed storage-ring buncher at the Soviet meson factory can have naturally positive chromaticities, as a result of nonlinear terms (usually neglected) arising from the smallness of the radius of curvature. The uncorrected positive chromaticity at the ANL Rapid Cycling Synchrotron has allowed the observation of the head-tail instability in that machine. The value of the chromaticity is readily modified using sextupole magnets to determine the need for such magnets. A. Dragt¹³ has developed a code that unambiguously determines the tune dependence on momentum to all orders in $\Delta p/p$. The code simultaneously integrates the equations of motion for a particle trajectory and the variational equations for neighboring trajectories, some 20 equations in all. Table VII summarizes the natural chromaticities for various possible tune values for the PSR.

The code can be modified readily to include nonlinear elements and will be used as a check on the results of simple tracking codes.

B. rf Stability

The significant beam loading of the rf cavities, particularly in the short-bunch mode, can give rise to unstable longitudinal motion known as the Robinson instability. A preliminary analysis¹⁴ showed that without any sort of feedback loop the rf system could be stabilized by a sufficient detuning of

TABLE VII
NATURAL CHROMATICITIES FOR VARIOUS POSSIBLE TUNE VALVES

<u>Tunes</u>	<u>Parallel-Faced Magnets</u>	<u>Normal-Entry Magnets</u>
Q_x, Q_y	ξ_x, ξ_y	ξ_x, ξ_y
2.25, 2.25	-0.412, -0.936	-0.477, -0.571
3.25, 2.25	-0.818, -1.296	-0.843, -1.114
3.25, 2.75	-0.855, -1.211	-0.880, -1.087
2.25, 2.75	-0.398, -0.851	-0.471, -0.582

the cavity resonant frequency. M. Donald¹⁵ formulated an analysis of the transient response of the rf system, including feedback. A computer code has been written to implement the solution to the system equations, which involves determining the complex eigenvalues of the system matrix, and then inverting the matrix of eigenvectors to diagonalize the system matrix. The code is available for studies of stability and will be used in the rf-system design process.

C. PSR Tracking Code

Most circular accelerator design codes are based on linear mechanics; that is, linear transformations in phase space, with some limited nonlinear elements included in an ad-hoc fashion. Space-charge forces are rarely included because of the difficulty involved. In high-intensity machines such as the PSR, however, space-charge forces can drive nonlinear resonances and are very much a part of the environment felt by a particle in the machine. We have attempted over the past several years to develop a tracking code that will include space-charge forces and nonlinear elements in a straightforward way that will not consume great quantities of computer time. This effort appears finally to have been successful, because it reproduces the results of previous simulations by Penner¹⁶ and Haber¹⁷ that dealt with transporting intense charged-particle beams in FODO channels. The code has been subjected to a series of checks against known analytic results and satisfies them all. The prospect for reasonable computation time for such a code arises principally from three features. The first, almost trivial, is the observation

that the PSR must operate, in the long-bunch mode where space-charge effects are most important, for a few thousand turns at most, so that tracking need be done for only this number of turns. Secondly, instead of directly integrating the equations of motion

$$x'' + K_x(s)x = \frac{F_x(s, x, y)}{\gamma^2 \beta^2 m_0 c^2}, \quad (1)$$

$$y'' + K_y(s)y = \frac{F_y(s, x, y)}{\gamma^2 \beta^2 m_0 c^2}, \quad (2)$$

where K_x and K_y are the lattice horizontal and vertical focusing functions, and F_x and F_y are the components of the nonlinear forces (space charge, sextupole magnet, octupole magnet, gradient error, etc.), these equations are integrated in terms of the solution to the homogeneous equation plus the particular integral. That is, we take our knowledge of the beta functions and phase advance of the unperturbed lattice and construct a Green's function for the inhomogeneous equation. Thus we write the solution of the Eq. (1) as

$$x(s) = a_1 x_1(s) + a_2 x_2(s) + \frac{1}{\gamma^2 \beta^2 m_0 c^2} \int_0^s [x_1(s') x_2(s) - x_2(s') x_1(s)] F_x[(s'), x(s'), y(s')] ds' \quad (3)$$

where $x_1(s) \equiv \beta_x^{1/2}(s) \cos \phi_x(s)$ and $x_2(s) \equiv \beta_x^{1/2}(s) \sin \phi_x(s)$ are the solutions of Eq. (1), with $F_x = 0$. The constants a_1 and a_2 are determined for a given particle by the initial conditions x_0 and x'_0 for the displacement and inclination of the particle trajectory. The simulation code tabulates x_1 and x_2 for each lattice period and computes for each particle the integral in Eq. (3) by trapezoidal integration. The apparent implicit character of Eq. (3) is circumvented by observing that knowledge of the force at $s' = s$ is not required, because the Green's function vanishes at that point.

This approach to solving the equations of motion should have the advantage that the sometimes complex focusing function (in general a piece-wise continuous function) need not be specified at all, so that it does not dictate the integration step within the focusing and bending elements. Thus the integration step is dictated only by the nonlinear or perturbation forces.

The third feature of the tracking code, which promises reasonable computing times, is the method of computing space-charge forces. A simulation employing Coulomb interaction forces between particles requires computing forces between $N(N-1)/2$ pairs of particles, where N is the number of particles being tracked. Recently it has been realized that an expansion of the space-charge potential in a series of nonorthogonal functions can be used to great advantage in the numerical computation of space-charge forces.¹⁸ This technique has been incorporated into the tracking code and provides a factor-of-two increase in speed over the Coulomb calculation, when 1000 particles are being tracked. The expansion-method computation time increases only linearly with N ; thus the time saving should be a factor of eight, when 2000 particles are tracked.

As of this writing, the dispersion from momentum deviations and the finite bunch length have not been incorporated into the code. Whether such features are feasible in the context of limited budget for computing has yet to be determined.

D. Space-Charge Limit

The standard space-charge-limit calculation, as first set down by Laslett¹⁹, assumes a uniform transverse particle density in a beam of elliptic cross section. The electric and magnetic fields of such a beam, along with the image fields from the surrounding vacuum chamber, are then included in the single particle equations of motion. For the x motion, neglecting image fields, the equation of motion (1) in the previous section is approximated by

$$x'' + \frac{Q_x^2}{R^2} x = \frac{eE_x}{\beta^2 \gamma^3 m_0 c^2} \quad , \quad (4)$$

where R is the average radius of the ring.

For the uniform beam the electric field E_x is linear in x and given by

$$E_x = \frac{\lambda x}{\pi \epsilon_0 a(a+b)} \quad , \quad (5)$$

where a is the beam semiaxis along the x direction, b is the beam semiaxis along the y direction, and λ is the linear charge density (C/m). One takes an average value of the right-hand side of Eq. (4) and rewrites Eq. (4) as

$$x'' + \left(\frac{Q_x^2}{R^2} - \frac{Q_{sc}^2}{R^2} \right) x = 0 \quad ,$$

where

$$\frac{Q_{sc}^2}{R^2} = \frac{e\lambda}{\beta^2 \gamma^3 \pi \epsilon_0} \frac{1}{a(a+b)} \quad . \quad (6)$$

Thus an individual particle has a tune

$$Q^2 = Q_x^2 - Q_{sc}^2 = Q_x^2 - 2Q_x \delta Q_x \quad ,$$

so that the tune shift is given by

$$\delta Q_x = \frac{e\lambda R^2}{2Q_x \beta^2 \gamma^3 \pi \epsilon_0} \frac{1}{a(a+b)} \quad . \quad (7)$$

A more detailed approach uses the formula for a shift in tune caused by a perturbation δK in the focusing function:

$$\delta Q_x = \frac{1}{4\pi} \beta(s) \delta K(s) ds \quad . \quad (8)$$

The quantity δK is identical to the right-hand side of Eq. (6), but without the brackets indicating the average.

In our calculations, both Eqs. (6) and (8) have been evaluated, with the beam sizes $a(s)$ and $b(s)$ being taken as the matched solutions to the Kapchinsky-Vladimirsky envelope equation. For nominal tunes of $Q_x = 3.25$ and $Q_y = 2.25$, emittances of $\pi\epsilon_x = 2\pi \times 10^{-5}$ radian-meters and $\pi\epsilon_y = 2.5\pi \times 10^{-5}$ radian-meters give tune shifts of -0.241 , in both horizontal and vertical planes, for a linear density appropriate to the long-bunch mode peak intensity, with 5×10^{13} protons. This tune shift is generally considered to be the allowed limit. The tune-shift formula (7) gives $\delta Q_x = -0.187$ and $\delta Q_y = -0.205$. Figure 42 shows the horizontal and vertical beam envelopes corresponding to the

beam envelopes corresponding to the emittances just cited.

One shortcoming of the calculations outlined above is that the beam-envelope calculations do not include the effects of momentum dispersion. Thus the horizontal beam size shown in Fig. 42 can be produced partly by momentum dispersion and partly by beam emittance. An envelope equation including momentum dispersion will be investigated, with an eye toward determining the required horizontal emittance with greater precision and performing calculations on the transverse beam envelope motion during injection.

Fig. 42.
Matched beam envelope sizes for one period with and without space charge in the envelope equation.

THE GYROCON rf-GENERATOR PROJECT

I. INTRODUCTION

Work on this project proceeded along two lines: an experimental effort to demonstrate the feasibility of the concept, and a theoretical effort to include in the computer models of the gyrocon some of the effects that previously have been neglected. These two areas are separately discussed below.

II. THE PROTOTYPE GYROCON

The major effort involved the completion of the output and deflection cavities, which were being built outside of LASL. Although the contractual delivery date for these large components was in September 1979, the final mechanical and vacuum acceptance tests were performed early in the reporting period. By the end of March, all of the outside-manufactured components had been delivered to LASL. A significant design change was made in the output cavity, to allow the output loops to be adjusted after the gyrocon is built. The output cavity, was sent to the main shops at LASL for modifications to accommodate this design change. A rough check of the output-cavity frequency was done at the main shops; the frequency was compatible with that of the deflection cavity.

In May, there were over 100 major components of the gyrocon that had to be assembled and leak checked. Also, there were 52 water passages, each requiring a connector; then the water passages had to be integrated into one water system. The test stand (Fig. 43) was ~95% complete, but over 100 connecting cables between the test stand and the gyrocon had to be made and installed. Thus, it was anticipated that several man-months of connecting, assembling and testing would be required before the gyrocon could produce rf power. A serious problem was that a dozen or so components had to be copper plated; this took more time than anticipated. Most of the parts for the coaxial-to-waveguide subassembly (Fig. 44) were copper plated. At the end of the reporting period, one of the halves of the output cavity had been copper plated and the other half still was in the plating shop.

A klystron was tested in the gyrocon modulator; this modulator operated well. The last problem on the test stand was an oscillation in the final amplifier stage caused by unevenness of the capacitor plates that ground

Fig. 43.
The gyrocon test stand.

Fig. 44.
The parts of the coaxial line to waveguide subassembly.

the tetrode's grids for rf signals. The bender coils were tested electrically; one was found to be shorted and was rebuilt.

Thus, at the end of the reporting period, it seemed likely that the experimental gyrocon could be assembled and initially tested in the next few months. The only known problem that might jeopardize this is the slow turn-around in copper plating, and discussions have been started with an outside vendor to expedite this process.

III. THEORETICAL WORK

The performance of spherical gyrocons as a function of input power and frequency, was calculated with the code GYROS. A summary of these results was accepted for publication.²⁰ The codes were improved in two ways: 1) The reactive beam loading of the output cavity was calculated by integrating the Poynting equation. The real part of the integral should be the power lost by the beam, and this agrees to within a few per cent to the change in kinetic energy. The reactive beam loading reduces the efficiency of the designed gyrocon by a few per cent, but it may be possible to adjust the output-cavity frequency to eliminate this effect. 2) A version of the design codes was prepared to allow SUPERFISH-generated fields to be used in the deflection calculations. This version should be useful for analyzing TE-deflection cavities. A few test runs were made that indicate that TE deflection could save from 80% to 50% of the drive power of a TM cavity. Much larger drive-power savings (almost 98%) could be achieved if beam loading were ignored. The beam loading is very high in the cases that were studied, and this greatly reduces the drive-power savings.

THE LASL-NBS cw MICROTRON

I. SUMMARY

The NBS-LASL racetrack microtron (RTM) is a joint research project of the National Bureau of Standards (NBS) and the Los Alamos Scientific Laboratory. The project has two goals: one is to determine the feasibility of the project and the second is to develop the necessary technology for building high-energy, high-current, continuous-beam, electron accelerators using beam recirculation and room-temperature rf accelerating structures. To achieve these goals, a demonstration accelerator will be designed, constructed, and tested. Parameters of the demonstration RTM are 5-MeV injection energy, 12-MeV energy gain per pass, 15 passes, 185-MeV final beam energy, and 550- μ A maximum current. One 450-kW cw klystron, operating at 2380 MHz, will supply rf power to both the injector electron linear accelerator (linac) and the RTM's main accelerating section. The disk and washer (DAW) standing-wave rf structure being developed at Los Alamos will be used. SUPERFISH calculations indicate that an effective shunt impedance (ZT^2) of about 100 M Ω /m can be obtained. Thus, 25-kW/m rf-power dissipation results in an energy gain of more than 1.5 MeV/m. Accelerators of this type should be attractive for many applications. At beam energies above 50 MeV, an RTM should be considerably cheaper to build and operate than a conventional pulsed rf linac of the same maximum energy and time-average beam power. In addition, the RTM provides superior beam quality and a continuous beam, essential for nuclear physics experiments that require time-coincidence measurements between emitted particles.

II. INTRODUCTION

The RTM offers a number of unique advantages as an electron accelerator for energies above 50 MeV. Of particular interest to the NBS-LASL project is that available high-power rf techniques offer the possibility of building a cw microtron. High-energy cw RTMs are expected to be of tremendous importance in nuclear physics.²¹ Now, two cw RTMs are in operation: MUSL-2, a 66-MeV, 6-pass machine (at the University of Illinois) that uses a superconducting accelerating section,²² and MAMI-1, a 14-MeV, 20-pass machine (at Mainz, Germany) that uses a room-temperature rf accelerating structure.²³ Our

project also is using room-temperature rf technology. With our RTM, we expect to achieve beam currents of several *hundred microamperes*, limited by "beam blowup."^{24, 25, 26} If the expected current is obtained, the power conversion efficiency (from the ac power line to the beam) can be 10% or higher, which is competitive with a modern (pulsed) linac. Other advantages of the RTM, compared to a linac, are smaller beam emittance and energy spread, much improved energy stability, and reduced construction and operating costs. The only applications for which the RTM is inferior to the linac are those requiring very high pulsed currents, such as neutron measurements in which time-of-flight techniques are used.

The impetus for the present NSF-LASL project is the perceived need for a 1- to 2-GeV, cw high-current electron accelerator for nuclear physics research.²¹ The most economical way to build such a machine would be to use a recirculating scheme, either an RTM or, especially at the highest energies, a double-sided microtron.²⁷ A recent study²⁸ has shown that a 2-GeV double-sided microtron could be built for about one-half the cost of the most promising alternative, a conventional pulsed rf linac and a pulse-stretcher storage ring. In addition, the microtron approach promises to provide better beam quality and stability, smaller energy spread, variable energy over a wider range, more total beam current (allowing several simultaneous users of the machine), and reduced operating cost. Our project's goals are to determine the beam-blowup-imposed current limit of such a machine by a combination of measurements and calculations, and to develop the required technology, especially a suitable rf accelerating structure. A major part of our project is to design, build, and operate a cw microtron of reasonable size to demonstrate viable solutions to the technological problems and make the necessary measurements of beam-blowup properties. This accelerator, described in this report, will be a powerful research tool in its own right for nuclear physics and other applications.

III. MICROTRON DESIGN

In a racetrack microtron,²⁹ the beam is returned to the accelerating section by uniform-field end magnets, as shown in Fig. 45. On successive passes, the beam must pass through the accelerating section near the same

Fig. 45.

Layout drawing of the Microtron. Achromatic beam transport from the injection linac to the RTM is performed with the dipole magnets D1-D6 and quadrupoles Q1-Q6. Compensation for the effect of D-6 on recirculating orbits is accomplished in the chicane system consisting of D-5, D-7, and Q-7. Orbit reversal after the first pass through the accelerating section is performed by D-8, D-9, Q-8, and Q-9, as shown in the inset drawing. The array of magnets D-10 and D-11 compensate the recirculating orbits for the displacements produced in D-8 and D-9. A quadrupole doublet (not shown) at the center of each return path provides adjustable focusing. Extraction from the RTM can be obtained after any number of circulations by moving D-14 to the appropriate orbit and adjusting the field strengths of D-14 and D-15.

"resonant" phase, ϕ , of the rf field. This resonance condition can be expressed by the relation ²³

$$(2\pi/c) \Delta V \cos \phi_r = \nu \lambda B, \quad (9)$$

where $\Delta V \cos \phi_r$ is the resonant energy gain per pass, λ is the rf free-space wavelength (12.596 cm), B is the end-magnet field strength, and ν the harmonic number. We have chosen to use $\nu = 2$, which makes the spacing between successive return paths $d = \nu \lambda / \pi = 8.019$ cm (when $\beta = \text{electron velocity}/c = 1$). This spacing allows installation of independent steering and focusing elements and beam-diagnostic instrumentation on each return path. The major disadvantage of $\nu = 2$, compared to $\nu = 1$, is reduced longitudinal phase acceptance. Because of this, we demand very good energy and phase stability and a small longitudinal phase emittance of the injected beam.

The frequency choice in an RTM is a compromise between many factors. Lower frequency (larger λ) eases construction and operating tolerances. Higher frequency increases the shunt impedance of the accelerating structure, thus tending to reduce the electrical power demand. In considering these factors, we have chosen an S-band frequency, which also allows multiple simultaneous high-current beams, (obtained by subharmonic rf-beam splitting), with the resulting 2, 3, or 4 beams still appearing to be essentially continuous in most experiments. The specific choice of 2380 MHz is dictated by the commercial availability of a high-power (450-kW) cw klystron with reasonable (55%) electrical efficiency. One klystron provides the rf power for the injector linac (5 MeV), the main accelerating section (12-MeV per pass), and the power given to the electron beam (100 kW).

Injection into an RTM can be accomplished either by sending the incident beam into one of the end magnets, or directly into the main accelerating section. The former method, which is used in all stages of the MAMI project, requires an injection energy of about one-tenth of the final energy of the RTM.²³ This would require either a very expensive injector linac (~ 20 MeV in our case), or an injection-stage microtron (like MAMI-1), adding both cost and complexity to the system. Injecting the beam into the accelerating section directly, as in MUSL-2,²² adds the complexity of an injection "chicane" where the injected orbit is merged with the recirculating orbits, and a "bypass" on at least one circulation path, to allow the recirculation path to pass clear of the accelerating structure. In the NBS-LASL RTM we will inject the beam directly into the accelerating section and use a reverse return after the first pass through the section.³⁰ Thus the second and subsequent passes will be in the opposite direction from the first pass, as shown in Fig. 46. This is feasible because our accelerating structure is of the standing-wave type. The reverse return feature simplifies the chicane design because the beam has gained energy from two passes before first encountering the chicane, and eliminates the need for bypass return orbits.

The reverse-return design requires the use of auxiliary magnets to provide orbit closure on subsequent passes. The closed-orbit correctors are located on the return paths, as indicated in Fig. 45, where they do not increase the overall length of the accelerator, and can be combined in function with steering magnets that are needed in any event.

Steel Weight: 26,600 Kg (approx.)
Copper Weight: 275 Kg

Fig. 46.
End-magnet design. For details, see Ref. 31.

Beam quality and ease of operation in an RTM are critically dependent on the properties of the end magnets.²² Good field uniformity is essential to maintain the resonance condition, Eq. (9), yet is difficult to achieve in a conventional C-magnet, having the very large ratio of gap-depth to height required in an end magnet. A novel magnet design,³¹ shown in Fig. 46, has been developed that has a calculated field uniformity of better than two parts in 10^4 , not only at the nominal field strength of 1.0 Tesla, but also over a wide range up to about 1.3 Tesla. The design incorporates a reverse-field active clamp needed to eliminate undesirable vertical defocusing in the fringing field.²³ In spite of expected excellent field uniformity, we plan to include correcting coils of the printed circuit-board type³² to compensate for machining errors and other imperfections that may be present in the actual magnets.

The injection system uses a 100-keV modulating anode-type electron gun with 5-mA current capability. A focusing lens system with two physical apertures limits the beam's transverse emittance to $\epsilon_T = 4\pi$ mm·mrad, at 100 keV ($\epsilon_N = 2.6\pi$ mm·mrad, where $\epsilon_N = \beta\gamma\epsilon_T$). The apertures are followed by a two-cavity chopper system that limits the longitudinal beam emittance ϵ_L , to less than 3π -keV degrees, with negligible dilution of the transverse phase space. Following the second chopper cavity, the beam is bunched in phase by a single-cavity klystron buncher before entering the capture section of the injection linac. The chopper-buncher system is shown schematically in Fig. 47

Fig. 47.

Schematic drawing of the chopper buncher system. G is the 10-keV electron gun. Magnetic lenses L₁ - L₅ provide focusing. Apertures A₁ and A₂ define the transverse emittance of the beam. Aperture A₃ and the rf chopper cavities C₁ and C₂ limit the beam phase spread of 60°. B is the buncher cavity. CS is the capture section.

and described in detail in Ref. 33. The injection linac consists of two 2-m accelerating sections of the same design as the main section of RTM, except that the capture section has a tapered- β design (from ~ 0.55 at the entrance to ~ 0.98 at the exit) and a lower average-accelerating gradient than the other sections, ~ 1.0 MV/m, compared to 1.5 MV/m.

Our design specifications for the beam out of the injection linac at 5 MeV include a normalized transverse emittance of $(\epsilon_N = 5\pi \text{ mm}\cdot\text{mrad})$ ($\epsilon_T = 0.47\pi \text{ mm}\cdot\text{mrad}$) and a longitudinal emittance of 20π -keV degrees; that is, a full-width energy

spread of 40 keV (0.8%) for a 2° phase-bunch length. These specifications allow dilution of the normalized transverse and longitudinal emittances in the capture section by factors of about two and seven, respectively. Our preliminary calculations indicate that these specifications are readily achievable. The Stanford superconducting recyclotron has in fact obtained considerably smaller emittances, albeit at a somewhat lower current.³⁴

Extraction of the beam from the RTM can be accomplished after any desired number of passes by a movable kicker magnet on the return paths. The kicker magnet deflects the beam onto a common extraction line from any return path. In this way, nominal output-beam energies of 17, 29, 41, ---- 173, or 185 MeV are obtained easily and rapidly. Intermediate energies can be obtained by changing ΔV and B [in Eq. (9)] proportionately, and the injection energy to match. A maximum energy up to 25% above the nominal 185 MeV could be obtained at low-beam currents with the available rf power, if the accelerating structure proves capable of an rf heating load 50% above the 25-kW/m design value.

IV. ACCELERATING STRUCTURE

An RTM's performance improves, and its cost tends to decrease, as the accelerating gradient is increased. Practical limitations are imposed by the

available rf power and the ability to remove heat from the structure. We have begun a testing program on the DAW standing-wave structure,³⁵ which appears to be ideal for the RTM application. In addition to a high-shunt impedance, it has a high cell-to-cell coupling factor that eases construction tolerances and reduces sensitivity to beam-loading effects. The high cell-to-cell coupling should also make external loading of blowup modes feasible.

Figure 48 shows the DAW structure with the washers supported in pairs from T-shaped supports. (There are four supports, equally spaced azimuthally, for each pair of washers.) The radial portion of the supports lies along an equipotential of the accelerating-mode electric field, and the longitudinal portion is in a region of low electric field. Consequently, this type of support minimizes the perturbation of the accelerating mode. However, these supports significantly perturb the coupling mode. Left uncompensated, these perturbations would open a stop band in the mode spectrum and create a bilevel distribution in the excitation of the accelerating cells. By experimenting with the geometry of a low-power test section, a technique has been developed to counteract these perturbations. The geometry of the DAW (without washer supports) was optimized with the aid of the computer program SUPERFISH. Then the measured perturbations caused by the supports were eliminated by a cut-and-fit procedure in which the disks that hold the supports are made thinner, and the radii of the cavities' outer wall are made larger. The corrected low-power

Fig. 48.
Disk and washer rf structure.

test section exhibits a Q value of 75% of the theoretical value predicted by SUPERFISH. These measurements were made with the T supports brazed to the washers and disks, but with the rest of the structure pressed together without brazing. In the completed structure, we expect to obtain a Q value of 85% of theory, which will provide an effective shunt impedance (ZT^2) of about 100 M/m in the 2380-MHz, $\beta = 1$ structure.

In addition to supporting the washers, the supports provide channels for carrying coolant to and from the washers. Heat-transfer calculations indicate that the practical limit for cooling the structure is in excess of 25 kW/m. This power level with the expected shunt impedance will result in an accelerating gradient >1.5 MV/m. Thus the main accelerating section will be about 8 m long to provide the 12-MeV energy gain required by the design parameters. The injector linac will consist of about 4 m of DAW structure.

V. CONCLUSIONS

Initial funding for the NBS-LASL microtron was received in September 1979. The conceptual design of the RTM was completed in June 1980.³³ In addition to the rf structure development and end-magnet design effort described above, our efforts to date have concentrated on the procurement and construction of long-lead items, such as klystrons, power supplies, the control-system computer, and electron gun. Our schedule calls for first operation of the injector linac in August 1982, and completion of construction of the entire accelerator in June 1983. The total cost of the project, including a year's operation of the RTM, to complete detailed performance tests, is estimated to be about \$7 million, including inflation. It is important to note that this cost includes a large research and development effort. The actual cost of building the RTM is estimated to be about \$2.5 million (in present dollars), which would make it an extremely inexpensive accelerator if the anticipated performance is indeed achieved.

THE FREE-ELECTRON-LASER PROGRAM

I. INTRODUCTION

The objective of the Los Alamos free-electron-laser (FEL) program is to develop high-efficiency, high-power free-electron lasers operating at optical wavelengths from the near infrared to the near ultraviolet. To achieve such short wavelengths, it is necessary to use high electron energy (30 MeV and more) that is best produced by rf linacs. Such machines are now highly developed at Los Alamos to a point where they are both reliable and efficient. Thus, the Los Alamos FEL program is centered on a means of producing high-power, high-efficiency FELs, using rf accelerator technology.

Theoretical calculations predict that by properly tapering the period of the wiggler along its length, the efficiency for extracting laser energy from the electron beam can be greatly enhanced over results obtained with uniform wigglers in experiments at Stanford. Studies carried out at Los Alamos indicate, however, that even by using these theoretical concepts (which remain to be tested experimentally), it will be difficult to exceed 10% conversion of the electron-beam energy to laser energy in high-average-power FELs. Therefore, to achieve satisfactory overall efficiency, it is necessary to recover some of the remaining electron energy. Concepts for accomplishing this have been developed at Los Alamos. In the most straightforward and promising approach, the electrons are returned to the accelerator, where they are decelerated to recover their energy. In this way it should be possible to achieve more than 25% overall efficiency, using a FEL that extracts only 10% of the incident electron-beam energy as laser energy.

Several issues have been identified that deserve immediate attention. The most fundamental issue is experimental confirmation of the high laser-extraction efficiency, which has been predicted only theoretically. The second issue is experimental demonstration of the energy-recovery system, and investigation into the stability of such a system at high electron-beam currents. To address these questions, a three-stage program has been undertaken.

In Stage I, an existing small electron linac is being modified to operate at 20 MeV, and a high-peak-power CO₂ laser and high-efficiency wiggler are being constructed. The 10.6- μ m CO₂ laser radiation will be amplified by the electron beam and wiggler, and the energy extracted from the electron beam will be measured to demonstrate high (about 3%) extraction efficiency. These experiments will be completed in mid-FY 81. In Stage II, the FEL amplifier will be converted to an oscillator. Because lasers operating from rf linacs are characterized by low gain, they must operate as oscillators to be effective. Thus, this step is necessary to complete the demonstration of high wiggler efficiency. In addition, it will be possible at this stage to examine the laser-beam quality from a FEL. These experiments will be completed in mid-FY 82. In Stage III, the energy of the electrons emerging from the wiggler will be recovered to increase the overall efficiency, and the stability of the recovery system will be investigated. These experiments, to be completed in FY 83, will provide a complete demonstration of a small-scale FEL operating with high overall efficiency.

During the period covered by this report, the experimental efforts have been dedicated to the construction of the experiment for demonstration of high extraction efficiency. This construction effort is expected to continue through the second half of FY 80 and, roughly, the first quarter of FY 81.

The critical path for the experimental construction is the modification of the linac, specifically the fabrication and tuning of the new cavity structure needed for 20-MeV acceleration. This is a lengthy process because of the large number of sequential brazing and tuning operations. However, the cavity structure is a standard Los Alamos design. The modifications to the linac injector have been fabricated and tested and await the completion of other accelerator commitments before installation.

The wiggler has been designed and is in fabrication. The permanent magnets are on order. A major problem, that of aligning the CO₂ laser and electron beams with each other and the wiggler axis, has been given much attention, and a sophisticated system of removable apertures and fluorescent screens has been developed to accomplish the alignment. This should greatly

reduce the difficulties and uncertainties normally encountered in experiments of this type.

The CO₂ laser oscillator is now being fabricated according to a design developed in the Antares laser fusion program, and the CO₂ laser amplifier (a commercial unit) is to be delivered in July.

Diagnostics represent an area of concern for the operation of the experiment. The principal diagnostic tool is an electron spectrometer, which will directly measure the energy extracted from the electrons. In addition, the resolution of this instrument will be sufficient to determine in detail the distribution of electron energy emerging from the wiggler. This diagnostic is straightforward and will demonstrate unambiguously the principal objective of the experiment: high extraction efficiency by trapping and adiabatic deceleration of the electrons in the wiggler. Optical diagnostics to complement these measurements, through observation of the energy gained by the laser beam, are more difficult to carry out. This is because the peak gain is expected to be small (~1.6%) and appears only during the electron microbunches, which last about 20 ps and are spaced about 770 ps apart. Because of interest in such developments, several techniques have been conceived, and will be developed for use in the experiment.

The theoretical effort has emphasized low-energy, high-intensity electron beams, including plasma effects and off-axis, multidimensional waves. Although the results shed some light on FEL physics in the high-energy, low-intensity regime characteristic of the Los Alamos experiments, they are motivated largely by the experiments being done at the Naval Research Laboratory. The Los Alamos intense-particle-beam codes provide a unique capability in this area. The results obtained during the present reporting period make use of the multidimensional code CCUBE, together with appropriate analytical work. The results document the importance of oblique waves, some of which are absolutely unstable and could severely impact FEL performance.

II. EXPERIMENT

The objective of the FEL amplifier experiment at $10.6\ \mu\text{m}$ is to demonstrate the operation of a high-efficiency tapered wiggler. Gain vs input laser intensity will be measured from weak-signal to saturation conditions, and the number of electrons trapped and decelerated by the wiggler and laser fields also will be measured. This section describes the experimental approach to these measurements.

The experiment is illustrated schematically in Fig. 49. A single CO_2 laser pulse is focused through the magnetic wiggler (composed of SmCo_5 permanent-magnet units) concurrent with the 5-ns electron-beam pulse. To enable sensitive detection of only the stimulated emission from the electrons, the input laser pulse is plane polarized at an angle to the linear wiggler field and crossed polarizers (stacked germanium plates with extinction ratio of 10^4 to 10^6) are placed in the collimated exit beam. Measurement of the energy gained and the pulsewidth provides the output intensity. At the same time, the electrons emerging from the wiggler are dispersed by a magnetic field so that the distribution of energy can be determined. In this way, the energy extracted from the electron beam can be measured and compared with the energy gained by the laser field.

A. Linac Modification

The existing accelerator is being modified to satisfy the requirements of the amplifier experiment. A comparison of the original accelerator parameters with the new ones is given in Table VIII. The injector pulser has been completely rebuilt to provide a 6-ns, 700-V pulse, rather than the previous 1- μs pulse.

The new accelerator-cavity structure, capable of 20-MeV energy and 20-A peak micropulse current, is being constructed. This structure consists of five sections that are bolted together to form a single tank.

The rf power for this new accelerator will be provided by the existing modulator and klystron system. Only minor modifications to the rf drive are planned. Modifications of the PIN modulator controller, for more versatile operation, have been designed.

Fig. 49.

Schematic diagrams of the FEL amplifier experiment. The energy extracted from the electrons is determined by dispersing the electrons emerging from the wiggler in a magnetic field to measure their energy spectrum. To measure the amplified laser signal, the CO₂-laser beam is suppressed by placing a crossed polarizer in front of the detector. The amplified signal from the FEL is polarized at 22.5° to the polarizer and passes through with some attenuation.

TABLE VIII
ACCELERATOR SPECIFICATIONS

	<u>Original Accelerator</u>	<u>New Accelerator</u>
o Energy (MeV)	3-6	20
o Frequency (GHz)	1.3	1.3
o Peak micropulse current (A)	20	20
o Operation	Steady State	Stored Energy
o Energy spread that is due to single-bunch beam loading (%)	± 1	± 1
o Energy droop per micropulse (%)	~ 0	0.1
o Emittance at 20A (mr-mm)	$\sim 10 \pi$	$\sim 2 \pi$
o Length (m)	0.5	2.5
o Pulse length (ns)	300-1000	5

B. Beam Line

The electron-beam transport line must provide for colinear-electron and laser-beam injection; focusing of the electron beam completely within the envelope of the laser beam, all the way through the wiggler; and a means of measuring the energy removed from the electron beam in the wiggler. A slit system also is required to "clean up" low-energy electrons that would otherwise interfere with the measurements. The beam line is shown in Fig. 50. The three identical magnets in the 60° bending system are doubly focusing; that is, they focus equally in both the vertical and horizontal directions, making it possible to rotate the wiggler and the quadrupole triplets at an arbitrary angle around the beam axis, as long as the quadrupole triplets are rotated with the wiggler.

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

Fig. 50.
 Diagram of the doubly achromatic, 60° bending electron-transport system.

The wiggler, which is described in another section, also affects the focusing of the beam. If the wiggler is oriented so that the magnets are horizontal, the focusing effect is vertical. This effect is beneficial, because the vertical size of the electron beam must remain small with respect to the gap of the wiggler magnet, so that the entire beam sees the same-strength wiggler field. This natural focusing produces an electron beam with nearly the optimum diameter for minimizing the effects of transverse electron momentum and off-axis increase of the magnetic field. The spectrometer will be able to measure a 20% spread in the energy spectrum with a resolution of about 0.25%.

At the center of the three-magnet 60° bend, the beam is dispersed; an adjustable beam scraper located at this point will be used to remove the low-energy electrons from the beam, so that a beam with an energy spread of $\pm 1\%$ or less, as desired, can be injected into the wiggler.

This beam-line design also preserves the electron-beam emittance in the presence of the $\pm 1\%$ energy spread. For the present purposes, an "acceptable" emittance is defined as one that gives an equivalent energy spread, caused by transverse wiggler effects, that is small compared with the actual energy spread of the electron beam. For an actual energy spread of $\pm 1\%$, under the conditions of the present experiment, the emittance should be small compared to 8π mm-mrad.

The available laboratory space will be supplemented by a concrete-block shielding enclosure outside the laboratory building, as shown in Fig. 51.

Fig. 51.
Plan view of the laboratory layout.

C. Wiggler

The wiggler should be designed to have an overall efficiency of several percent to demonstrate significant improvements over the Stanford wiggler; but should be designed as simply and conservatively as possible, with much flexibility, to allow for unexpected surprises and possible upgrades. Most important, the wiggler should unequivocally demonstrate the capture and deceleration of particles, as predicted by theory.

Within these general guidelines, there is a great deal of room to maneuver, wherein quite different wigglers can be designed, following different design philosophies.

In descending order of importance, the variables that affect the wiggler efficiency are listed below.

CO₂ Laser Parameters

1. Single laser line vs all four strong CO₂ lines
2. Total laser power
3. Strehl ratio of laser
4. Angle of laser polarization relative to wiggler
5. Rayleigh length

Wiggler Parameters

6. Magnet aperture
7. Magnet strength (material)
8. Magnet shape
9. Magnet length
10. Minimum magnet spacing

1. Laser Parameters. We plan to use an internal grating to operate on the P(20) line alone, to avoid superposition effects that would cause different electron bunches to see different fields.

A laser similar to the one to be used has been operated at the Gigawatt Test Facility. Their single-line output power is usually about 2 GW, but an output of up to 5 GW has been achieved on occasion when an optimum alignment was realized (hard to obtain). To assess the saturation properties of the wiggler (that is, how it operates when the laser power is above the design value), we have assumed that the maximum laser power is 2 GW and have designed the wiggler for a laser power of half that value, 1 GW. In addition, we have incorporated flexibility, described below, to allow a change in the design if the real maximum power is significantly higher or lower than 2 GW.

A laser is not a perfect light source. This shows up clearly when the intensity distribution at the focal plane is examined. The peak power density on axis is less than the theoretical value for a Gaussian beam by a factor called the Strehl ratio. The Strehl ratio measured on the prototype system mentioned above was 1/4, which we feel is due to optical distortions in the amplifier optics, and could be improved to a ratio of 0.5 to 0.8. To be conservative, we have designed the wiggler on the assumption of a Strehl ratio of 1/2. This has a large effect on the design of the wiggler and reduces its efficiency by about 30%, compared to the case of a Strehl ratio of 1.0.

The laser light is polarized and is conventionally oriented at 45° with respect to the plane of the wiggler, which will reduce the optical power delivered from the laser to the wiggler by 50% and the wiggler efficiency by about 30%. The choice of an angle closer to zero will give a higher wiggler efficiency, but perhaps a lower sensitivity for the gain experiment. For the initial experiment, we will use an angle of 22.5° . The light intensity at the wiggler will be about 90% of the total input, whereas the sensitivity of the gain experiment will suffer by only a factor of four, in comparison with the case of the 45° angle.

The efficiency of the wiggler peaks when the Rayleigh distance, Z_0 , is about 0.3 times the length of the wiggler, because the optical beam size is small at the wiggler entrance and exit, allowing the magnet aperture to be minimized. Other considerations concerning windows, mirrors, and bending magnets caused us to choose $Z_0 = 0.4$ m, with an efficiency loss of about 10%.

2. Wiggler Parameters. We chose a constant aperture that cuts the laser light off at the expected $(1/e)^4 = 0.02$ field points: a conservative decision based on Strehl ratio, wiggler efficiency, and beam-alignment-diagnostics considerations. Provisions have been made in the wiggler design to allow a reduction in the aperture at a later date.

For reasons of cost, availability, uniformity, and handling-stress tolerance, we chose conventional-grade, SmCo_5 , permanent-magnet material, even though the efficiency is about 12% less.

A square magnet cross section was chosen, in spite of some loss in field strength and efficiency, because we wanted every magnet to be identical, thus allowing a simpler measurement and selection process. We expect this process to be lengthy and tedious at best.

Calculations show that a magnet 35 mm long generates a field on axis that is only 3% less than the field of an infinite magnet, while keeping the effects of individual magnet variations reasonable.

If the magnets are all of the same size, but their separation is progressively reduced along the length of the wiggler, there must be a considerable gap between the magnets at the front end of the wiggler that then reduces to a much smaller gap at the back end. For maximum efficiency, the minimum gap should be as small as is consistent with dimensional tolerances. We have made the minimum gap larger than this (that is, about 1.0 mm) and have sacrificed about 15% in efficiency in doing so. This was done to allow for possible improvements in efficiency that might occur at some time because of an improved Strehl ratio, a higher laser intensity, or a reduced magnet aperture. If any of these occur, the magnet support structure can be modified rapidly to accommodate the required closer magnet spacing, giving much-improved efficiency. Special transition magnet sections are included at the wiggler ends to "smooth" the entrance and exit of the electron beam.

When all the above design decisions have been made, the wiggler gives an electron-beam energy-transfer efficiency of 2.8% and a laser gain of 1.6%.

The mechanical design for the wiggler-magnet mounting structure is shown in Fig. 52. Magnet material has been ordered and test facilities designed.

WIGGLER DESIGN

Fig. 52.

Design of magnet-mounting technique showing toothed locating bars used to hold magnets, slotted section over diagnostic port to accept spline, and single magnet in place. Each magnet has perpendicular grooves cut into each end.

We measured the outgassing performance of the SmCo_5 material and found it equivalent to stainless steel. Conceptual design work has been completed for trim coils, magnetic-field shielding, and alignment and support systems.

D. CO_2 Laser Oscillator and Amplifier

The single-mode, single-line, tunable CO_2 laser oscillator uses a design borrowed from the Los Alamos Antares laser fusion research, with a nominal 0.25-J output in a 1-ns pulse at a 1/5-Hz repetition rate. Figure 53 illustrates typical pulseforms obtained from the prototype laser built for the Antares program. The switched-out pulse is then expanded and directed through a Lumonics 600-A amplifier (0.04-cm weak-signal gain over a 9-cm diam) that can be pulsed at a nominal 1/10-Hz rate. The resultant energy in a 1-ns pulse is several joules or more, if a triple-pass scheme is used. Table IX summarizes the laser parameters.

The oscillator mainframe now is being fabricated and the pulse-switching optics have been ordered. Because a nearly identical laser system is presently operating in the laser fusion program, no significant problems are anticipated. The Lumonics final power amplifier has been ordered.

E. Diagnostics

The electron energy spectrum will provide details of the energy extracted from the electrons in the interaction between the laser beam and the wiggler field. The spectrum will be determined in a spectrometer consisting of an analyzing magnet, converter screen, and imaging system.

Initially, a sensitive vidicon will be used to view the converter screen. With this arrangement, the spectrum of the entire 5-ns electron-beam pulse will be obtained. If necessary or desirable, a gateable image intensifier will be added. This intensifier would be gated by a signal from the laser Pockels cell and with proper gate delay. In this way, the energy spectrum of those electrons arriving during the 1-ns laser pulse would be obtained.

Measurement of the amplification of the CO_2 laser beam is more difficult. A spherical copper mirror is used to collimate the output through germanium stacked-plate analyzers, which are crossed with respect to the input CO_2 laser polarization. A portion of this is reflected to a fast detector

Fig. 53.
CO₂ laser pulseforms: a) output of gain-switched oscillator, 65-ns FWHM;
b) switched and amplified output, 1.7-ns FWHM.

TABLE IX
CO₂ LASER SYSTEM OUTPUT

Single-line (tunable, single-longitudinal mode)
Wavelength: 10.6 microns (P-20)
Pulsewidth: 1 to 70 ns (FWHM)
Energy: 2 J (1-ns pulse)
 15 J (70-ns pulse)
Focusability: Strehl ratio of 0.5
Repetition Rate: 1/5 to 1/10 Hz

and oscilloscope for determining the laser intensities corresponding to the observed energy gained from the electron bunches. The second polarizer essentially quenches any of the remaining CO₂ pulse and transmits only the energy gained from the electrons. The extinction ratio of the second polarizer can be set at 10⁴ with one analyzer, or 10⁵ to 10⁶ with two analyzers.

We may use a hot CO₂ cell ($T = 400$ to 600°C) to further discriminate between the short (~ 20 ps) gain pulses and long (~ 1 ns) CO₂ laser pulses. Because of the widely different frequency content of the short pulses, they are transmitted essentially unattenuated, whereas the long CO₂ pulse is absorbed. Using a 2- to 3-m cell, we expect to obtain a discrimination ratio of 10³:1. Measurements of extinction ratios of this magnitude have been demonstrated by Feldman,^{3,6} et al. Figure 54 shows the transmission of a 1.6-ns CO₂ laser pulse (P-20) through a 1.2-m cell, as the width of the absorption line is varied by varying the pressure. If necessary, this technique can be used in tandem with the polarizer technique.

All of the signals from the above diagnostics will be digitized using a Tektronix 7912 transient digitizer and will be fed to an on-line minicomputer for processing. The immediate printout will be essential for real-time adjustments in the accelerator or laser output, alignment, and synchronization to maximize the gain.

Fig. 54.

Transmission of very low-intensity (nonsaturating), 1.6-ns, 10.6- μ m, P18 pulses through ~ 1 m of pure CO_2 at 400°C and various pressures. The ratio of the bandwidth of the pulse (calculated for a Gaussian pulse; the experimental pulse shape was not Gaussian) to that of the CO_2 absorber varies from 1.54 at 50 torr to 0.128 at 600 torr. The cw or long-pulse (calculated) transmission of the cell is essentially constant at ~ 0.12 (rising to 0.15 at 50 torr) and much smaller than the observed transmission (by a factor of ~ 2.5) at the smallest pressure.

III. THEORY

Computer simulations of the FEL have been done using the two-and-one-half dimensional, fully electromagnetic, relativistic, particle-in-cell, plasma-simulation code CCUBE.³⁷ Waves propagating obliquely with respect to the electron beam are always unstable, with appreciable growth rates; therefore, mode competition is an important consideration in the design of FELs. Furthermore, electromagnetic waves with group velocities opposite to the direction of electron beam propagation can be absolutely unstable, and can completely disrupt the electron beam and laser oscillation. However, the absolute instability can be avoided by taking careful precautions in the design of FELs.

A. Computer Simulation Model

The CCUBE simulation code uses an algorithm based on Galerkin's method³⁸ to solve dynamically the trajectories of tens of thousands of particles and their self-consistent electromagnetic fields on a spatial grid, including the effects of any given external electromagnetic fields, in the dynamics of the particles. The code has the following desirable characteristics:

1. The equation of continuity for the interpolated charge and currents is identically satisfied.
2. Total energy is conserved to a high degree (less than 1% error at $1200 \omega_{pe}^{-1}$).
3. The numerical Cerenkov instability is eliminated.
4. The code is applicable in any orthogonal geometries.
5. It supports periodic, absorptive, and reflective boundary conditions for particles and electromagnetic fields.

The code also is capable of injecting particles into the system and launching electromagnetic waves of particular frequency and angle of propagation.

Furthermore, mixture of boundary conditions is often used to facilitate the simulations of certain problems.

In the simulations of FELs, a relativistic electron beam with a specified energy is injected into the system. Immobile background ions are used to maintain the electrical neutrality of the electron beam. The electron beam is subjected to an external force, because of the applied static periodic magnetic field of the wiggler. When the electrons exit from the other end, they are automatically annihilated. Special precautions are taken when new electrons are injected, to avoid any imbalance in the total electrical charge of the system arising from the electrons being slowed down in the process of emitting electromagnetic radiation. Extensive diagnostics are built into the code; important information concerning the dynamic behavior of the electron beam and the electromagnetic fields is constantly monitored during the course of a simulation. Examples of various diagnostics will be presented in the next section, when we discuss the results of the simulations. The simulations were done in rectangular geometry, to facilitate the comparison between the simulations and the theory. However, note that the code is capable of initializing a wiggler field in any geometry, because of any specified current distribution.

B. Results

1. Two-Dimensional Dispersion Relation of FELs. In the beam frame, the physical process of FELs is equivalent to that of stimulated scattering of electromagnetic waves in a plasma, for which the dispersion relation of the scattering process is known. By applying a Lorentz transformation, the two-dimensional dispersion relation of FELs in the laboratory frame is derived in rectangular geometry. This relation clearly indicates the mode-coupling characteristics of the device, showing the coupling of the electromagnetic and electrostatic dispersion relations, through a term proportional to the second power of the static periodic magnetic-field strength.

One can rewrite the dispersion relation as a sixth-order polynomial in ω , which readily can be solved numerically in a computer. We present, in

Fig. 55, an illustrative contour plot of the temporal growth rates in the x and z wave numbers, k_x and k_z . The contours of the growth rate are symmetric with respect to k_z axis. Note that the scales of the two axes are different and the contours are centered around a rather flat and skinny ellipse, where the crossings of the beam modes and the electromagnetic modes occur. Waves at all angles are unstable and the frequency range is very broad. Furthermore, coupling of electromagnetic wave and electrostatic wave with opposite group velocities leads to absolute instability.^{39,40} Therefore, the part of the ellipse with negative k_z will be absolutely unstable. In the following, we will present results from simulations on the absolute instability and its effects on the operation of FELs.

Fig. 55.
Contours of growth rates of the FEL in two dimensions center around the resonant ellipse.

2. Absolute Instability of FELs.

a. One-Dimensional Case. A simple illustration of the absolute instability can be made in the one-dimensional geometry where all physical quantities vary in only one spatial variable, z . By setting $k_x = 0$, we can obtain the one-dimensional dispersion relation and solve it numerically to yield the temporal growth rate as a function of the wavenumber, k_z , as shown in Fig. 56. The low-frequency and the high-frequency electromagnetic waves are unstable, and their growth rates are quite comparable. The low-frequency region of the instabilities represents the coupling of beam modes and electromagnetic waves of opposite group velocities, which can result in absolute instability. The one-dimensional, high-frequency instability, which is a convective instability, has been studied in detail.^{4 1-4 3}

Fig. 56.

Growth rates of the FEL in one dimension indicate that forward and backward instabilities are comparable.

To determine the nature of the instability (that is, absolute or convective), one can make use of the resonant approximation and expansions to search for conditions where the roots of the coupled dispersion relation coalesce to a saddle point indicative of absolute instability.

To verify the existence and to examine the effects of the absolute instability in FELs, we set up CCUBE to run a simulation in which only one-dimensional physical phenomena were retained. The electron beam had an initial energy spread of $\Delta\gamma/\gamma = 0.05\%$. There were no electromagnetic waves launched, and unstable waves were allowed to grow from noise. The high-frequency electromagnetic wave was observed to be unstable convectively and the most unstable mode was being spatially amplified as the electron beam traversed the wiggler field, as shown in Fig. 57.

Fig. 57.

Spatial growth of the high-frequency electromagnetic field as obtained from computer simulation.

The phase space of the electron beam at a particular time is shown in Fig. 58. The process of electron trapping by the pondermotive potential occurred when the electron beam was about to exit from the system. This was particularly designed in the simulation so that the absolute instability of the low-frequency waves would not be obscured by the nonlinear state of the high-frequency waves. Note in Fig. 57 the convective nature of the high-frequency unstable waves. The spatial growth rate and the wavelength of the most unstable electromagnetic wave, as measured from Fig. 57, are within 5% of the theoretical prediction.

However, the steady-state production of the high-frequency electromagnetic radiation, as shown in Fig. 57 and 58, could be maintained only as long as the low-frequency instability was at relatively low level. Because the low-frequency instability is absolute rather than convective in its nature, the absolutely unstable low-frequency waves eventually achieved large

Fig. 58.

Spatial growth of the high-frequency electromagnetic field as obtained from computer simulation.

enough amplitudes to trap the electron beam. The phase velocities of the low-frequency waves were relatively low, as compared to the velocity of the electron beam;^{39,40} therefore, trapping of the electron beams by these waves would significantly alter the electron dynamics. In Fig. 59, we show the phase-space diagram of the electron beam after the trapping process had set in. The beam was practically destroyed at this stage and, consequently, the amplification of the high-frequency waves was no longer possible.

The time history of electromagnetic waves, as registered by probes placed at two different positions in the system, also confirmed the physical process. In Fig. 60 we show the time history of one component of the electromagnetic field (E_y) and also its Fourier transform, which illustrates its frequency decomposition. The probe was placed near the end of the system. Figure 60 clearly shows the generation of a well-defined, high-frequency

Fig. 59.
Phase-space diagram (p_z vs z) of the electron beam at $\omega_{pet} = 42.16$. The effects of the absolute instability caused the disruption of the electron beam.

Fig. 60.
The time history and the Fourier transform of the electromagnetic field at a position near the end of the system.

electromagnetic wave, as predicted by the theory. However, the process of radiation production was disrupted later because of the onset of the absolutely unstable low-frequency wave. The detrimental effect of the absolute instability was clearly demonstrated in our simulation. In Fig. 61, we show the time history of E_y , as registered by a probe placed near the entrance of the system; this figure also shows the growth of the high and low-frequency waves. By comparing the amplitudes of the high-frequency wave in Figs. 60 and 61, the convective nature of the high-frequency instability is confirmed. Similarly, the low-frequency instability was proved to be absolute. The observed frequencies of the high- and low-frequency waves were in excellent agreement with the theory.

b. Two-Dimensional Case. The two-dimensional analysis of the instability can be obtained by examining the two-dimensional dispersion relation. However, an analytical expression for growth rate is difficult to obtain in a general case; therefore numerical analysis is most suitable. We have studied the dispersion relation theoretically in great detail, and the results will be presented in another article.⁴⁰ Specifically, we discovered that, in the regime where the ellipse of the instability encloses the origin in k -space, electromagnetic waves propagating at all angles are unstable; furthermore, those propagating between 90° and 270° are absolutely unstable. We have simulated the FEL in two dimensions (using CCUBE) to verify that the off-axis, backward-propagating, low-frequency, electromagnetic waves are absolutely unstable. We have observed in the simulation that the generation of high-frequency radiation was severely degraded because of competition among various modes. The physical parameters used in the simulation were the same as in the one-dimensional case. In Fig. 62, we show the phase space (p_z vs z) of the electron beam at a time when a low-frequency electrostatic wave, coupled with a backward electromagnetic wave, had grown large enough to start trapping the electron beam. This electrostatic wave had a well-defined longitudinal wavelength.

Fig. 61.

The time history and the Fourier transform of the electromagnetic field at a position near the entrance of the system.

Figure 62 also shows the existence of short wavelength (high-frequency) waves that were trying to grow at the same time as the low-frequency wave. One component of the electromagnetic field at a particular axial position is shown in Fig. 63 as a function of x , which clearly showed that the perpendicular perturbation had two wavelengths (mode two). Note that the number of wavelengths in the perpendicular direction had to be an integer, because periodic boundary conditions were used in that direction in the simulation. The perpendicular wavelength indicated in Fig. 63 corresponds to angles of electrostatic and electromagnetic wave propagation of about 20° and 128° , respectively. The absolutely unstable low-frequency waves eventually grew to the point where they totally disrupted the electron beam and, thus, the generation of the high-frequency radiation. The time history and its Fourier transform of the electromagnetic field at a fixed position near the system's entrance is shown in Fig. 64, which clearly illustrates the onset of the low-frequency absolute instability. The frequency, longitudinal and perpendicular wavelengths, and angle of propagation of the absolutely unstable wave obtained from the simulation agree with the theoretical results well within 10%.

Fig. 62.

Phase-space diagram (p_z vs z) of the electron beam at $\omega_{pe} t = 42.41$. The long wavelength modulation was caused by the low-frequency absolute instability, and the short wavelength perturbations were caused by the high-frequency convective instability.

Fig. 63.

Phase-space diagram (p_z vs x) of the electron beam showed a standing wave pattern caused by the symmetric off-axis mode production.

Fig. 64.

The time history and the Fourier transform of the electromagnetic field at a fixed position near the system's entrance. The onset of the absolute instability is clearly demonstrated.

Finally, we show the temporal growth rates as a function of angles of propagation in Fig. 65. The growth rates were obtained by the pinchpoint analysis, as outlined in another article by Cary and Kwan.⁴⁰ The physical parameters are the same as in the simulation. The growth rate increases rapidly from $\theta \approx 90^\circ$ and flattens out after $\theta = 120^\circ$. Our numerical evaluation indicates that mode three, or higher, in the perpendicular direction corresponds to wave propagating at an angle of 105° or smaller, and they have

Fig. 65.

Temporal growth rates as a function of angles, obtained by numerical pinch-point analysis of the two-dimension dispersion relation.

substantially smaller growth rates than modes one and two. Therefore, one would expect that waves corresponding to higher mode numbers in the perpendicular direction would be overwhelmed by modes one and two in the simulation. The fact that mode two was the only dominant mode observed in the simulation was probably because of the uneven level of the noise spectrum that existed in the simulation.

c. Suppression of Absolute Instability in FELs. In the previous sections, we have demonstrated the existence of absolute instability that can severely affect the operation of FELs. However, by placing proper constraints on the design of the FEL, the detrimental instability can be avoided. We have investigated several schemes to achieve the stabilization.

(1) Effects of Finite Length. The analysis of the absolute instability was based on the assumption that the system is infinite and homogeneous. However, in any real device the length of the interaction region is finite. It has been shown that the length is extremely important to the onset of the absolute instability. The critical length of the system is defined⁴⁴

$$L_c = \frac{\pi}{2} \frac{|v_1| |v_2|}{\text{Im}(\omega)},$$

where v_1 and v_2 are group velocities of the two coupled waves, and $\text{Im}(\omega)$ is the growth rate obtained from the infinite homogeneous theory. If the length of the interaction region (that is, the total length of the wiggler magnetic field) is less than the critical length ($L < L_c$), then there can be no absolute instability.^{44, 39, 45} We have verified the criterion as applied to FELs by computer simulations. The critical length for the one-dimensional simulation presented in Sec. III.B.2.a is found to be $L_c = 5.0 \, c\omega_{pe}^{-1}$. By reducing the system length to $4.0 \, c\omega_{pe}^{-1}$ in the simulation, we found that there was no evidence of the absolute instability. In Fig. 66, we show the time history of one component of the electromagnetic field, as registered by a probe situated near the end of the system. The simulation has

Fig. 66.

The time history and the Fourier transform of the electromagnetic field at a fixed position showed the stabilization of the low-frequency absolute instability in a short system.

been run out to $t = 105 \omega_{ep}^{-1}$ (as compared to the previous case $t = 50 \omega_{ep}^{-1}$) and there were no low-frequency unstable waves. The Fourier decomposition of the electric field (E_y) is also shown in Fig. 66, and it clearly indicates that the only unstable waves were caused by the high-frequency instability that was convective in its nature.

(2) Increase of the Cutoff Frequency of the Electromagnetic Wave.

By increasing the cutoff frequency of the electromagnetic wave, one can have the ellipse resulting from the crossing of the beam mode and the electromagnetic mode entirely in the forward direction; therefore, there will be no backward waves becoming unstable. Consequently, there will be no absolute instability. The most apparent way to achieve this is to increase the density of the electron beam or to decrease the radial dimension of the waveguide that encloses the interaction region.

We have verified the stabilization of the absolute instability in the limit of high-density electron beam by computer simulations. An electromagnetic wave, with frequency corresponding to the most unstable high-frequency forward electromagnetic wave, was launched in the simulation. The expected amplification was observed. In Fig. 67 we show the time history of the electromagnetic field at a given position, and also its Fourier transform. There were no detrimental absolute instabilities observed in the simulation. Raising the cutoff frequency of the guide mode by decreasing the radial dimension of the waveguide should have the same stabilizing effects on the absolutely unstable waves. Therefore, one can avoid the undesirable instability by carefully choosing the parameters in the design of FELs.

(3) Effects of Damping.

In the discussion of absolute instability, we used the cold-fluid approximation of the electron beam to illustrate theoretically that the coupling of a backward electromagnetic wave and a forward electrostatic beam mode can lead to an absolute instability. The cold-fluid analysis neglected the effects of damping on the waves; therefore, there was no threshold for the absolute instability. However, if one includes a phenomenological damping term in the theory (which may be due to collisions between electrons and background neutrals or cavity damping), there exists, in general, a threshold of the onset of the absolute instability.⁴⁶⁻⁴⁸

Fig. 67.

The time history and the Fourier transform of the electromagnetic field at a fixed position showed the steady-state generation of the high-frequency radiation and the stabilization of the low-frequency absolute instability in a case with increased cutoff frequency of the electromagnetic wave.

Therefore, one can design an optical cavity of the FEL to discriminate the low-frequency backward waves and, consequently, achieve an effective enhancement of damping on these waves. It is then possible to increase the threshold of the absolute instability so that the low-frequency backward waves can be prevented from becoming absolutely unstable.

3. Off-Axis Mode Production in FELs. In Sec. III.B.1 we showed that waves at all angles can be unstable, by numerically solving the dispersion relation. In particular, we pointed out that waves with group velocities in the forward (electron beam) direction are convectively unstable, whereas waves with backward direction are absolutely unstable. Here we want to present the computer-simulation results of the convective instability of the off-axis waves.

The most obvious way to study the growth of the off-axis electromagnetic waves in a computer simulation is to launch a particular off-axis electromagnetic mode and to observe its amplification as it propagates and interacts with the electron beam. The boundary conditions of the simulation are periodic in x and absorptive in z for both particles and fields. Because of the periodicity in x , the wave numbers of the waves in the perpendicular direction (k_x) in the simulation were quantized; that is, $k_x = 2\pi n/L_x$, where n is an arbitrary integer and L_x is the length of the system in the perpendicular direction. The arbitrary integer, n , is limited by the resolution of short wavelength waves in a particular simulation. In our simulation, mode eight ($n = 8$) in the perpendicular direction is the shortest wavelength that still can be accurately resolved. We have modified the simulation code CCUBE to have the capability of launching an electromagnetic wave with specified perpendicular wavelength and frequency. In this way, the launched wave assumes an appropriate axial wavelength to satisfy the dispersion relation. By observing its propagation and amplification, we can determine its growth rate and phase velocity, and comparison with the theory then can be made.

An off-axis electromagnetic wave was launched in our simulation with $n = 6$ ($k_k = 2\pi n/L = 2.69 \text{ c}^{-1} \omega_{pe}$) and $\theta = 40.0^\circ$, which is the angle between the directions of the wave and the electron beam propagation. The initial amplitude of the wave was $eE_0/m_0 c \omega_{pe} = 0.08$, which corresponded to a power density of 4.35 MW/cm^2 . In Fig. 68, we show the electric component of the electromagnetic wave as a function of the axial distance at a fixed

Fig. 68.

Amplification of an off-axis electromagnetic wave in a computer simulation. The solid line is the least-square fit of the data obtained from the simulation.

perpendicular position at $\omega_{pe} t = 22.0$. The dots in Fig. 68 are data obtained from the simulation, and the solid curve is obtained by a least-square fit of the data. The axial wave number is found to be $k_z = 2.96 c^{-1} \omega_{pe}$, and this wave is a mode six ($k_x = 2.69 c^{-1} \omega_{pe}$) in the perpendicular direction, as expected. The angle at which the wave propagates with respect to the electron beam is given by $\theta = \tan(k_x/k_z) = 42.3^\circ$, which agrees quite well with the theoretical predicted value of 40.0° . In Fig. 69, we show in a semi-log plot the maxima of the electric field as a function of the axial distance. Note that the early part of the data was not included in Fig. 68, because a launched wave, in general, required a certain distance for propagation sufficient to settle in as a normal mode of the system. The phenomena of wave beating is quite evident in Fig. 69. This is believed to occur because, even though only a single electromagnetic mode was launched, a few other modes in the system also were excited and grew to amplitudes large enough to cause beating between the unstable waves. The solid line in Fig. 69 was obtained through the least-square fitting of the data, and it yielded a convective growth rate about 10% smaller than the theoretical value given by the dispersion relation. The small discrepancy probably is due to collisional damping in the simulation and the cold-fluid approximation used to obtain the dispersion relation. In any case, the difference is rather small, and we believe it is quite acceptable in the context of comparing results between theory and simulation, particularly growth rates of unstable waves.

C. Summary

In this section, we have presented some very important results on FELs. We have discussed at length the results obtained from one- and two-dimensional, state-of-the-art, particle-in-cell simulations. We showed that waves at all angles can be unstable and, therefore, competition between unstable modes could lead to a significant decrease in the efficiency of FELs. Theoretically, we have illustrated the concept of absolute instability and demonstrated that the one-dimensional dispersion relation of FELs has a pinch point in the complex k -plane that signifies the existence of absolute instability. We showed the detrimental effects of the absolute instability on the dynamics of the electron beam and the desirable lasting phenomenon obtained by one- and

Fig. 69.

The maxima of the off-axis electromagnetic wave as a function of the axial position. Phenomenon of beating indicated that more than a single mode was excited in the simulation.

two-dimensional simulations. Various schemes to stabilize the absolute instability were presented in detail, and the effectiveness of the schemes was confirmed by computer simulations. We also presented results from computer simulations on the convective instability of the off-axis electromagnetic waves. We obtained reasonable agreement between theory and simulations.

The idea of developing the FEL to be a high-power, tunable, coherent, radiation source, with relatively high efficiency, may be viable only if one can avoid the onset of the absolute instability and the production of the off-axis modes. One way to suppress the off-axis modes is to build the waveguide with a lossy wall. However, a controlled production of an off-axis electromagnetic mode can be another way to tune the output frequency of the FEL without changing the energy of the electron beam and the wavelength of the static periodic magnetic field. If one desires to do that, a waveguide with a reflective, rather than absorptive, wall is called for. Furthermore, one might benefit from the fact that the efficiency of the electromagnetic wave increases monotonically as its angle of propagation increases.

So far in our work we have not addressed the effects of radial inhomogeneities of the electron beam and the electromagnetic field. The finite radial profiles of the electron beam can lead to nonuniform diffraction, and thus leakage, of radiation field in the radial direction. On the other hand, finite radial profiles of the electromagnetic field can cause the phenomenon of self-focusing and filamentation. More research is needed in these areas as we proceed toward a thorough understanding of the physics of FELs.

THE RADIO-FREQUENCY QUADRUPOLE LINEAR ACCELERATOR

THE RADIO-FREQUENCY QUADRUPOLE LINEAR ACCELERATOR

The radio-frequency quadrupole (RFQ) linear accelerator is a new concept for the acceleration of low-velocity particles. This type of linac can accept a low-velocity dc beam, and bunch and accelerate it with high-transmission efficiency and low emittance growth. Spatially continuous radial focusing is provided by the electric quadrupole force. The RFQ may be used as a stand-alone low-energy accelerator; or, in most applications, it could be used as a high-performance accelerator stage between a dc ion source and a conventional accelerator. In 1978, AT-Division initiated a program to develop the RFQ; considerable progress was made in the beam-dynamics design and analysis, and in the development of RFQ resonators.

The first experimental test of the RFQ principle, outside of the USSR, was performed early in 1980. This test was so successful that the RFQ was adopted as an essential part of several Los Alamos accelerator projects. These include the Fusion Materials Irradiation Test (FMIT) accelerator, the Pion Generator for Medical Irradiations (PIGMI), and the experimental program on directed energy beam technology. In addition, the RFQ may have important applications in the radio-frequency linac approach to heavy ion fusion.

A. The RFQ Proof-of-Principle Test

The RFQ accelerator concept was published^{4,9} in 1970, and an experimental test in the USSR was reported^{5,0} in 1977. Because outside observers were unable to witness this test, or to see the equipment, it was important to carry out an independent test^{5,1} of the RFQ principle. Performing such a proof-of-principle (POP) test on a short time scale was possible because of equipment developed by the PIGMI project. This included an ion source and injector system, a 425-MHz klystron, and a computer-based beam-diagnostic system. Figure 70 shows this arrangement, including the 45° analyzing magnet used to measure the output-beam energy.

The RFQ beam-dynamics design for the POP test has been described previously;^{5,2} see Table X for the design characteristic. Although the nominal input-beam current was considered to be 15 mA, the characteristics for a 30-mA input beam were also attractive. Table XI, taken from Ref. 52, shows the results of beam-dynamics simulation calculations from the program PARMTEQ for input-beam currents up to 100 mA. This shows the predicted saturation

LINAC PARAMETERS

INJECTION ENERGY	100 keV
FINAL ENERGY	640 keV
FREQUENCY	425 MHz
INTERVANE VOLTAGE	44 kV
BORE RADIUS	200 126 mm
VANE LENGTH	110 84 cm

BEAM PARAMETERS

FINAL CURRENT	26 mA
PULSE LENGTH	~20 μ s
REPETITION RATE	15-360 Hz
CAPTURE EFFICIENCY	~87%
FINAL EMITTANCE (RMS NORMALIZED)	0.11 cm mrad

Fig. 70.
RFQ test stand.

TABLE 1
425-MHz RFQ DESIGN PARAMETERS

Ion	H^+
Frequency	425 MHz
Input energy	0-300 MeV
Output energy	0-640 MeV
Intervane voltage	44 kV
Maximum radial displacement	5.126 cm
Overall cavity length	110.8 cm
Number of cells	65
Nominal input current	30 mA

TABLE 2
SIMULATION OF 425-MHz RFQ DESIGN

Input Current (mA)	Simulation Efficiency (%)	Output Current (mA)	Radial Emittance Growth (90% Contour)
1	96.7	0	1.04
15	96.3	14.4	1.13
30	96.4	25.9	1.23
45	97.6	33.1	1.19
60	98.6	41.7	1.22
100	94.4	54.4	1.07

characteristics of the beam, as well as the predicted emittance growth. With a 30-mA input beam, the simulation calculations predicted a 25.9-mA output beam. Soon after the experimental test began, a 30-mA beam was injected into the RFQ; the output beam observed in a Faraday cup was 26 mA.

The only adjustable parameter in the RFQ itself is the intervane voltage. The structure is an excellent transport element, transmitting some beam even at very low voltages. As the intervane voltage is increased, the transmitted

beam current increases almost linearly and becomes partially accelerated. At a threshold level of about 50% of the design voltage, a small fraction of the beam is captured longitudinally and is accelerated to the final 640-keV design energy. When this occurs, a measurement of the electric field in the manifold (a cavity that couples power from the waveguide into the accelerating structure) provides a reference point for estimating the design rf field level in the RFQ.

As the vane voltage is further increased, the transmission is also increased; but, in addition, the longitudinal acceptance grows and a larger fraction of the beam is captured and accelerated to the final design energy, as shown in Fig. 71. The accelerated beam was measured in a Faraday-cup beam stop (FC-5) located downstream from a 45° analyzing magnet; whereas the total transmitted beam current was measured in an insertable Faraday cup immediately following the accelerator (FC-4 in Fig. 70). At the design vane voltage, the transmitted beam was carefully analyzed for low-energy components. Consistent with numerical calculations (which indicate that, in the presence of space charge, stragglers become radially unstable) no low-energy components were found. Therefore, at design rf field levels, all beam emerging from the RFQ is fully accelerated.

Fig. 71.
RFQ transmission as a function of intervane voltage.

Because of a limited acceptance in the analyzing system, not all of the beam transmitted by the RFQ is transported to the beam stop (FC-5), which accounts for the difference between the maximum values of the two curves in Fig. 71. The peaks and valleys in the FC-5 curve are an artifact of this limited acceptance, and are caused by variations in the energy spread of the beam that are translated by the bending magnet into variations in the beam width.

Numerical simulation of the particle dynamics show that, for a 15-mA beam, the longitudinal phase space divides itself into two "hot" spots that oscillate around each other. The number of oscillations experienced is a function of the rf field amplitude. When the vane voltage is set to $\sim 95\%$ of the design level, the energy width is at a relative maximum. As the voltage is increased, the energy width becomes smaller and the amount of beam current transported to the beam stop increases. At $\sim 112\%$ of the design voltage, another relative maximum occurs in the energy spread, indicating 180° rotation of the beam in longitudinal phase space. This observed structure in the energy spectrum gives us an independent method of estimating the actual intervane voltage in the RFQ. Examples of the longitudinal dynamics and energy spectrums, calculated numerically, are compared with energy profiles, measured experimentally, in Fig. 72.

The injected beam current was measured in an insertable Faraday cup (FC-2) located just ahead of the RFQ cavity; the output current was measured in a similar cup (FC-4) just following the linac. Transmission efficiencies were measured at the design rf field level for several injection currents (I_{in}). These results are compared with those predicted by numerical calculations in Fig. 73. Because of the small entrance aperture (4-mm diam) of the RFQ, the matched beam was necessarily highly convergent in both transverse planes. The magnetic field of the solenoid, the single-transport element preceding the RFQ, was therefore a very sensitive parameter. As described above, all beam transmitted at design rf field levels was determined to be fully accelerated.

The total emittance of the accelerated beam is an important consideration when an RFQ is to serve as an injector to a subsequent structure. The rms emittance growth is considered to be a fundamental property of the structure and is treated as a parameter in the design of RFQs. The initial (EM-1 and

Fig. 72.
Longitudinal phase space and energy spectra, calculated and measured.

Fig. 73.

RFQ transmission and emittance growth as a function of injected current.

EM-2) and final (EM-3) emittances were measured, using an automated slit-and-collector technique, with data simultaneously displayed and stored on disk. Emittance data were gathered at design rf field levels for several injection currents (I_{in}). In analyzing the data, extraneous points caused by measurement noise were eliminated, as were contributions caused by H_2^+ and H_3^+ ion components in the beam. The resulting data were properly scaled and the first and second moments calculated for the distribution. The rms emittance quoted here is the area of an ellipse having the same rms properties as the measured distribution. If the distribution were uniform, the total emittance (E_{tot}) would equal four times the rms value (E_{rms}).

The RFQ structure is terminated in a full cell, having a very narrow aperture in the vertical direction (2.52-mm diam). The final beam is therefore highly divergent in one plane and exceeds the angular range of the measurement hardware in the vertical dimension. Emittance growth, for the horizontal plane, corrected for $\beta\gamma$ is plotted as a function of injected current (i_{in}) and is compared with calculated values in Eq. (3). The accelerator operated best at the highest beam current available from the ion source, corresponding to the design case. Under these conditions the final normalized rms emittance was typically 0.611 mm-mrad.

The POF test began on February 14, 1989 and continued on an intermittent basis for about six months. The regularity and complexity of its operation were outstanding. After an initial reconditioning period, the linac operated continuously, accelerating a 100- μ A beam current for more than a month at a duty factor of 0.1%. After the test was over, the beam transport at both constructional error and operation of the rf resonator was good.

d. The Design of a Constant Aperture

Our pre-selected design for the test structure involves the use of four sections: radial matching, shaper, gentle buncher, and accelerator. In all RFQ designs made so far, we have held the average bore radius (r_0) constant in the first three sections. Also, we have held the peak-surface field constant along the linac. This, together with a flat voltage distribution along the linac, results in a constant value for the focusing strength (ϕ). This procedure produces a bore radius r_a that varies along the length of the RFQ. After the radial matching section, the bore radius equals r_0 ; it decreases slowly at first and then more rapidly to its final value, as the end of the gentle buncher is reached. This constant r_0 method was adopted to reduce problems associated with the retuning of the 4-vane RFQ resonator. The constant r_0 requirement tends to produce a constant distributed capacitance per unit length that is compatible with the required flat voltage distribution along the vanes.

It may be possible to use RFQ resonators with variable distributed capacitance, and with vane voltages that vary in a specified way with length.⁵³ This should enable us to use RFQ linacs that have a constant bore radius.⁵⁴ Originally, the constant bore was suggested to facilitate gauging

procedures that determine the accuracy of RFQ pole-tip positioning. It would allow a "rabbit" containing sensors or cross hairs to be passed completely through the length of the RFQ aperture. In addition, the constant bore has another important advantage: it can reduce the rf power required to operate the resonator. One estimate shows that a saving of up to 40-50% may be possible in some cases. The rf power per unit length required for an RFQ varies as the square of the aperture radius. In the constant-aperture design, the bore always can be made just large enough to fit the beam, so that no power is lost by having the aperture larger than necessary. To show these effects, FMIT parameters were used to make two RFQ designs: one constant r_0 and the other constant-bore aperture.⁵⁴ In the constant-bore design, the structure power required by the shaper, plus gentle buncher sections, was reduced by 50%.

3. Preliminary RFQ Design for FMIT and Modifications to Facilitate Radial Matching

Although the constant-aperture RFQ can save rf power, it imposes more difficult rf-tuning requirements. The tight schedule for the FMIT accelerator prototype dictates that we do not use the constant-aperture idea, but go back to the better-understood constant- r_0 case. A preliminary FMIT RFQ was designed to furnish the mechanical engineers with some working dimensions. This design was called F6. It accepted a 103-mA beam of protons and accelerated it to an energy of 20 MeV. The output beam was 100 mA and the 90% emittance growth was a factor of 2.3. The overall length was 6.5 and the estimated total power input was 550 kW with beam.

The RFQ linac tends to have a small aperture and an output beam that is small and highly divergent. Such a beam is difficult to match radially to the following drift-tube linac, using a magnetic quadrupole of reasonably small aperture.

A modification to the RFQ design procedures has been developed to facilitate matching. It consists of linearly tapering the strength of the radial focusing to a smaller value at the end of the accelerator. This allows the beam to increase its average radius and to decrease its divergence. This idea was applied to the F6 design and the focusing strength was decreased to 82% of its value at the end of the gentle buncher. The corresponding increase in the average radius of the pole tips (r_0) was 10%. This technique must be applied

carefully, because it relies on a transient response of the beam which, if allowed to reach a steady-state condition, would greatly reduce the transmission efficiency.

D. Preliminary RFQ Beam-Dynamics Designs

The design flexibility of the RFQ accelerator, together with the success of the proof-of-principle test, have stimulated interest in a wide range of possible RFQ applications. Many Laboratories have requested information on how well an RFQ accelerator would perform in solving specific problems. Often, the best way to respond is to make a preliminary beam-dynamics design of an RFQ system. A great many such designs have been made, and usually they are sufficiently challenging that we benefit by working toward a solution. In this period, all beam-dynamics designs were carried out with a peak surface electric field of 1.5 times the Kilpatrick limit. The following is a brief summary of four of these preliminary designs. They illustrate the range of requirements that an RFQ can satisfy.

1. RFQ for a 200-MHz Proton Linac. Many high-or medium-energy facilities have a low-energy accelerator system consisting of a 750-kV Cockcroft-Walton generator, plus a 200-MHz drift-tube linac. This first design illustrates how an RFQ linac could provide a high-performance interface between the dc injector and the drift-tube linac. It accepts a 50-keV proton beam and provides suitable radial matching and focusing. It bunches with a final synchronous phase of -30° , and accelerates to a final energy of 2.0 MeV. A 2-MeV initial energy for the drift-tube linac tends to relax its input design requirements. With a beam of 42 mA injected into the RFQ, the output beam is predicated to be 41 mA, and the 90% radial emittance growth is expected to be a factor of 1.3. The RFQ resonator would be about 0.35 m in diameter and 3.3 m in length.

2. RFQ for the PIGMI Project. A preliminary design for the PIGMI proton linac was developed. The following example is one of many attempts to optimize the design parameters. The RFQ accepts a 50-keV beam and accelerates it to a 2.5-MeV final energy. The frequency is 440 MHz and the input beam current is 33 mA. Under these conditions, the transmission efficiency is 90% and the radial emittance growth is negligible. The pole length is 2.6 m, and the diameter of the RFQ resonator would be about 0.15 m.

3. RFQ for the Karlsruhe Spallation Neutron Source. The accelerator group at Karlsruhe requested information on the possible use of the RFQ in their proposed Spallation Neutron Source (SNQ) accelerator. Their requirements were to accelerate a proton beam from 100 keV to 2.0 MeV in an RFQ operating with a 108-MHz frequency. With an input beam of 52 mA, the RFQ we designed had a transmission efficiency of 98.6% and a 90% radial emittance-growth factor of 2.8. The length of the poles was 6.1 m, and the RFQ resonator diameter would be about 0.65 m.

4. RFQ for a Low-Energy Research Accelerator. The Los Alamos Physics Division has inquired about an RFQ for use as part of a low-energy research accelerator that could accelerate two charge-to-mass ratios, 1/2 and 1/4. The design was made for the value of 1/4 (He^{+1} , C^{3+} , O^{4+} , etc.), and when used with deuterium ions, it provided an even better performance. The injector energy was 25-keV/nucleon, and the final energy was 0.5-MeV/nucleon. A 100-MHz frequency was chosen, and the poles were 4.4 m long. When a 10-mA current of He^{+1} ions was injected, the predicted transmission efficiency was 89%. We plan to follow the RFQ with another type of linac, to obtain energy variability both above and below the RFQ final energy. One possible choice would be an array of independently phased spiral resonators operating at room temperature.

The P-Division accelerator would be used to accelerate polarized deuterons. It was important to determine if the polarization parameters of the beam would be changed by the RFQ acceleration process. A study⁵⁵ of polarized beams in RFQ linacs has concluded that the effects are negligible.

THE HEAVY ION FUSION ACCELERATOR DEVELOPMENT

I. INTRODUCTION

Heavy ion activity in AT Division has been carried out in the area of the RFQ accelerator structure development for Heavy Ion Fusion (HIF). The RFQ effort has led to experimental demonstration of an RFQ accelerator that performed with high efficiency and low emittance growth, confirming computer simulation calculations.

II. DEVELOPMENT OF THE RFQ LINEAR ACCELERATOR

Development of the RFQ linear accelerator has continued at a rapid pace for a wide range of applications. Both calculational and experimental studies have confirmed its excellent properties as a low-velocity injector capable of meeting very stringent requirements. We will discuss first the RFQ activities that are of interest to both light and heavy ion applications, and in the next section will discuss those aspects of the RFQ more directly related to its possible use in heavy ion fusion accelerators.

We have continued to develop methods to design RFQ systems that will produce output beams having specified characteristics. Calculational methods to synthesize the beam dynamics of RFQ linacs have been improved and extended. They have been used for the first time to design systems with a constant aperture that require considerably less rf power to excite the RFQ structure. The use of these constant aperture systems now depends upon our ability to design resonators with the correct longitudinal distribution of vane voltage.

After we synthesize an RFQ design, we analyze its behavior, using multi-particle beam-dynamics simulation programs. These have been further developed so that there are now two main schemes: one based upon integration over the longitudinal space coordinate, and the other based upon the use of time as the variable of integration. Both schemes include the effects of space charge, as well as the effects of electric quadrupole focusing, radio-frequency defocusing, longitudinal bunching, and acceleration. The two methods provide an independent check on our ability to predict the behavior of particle beams under widely varying conditions.

Fundamental studies^{5,6} of emittance growth in rf linacs have been done with the PARMILA beam-dynamics simulation program. The Alvarez linac was used as a model, and calculations were made with beam intensities that approach the

maximum possible currents. Widely different frequencies, input emittance values, and radial-focusing conditions were simulated. Although much more work is needed, these studies have begun to show that certain types of parameter scaling tends to give the same emittance growth behavior.

A milestone in the development of the RFQ occurred in February 1980 with a highly successful experimental test of an RFQ accelerator. The test was designed to accelerate protons from 100 keV to 640 keV in a length of 1.1 m. The test accelerator operated with a frequency of 425 MHz and was equipped with an array of diagnostic equipment necessary to characterize the output beam. The beam-dynamics design of this test and its predicted performance were described^{5,7} in September, 1979. The test confirmed the general properties of the RFQ linac and gave excellent detailed agreement between the measured characteristics of the output beam and the predicted performance. For example, with a dc input beam of 30 mA, the output beam was 26 mA, and the radial emittance grew by less than a factor 1.5. The test showed that the RFQ operates in a highly stable manner and is insensitive to resonator tuning errors and to errors in the pole-tip geometry. It also confirmed the utility of the method of coupling rf power to the RFQ by using of a coaxial manifold.^{5,8} More detailed descriptions of this experimental test are available in other reports.^{5,9,6,6}

III. HEAVY ION ACCELERATOR DEVELOPMENT

One of the problem areas in heavy ion fusion accelerators has been the low-velocity region. In conventional low-velocity linacs, there tend to be severe limits on the beam current that can be accelerated. Also, the largest growth of radial emittance tends to occur in the early linac stages, and this growth is amplified when high-current beams are accelerated. The RFQ linac structure offers a highly attractive solution to these low-velocity problems. Its design flexibility allows it to be adapted to a wide range of applications, each of which may require optimization of specific operating characteristics.

One of the important areas of RFQ design is the predication of the maximum beam current that a given RFQ accelerator will transmit. This becomes especially important in heavy ion fusion systems, where there is a premium placed on a high currents. We have developed a calculational method^{6,1} to predict the current capacity of linear accelerators, including the RFQ. This method has become an important part of our RFQ design procedures. Also, from

these current-limit systematics, we have learned that an RFQ can carry higher currents than a conventional linac. This results from the initial slow bunching and acceleration cycle that delays the onset of the current limit until the beam has moved downstream to a point where the energy is a factor of ten greater than at the input.

To demonstrate the heavy ion capability of an RFQ, we designed a system^{6,2} to accelerate Xe^{+1} from 0.24 to 5.0 MeV. The operating frequency was 12.5 MHz, and the linac was 27 m long. For an input beam of 30 mA, the predicted output beam was 29.1 mA, and the growth in rms radial emittance was a factor of 4.0. In the rf linac approach to heavy ion fusion, 1-A beam currents are often required. This means that multiple RFQ channels must be used and the beams combined in an arrangement called "funneling." In a stepwise manner, this scheme^{6,3} combines many initial beams into a single final beam and, in principle, results in no radial emittance growth. We have developed concepts^{6,3} for constructing RFQ linacs in arrays containing four channels per module. These arrays contain parallel beam channels that are closely spaced and offset longitudinally, so that funneling can be performed in an efficient symmetric manner.

The Berkeley Heavy Ion Fusion Accelerator Study was held in November 1979. Following the conference, papers^{5,6, 6,2-6,4} were written and submitted for inclusion in the proceedings. In addition, papers^{6,5, 6,6} have been submitted to the CLEOS Topical Meeting on Inertial Confinement Fusion held in San Diego in February 1980, and to the International Conference on Low-Energy Ion Beams 2, Bath, England, April 1980.

IV. CRITICAL REVIEW OF HEAVY ION DEPOSITION MODELS

One of the principal attractions of HIF is the expectation that energy deposition by heavy ions can be characterized in target calculations with little, if any, uncertainty introduced by unknown or little-understood effects. However, a critical review of the physics of the interaction is lacking in the open literature. We have undertaken a review to evaluate both the sensitivities of target calculations to major features of the interaction and the need, if any, for benchmarking the models of ion deposition with appropriate experimental measurements.

We have begun a detailed study of the model for ion-beam deposition that was developed by T. A. Mehlhorn of Sandia Laboratories.^{6,7} Because this

deposition model is employed in the LASNEX code used at Los Alamos for target calculations, parameters in the model are being defined to carry out sensitivity studies in target performance.

Although these extrapolations may appear reasonable, they remain unsupported by experiment. Secondly, the energy deposition profiles are expected to be sensitive to the details of the ion interactions in the stopping material, especially in hot, partially ionized material. There are no experimental data of any kind to benchmark the (again, reasonable) models proposed for the ion-stopping mechanisms in such conditions.

In view of the above concerns, we plan to examine the extent to which target calculations depend on variations in the deposition model input parameters. From this examination, we expect that crucial experimental measurements may be defined and performed, leading to a firmer basis for the credibility of HIF target-performance calculations.

THE FUSION MATERIALS IRRADIATION TEST FACILITY

I. INTRODUCTION

A. Prototype Building

The construction of the prototype building continued with the installation of the partitioning, fire protection system, and as much of the utilities as budgetary constraints allowed. At present, the building houses 26 people engaged in various design and development, or installation, activities for the prototype. To support these activities, small staff machine and welding shops were set up. Other support was provided by the procurement and installation of storage facilities, trench covers, a 0.5-ton jib crane for the injector area, heat exchangers and a chiller for the injector water system, and an air-conditioning unit to cool the mechanical equipment room presently housing the control computer systems.

Early in FY-81, a 10-ton full-coverage crane for the high bay area of the building will be installed. A rough draft of the specifications for this crane was prepared; also, specifications were generated for the platform that will support some of the rf and dc power equipment. For the required shielding at the high-energy end of the prototype accelerator, a re-evaluation was made, based on the most recent estimates of the prompt neutron and residual gamma-ray fluxes. Though some shielding will be required, proper selection of materials will minimize the amount of shielding required.

Three administrative tasks were accomplished: an estimate of the installation costs, several logic scenarios for the installation and start-up, and a detailed schedule for the prototype activities.

B. Office Building

The office-building design was completed through Title I, and Title II was started. It is expected that Title II will be completed and construction can start in October 1980.

II. ACCELERATOR SYSTEMS DESIGN STATUS

A. Injector

In early December, 1979, the injector personnel moved the preprototype injector hardware from the physics building into the prototype building.

Because the new high-voltage power supply (125 kV, 250 mA) had not arrived, the old 200-kV, 2-A supply (which had been transferred from the Intense Neutron Source (INS) project) was brought along. Although originally it had been intended to first assemble the prototype injector inside the prototype building, that plan was not feasible, because of delays in completion of necessary utilities and in delivery of several essential injector components. The move served to establish the injector as the major full-time developmental activity inside the new building.

Tests on the injector test stand have concentrated on several components: ion source, extractor, and beam performance in the low-energy beam transport (LEBT).

Ion-source testing included developmental work on filaments, and experiments with the configuration of permanent cusp magnets on the source exterior. Calculations indicated that the species ratio might be modified significantly, simply by changing the location and spacing of the magnets; experiments confirmed this. Based on these tests, a new design for a source was completed. Extreme difficulties in obtaining a leak-tight weld in the all-copper version of this design forced abandonment of that unit. Efforts then switched to a stainless-steel model. Also, plans were made to fabricate an all-copper unit in a single piece, by electroplating onto a suitable mandrel. Meanwhile, further tests continue on the MK II unit, built more than a year earlier.

Extensive calculations were done with the Sandia-developed SNOW code, in an attempt to generate a new extractor design that simultaneously would deliver the full H_2^+ current required for the prototype, and would maintain the beam quality that had been achieved with the half-current extractor. New molybdenum electrodes and an improved support were tested. This testing program was delayed by the many problems encountered with the new high-voltage power supply after its delivery in early May.

A 2-m-long drift tube and pepperpot emittance-measuring device were assembled at the output of the analyzing-magnet box, when the test stand was set up after the move. This made it possible for the first time to observe the beam with the TV cameras at several points along the drift space. Reconstructions from the TV images confirmed the pepperpot measurements of a maximum normalized emittance of 0.06π mrad $\cdot$ cm.

A new V-shaped beam dump was implemented that has proved capable of handling the much higher power densities now routinely encountered. A flat-style beam dump in the bottom of the analyzing-magnet box has proved inadequate to handle the power density, even where the beam is relatively diffuse. The sputtering of copper from the heated surfaces of the dumps has been a continuing problem. Solutions being pursued are: a better dump geometry, improved cooling, and possibly the use of materials with a lower sputtering coefficient. Improvements must be made, or the operating lifetime of the FMIT injector may be compromised.

B. Radio-Frequency Quadrupole (RFQ) Low-Beta Linac

A major achievement in the first half of 1980 was the successful operation of the proof-of-principal (POP) RFQ. This device accelerated a proton beam and represented a functional low-beta linac, the first of its type to be tested in this country. All required beam-dynamic parameters, to prove the principle of operation, were achieved. The tests were conducted at 425 MHz, which resulted in a reduced physical scale for the model over that required in FMIT. The rf coupling to the POP RFQ was by means of a waveguide. Tuning of the structure presented considerable difficulties, because of the precision with which the RFQ vanes had to be positioned relative to each other. During brazing, excessive errors of up to 0.25 mm resulted and, as a consequence, special fixtures had to be devised to mechanically bend the vanes into position. This also was accomplished and the POP RFQ met its operational goals within 2 days of turnon.

From this point, the beam-dynamics design of the FMIT RFQ proceeded with confidence. By early summer, a firm set of design parameters had been developed that defined both transverse and longitudinal characteristics of the vane tips and aperture. Meanwhile, the rf design also developed around loop drive into a coaxial manifold surrounding the RFQ core, because waveguides (as used in the POP RFQ) are not practical at 80 MHz. A conceptual design review was held that revealed the major mechanical difficulties associated with a coaxial system of this type: namely, cooling the inner core, and vane replacement. The question of vane alignment also is difficult because of the precision required over long lengths, but the balance of opinion is in favor of rigid, rather than flexible, vane supports.

C. Beam Diagnostics

Several diagnostic installations were provided for the POP test on the PIGMI beam line, both for transverse and longitudinal measurements.

The use of BPM's in the FMIT drift tubes requires a rad-hard seal on a high-bandwidth cable of small diameter. The cable was located and tested to > 3 GHz. Seals were designed by a HEDL group that has tested similar seal designs to 10^{23} n/cm². A model was assembled, with cables and seals welded in.

Digitizing electronics were purchased, and were used to collect beam profiles from the preprototype injector. The data were input to reconstruction codes, and spatial density and transverse emittance distributions were calculated. These distributions compare favorably with measures of these parameters by other techniques. The CAMAC and PDP 11/60 hardware and software interfaces were optimized for high speed in their data-handling and transfer capabilities.

Preliminary versions of both the fast-rise (< 1 ns) 80-MHz impulse generator and the transducer (dc beam current transformer) were constructed, and evaluation testing began. The impulse generator is used to simulate bunched-beam signals through other diagnostic sensors, such as current transformers, beam-position monitors (BPM), and time loops.

Mirror mounts were designed and fabricated for use in a mockup of an optical system to place four different transverse beam profiles onto a single TV-camera faceplate. The excellent response of this system is being drawn up in a final design.

D. Radio-Frequency (rf) System

Seventeen high-power rf systems have been ordered from Continental Electronics. Four units will be used on the prototype and 13 units on FMIT. The maximum output power is 600 kW cw. Each unit will consist of 5 modules: the final power amplifier, the IPA/Driver, the dc power supply, the filament power supply, and the crowbar cabinet. Switchgear connecting a unit to the 13.8-kV ac power line is also provided. The first complete unit is scheduled for delivery in May 1981. The remaining units will be delivered piecemeal over the next two years.

Preliminary work has been done on rf sources for the Energy-Dispersion Cavity (EDC). It appears that the most economical approach will be to use commercially available FM transmitters and a coaxial combiner.

The breadboarding of the low-power rf system (100-W output) is nearing completion. Work has begun on the low-power rf system for the Continental test stand. This will be shipped in late October or early November.

The digital phase detector has been breadboarded and it appears that it will exceed the requirements for detection of 1° shift over a lead, or lag, of 180° . A prototype of this circuit is now being built. This was the last remaining potential technical problem in the low-power rf system.

The order for the coaxial line has been placed with Dielectric Communications. The line has a 14-in. diam and $75\text{-}\Omega$ characteristic impedance.

It was decided to design the control system to facilitate manual operation of each rf system, or combination of systems, and to provide the interface for later connection to the facility control system. Continental's control diagram was recently received, which has enabled us to proceed with our own design. This design is now about 50% complete.

E. FMIT Facility Control System

During this reporting period, the integrated LASL and HEDL instrumentation-and-controls team specified and selected vendors for the major items of equipment for both the FMIT facility and accelerator prototype. Purchase orders were placed, and most of the equipment was received for over half of the prototype computer and instrumentation subsystems. Implementation of the control system software has been initiated.

The complete prototype central computer system was received and vendor installed in the mechanical equipment room of the prototype building. This is a temporary installation, pending completed construction of the central-control and computer room. The real-time software-operating system and communications-network software were installed on the primary and support control computers (PDP-11/60). The first of four microcomputers (LSI-11/23) was received and has been installed in a CAMAC auxiliary crate controller, the communications-network-processor portion of one instrumentation subsystem. The vendor-supplied data-communications software (DECNET) was staged through several steps to arrive at the communications network, as proposed for the

FMIT facility and prototype; that is, a 1-M-baud link between the primary and support control computers and a 56-k-baud link between the primary control computer and the instrumentation-subsystem-communications node processors (LSI-11/23). A test criterion has been established in an attempt to prove that DECNET can satisfy the message-transfer rate required by the FMIT control system. Initial software design and implementation of the applications codes for the PDP-11/60 primary control computer is complete. Testing of the interaction of these codes in a multitasking environment has been initiated.

Wherever appropriate, FMIT and prototype equipment specifications were consolidated to insure that software-compatible equipment will be procured for both facilities. This was done for the computer- and console-graphics system. Purchase orders for the prototype color graphics and touch-panel systems have been placed. Equipment for the console control panel (plasma display, touch panel and control knobs) has been received, installed, and is currently undergoing operational tests.

Approximately 50% of the CAMAC equipment required for the prototype, the prototype console frame, and 25 instrumentation racks have been ordered and received. Two programmable controllers were purchased and received. The first programmable controller unit has been installed, and programmed to operate the prototype injector vacuum system.

Partial shipment of the 27 instrumentation and control power supplies has been received. These power supplies provide +5, ± 15 , and +24-volt dc for signal conditioning and control use. Electronic design of seven signal-conditioning modules has been completed. The signal-conditioning modules provide for additional isolation and transient suppression of the digital and analog signals in and out of CAMAC modules. The circuits are currently in the process of drafting layout and design.

The initial wiring requirements for the FMIT trunk wiring system have been developed. The computer-generated (WIRERUN program) installation packages have been released for review. The WIRERUN packages consist of two instrumentation and control wiring packages and one each of thermocouple, ac controls and diagnostics/timing wiring packages.

The initial channel-list input into the signal data base has been completed for the dc power supplies of the drift-tube linac section of the accelerator. Preliminary design of the cable tray, intercom, public address, telephone and Kirk key systems has been completed and transmitted to R. M. Parsons for final design.

F. Drift-Tube Linac

The final design of the prototype drift-tube linac tank was completed, and the request for quotation was prepared by LASL's Materials Management Department. Simultaneously, the copper-clad plates for rolling into the tank shell were fabricated. Some difficulty was experienced in finishing the plates, and a uniform copper thickness was not achieved, although adequate for radio frequency, cooling, and welding purposes. It should be stressed that care must be taken in rolling the plates to their required thickness, and adequate flattening is essential before grind-finishing.

A scale model of the prototype was also built that operates at 368 MHz; it was used to test previous calculations for field effects of the open vacuum ports, girder slot, and post-couplers effects that were not addressed by SUPERFISH. In addition, the model was used to test out-of-roundness of the shell to determine cylindricity tolerances. From these measurements, the dimensions and tolerances for the rf surfaces, after fabrication, were specified.

The specifications for the end closure of the prototype tank were completed, and design of this component begun. This unit is required to support the last linac quadrupole, and this requires precise transverse alignment. The upstream quad is supported by the RFQ.

G. Drift Tube Girder Assemblies

Design efforts on the quadrupole magnets, drift-tubes, and girder progressed in parallel paths in 1980. Beam-dynamics studies showed that losses in the front end of the linac, caused by matching the RFQ beam, required the provision of water-cooled bore tubes up to cell #4. This resulted in the need for larger apertures in these quads than those in use with the uncooled bores, and introduced a fourth member to the family of quads needed for FMIT. Both quads for the prototype were built and tested at Lawrence Berkeley Laboratory (LBL). It was discovered that the large-aperture quad could not provide the

required fields, without saturating the steel and requiring excessive coil current. It was decided to use high-cobalt magnet steels for this quad's pole tips and to match the pole tips into the low-carbon-steel yoke by an enlarged foot pad. Pole-shimming studies at LBL provided the information needed to predict the pole-tip profiles for both the prototype quads (known as A1 and A2), and procurement of these quads is now under way.

The drift-tube (DT) body design to accommodate the quads, and the DT stem design needed for support from the girder, were developed. Early in the year, the use of castings for the DT body was being actively pursued; no fabricators could be found that were interested in the job, so the designs were changed to spinnings. The switch to wrought fabrication (spinings, drawings) requires more machining, but will result in a better vacuum envelope. Many fabricators have indicated interest in working with us on this design approach. The most difficult choice will be that of determining the fabricator of the final assembly. The fabricator for the prototype drift tubes will be LASL; for FMIT, it is possible that HEDL will do the job.

The girder design has gone through several iterations in all of its major components: the kinematic supports joining it to the tank, the precision-positioning device for drift-tube alignment, and the drift-tube clamp/support. An expanded effort in mechanical design and structural analysis was started, with the object of readying the girder design for a preliminary design review about mid-summer.

H. rf Peripherals

An active design effort continued on the rf peripherals, particularly the post couplers, slug tuners and monitor loops. The final design of the post coupler was approved, and fabrication of a working model was begun. Preliminary design of the slug tuner was also approved, and the final design drawings were begun. Two models of the rf monitor loops were approved, and their fabrication initiated.

A study was made of the Blue Ribbon Panels' recommendation to isolate tanks 1 and 2 with a vacuum valve at the intertank spacer (ITS). When beam-dynamics considerations, alignment, maintenance, and vacuum were taken into account, no better design than the present one could be found. Further design effort on the ITS will begin in the fall.

The EDC has received no further attention in 1980, although this unit's importance to the target designers continues to grow, as beam-dynamics studies indicate the linac energy dispersion may be less than 200 KeV. Incorporation of the EDC into the prototype program (at least for disconnected development) is essential, and mechanical design of the unit will begin late in the year.

I. FMIT HEBT Mechanical Design

The first detailed mechanical design studies of the FMIT HEBT were conducted with the formation of the Test End Working Group (TEWG), a joint LASL-HEDL technical team devoted to defining and solving problems that exist at the HEBT-target interface. A module containing the last two quads in the HEBT will be inserted into the test-cell wall. Preliminary design of this plug yielded several concepts that are applicable to the other HEBT modules, and help define expected maintenance problems for FMIT. As a direct result of these studies, a radiation-hardened design concept for the HEBT quadrupoles is now evolving, utilizing mineral-insulated conductor.

The TEWG faltered when the maintenance problems on the lithium system showed the need for considerable redesigning of that system. It became apparent that complete definition of FMIT maintenance (of both the lithium system and the HEBT) required the joint efforts of a LASL-HEDL operations and maintenance team. Such an effort is now underway, and should result in a mutually satisfactory design by the fall.

J. Beamstops

Beamstop efforts moved toward a graphite-clad calorimetric system. A calorimetric beam stop constructed of heavy copper is feasible for pulsed-duty operation in FMIT, and if adequate water cooling is provided, may perform satisfactorily for the prototype. Activation analysis indicated that even an H_2^+ beam will produce significant activation because of released protons; therefore, graphite-cladding now is being considered.

K. Cooling Systems

1. FMIT. All interface information necessary for Parsons to complete Title II design work on the accelerator cooling systems was transmitted and recorded on Piping and Instrumentation Diagrams.

2. Prototype. Detailed design of the prototype cooling facility was completed, and a bid package was prepared for DOE to use in selecting a contractor.

All control valves, thermocouples, and other government-furnished equipment to be supplied to the cooling-facility contractor, have been ordered.

L. The dc Magnet Power System

Schematic-diagram designs have been completed for control and polarity switching of 40-A dc steering power supplies used to excite the linac-quadrupole steering coils. These steering coils are separately wound on the pole tips and provide horizontal and vertical steering. Power "ON-OFF", polarity reversing and current control may be controlled by the computer, or locally.

A similar control schematic design for switching polarity of the selectable horizontal-steering power supply and shunts has been completed. These units will modify currents in the quad windings to produce horizontal steering. The dc power conduit and cable requirements were defined to Parsons. Computer analysis of the 45° bending magnet for the FMIT HEBT has been started.

M. Prototype Power Distribution

The "Phase B" power-distribution design for the prototype building was completed and issued. This completes distribution of 480-V 3-phase and 208/120 V to the local power panels in the building. The building's 480-V, 3-phase power source was moved from the temporary pole transformers to the permanent, pad-mounted, 13.8 kV/480-V switchgear.

N. Vacuum System

The use of titanium sublimation pumps was reconsidered when it was found that the cost of titanium sources would be larger than expected for the size necessary to operate (for extended periods) at the FMIT operating pressure of 10^{-6} torr. It was determined that titanium sublimation pumps would not be cost effective for FMIT. A high-vacuum system, initially composed of ion pumps, was then proposed and further developed during this period. Ion pumps were proposed because they had been demonstrated to be suitable under conditions identical to FMIT, insofar as gas load and other operating conditions were concerned.

During this period, a vacuum laboratory was equipped to make the measurements necessary in further FMIT vacuum-system development.

0. HEBT System

1. FMIT HEBT. In the fall of 1979, William Brobeck & Associates finished a study on the FMIT HEBT beamline transport tolerances. In late 1979 and early 1980, S. Cheng and J. Farrell of LASL wrote computer programs to generate Gaussian input beams for use with the code RAYTRACE. Studies with the RAYTRACE code seemed to show large differences in the spot on target, because of higher order aberrations. These results were reported to the lithium-target engineers at a HEBT/Target interface meeting. A decision was made to place the target 53 cm from the effective edge of the last HEBT quadrupole to minimize the effect of higher order aberrations on the target spot. The HEBT/Target interface group held several other meetings to discuss engineering problems related to the test-cell wall plug, the beamline and support-gear design in the test cell, interface responsibilities, and target and test-cell problems.

Early in 1980, design began on the FMIT HEBT quadrupoles. This program led to a HEBT redesign, using longer quadrupoles (with more reasonable pole-tip fields) for the desired 5-in. aperture. Discussions with Klaus Halbach, LBL, confirmed the basic design approach for the quadrupoles. Halbach also stated that although the bending magnets would require detailed study and special care in the design process, they are not impossible to build. POISSON runs have been completed on both types of FMIT quads; however, only preliminary work has been done on the bending magnets.

Detailed engineering design of the HEBT began with the addition of a mechanical engineer assigned to this task. Discussions were held to resolve interface problems (for example, the EDC and target interfaces) and with engineers responsible for "in-line" gear (for example, vacuum and diagnostics). By May 1980, serious design effort led to a conceptual-design review for the test-cell wall plug. Beamline-component layouts showed the beamline to be very "tight"; minimal room was available between quadrupoles for the necessary flanges, bellows, diagnostics, and vacuum gear. Other periodic structures, including a periodic doublet system, were studied for the EDC to switching-magnet section, but none provided any additional room for components.

General beamline optics studies have included: some use of PARMILA; TRANSPORT studies of the beamline's individual periodic structures; a study of mismatched beams and betatron oscillations; off-axis and off-angle beams; and alignment errors. A variety of beam-dynamics information was provided to

support the beam diagnostics-effort. In particular, G. Minerbo (LASL's Theoretical Division, T-9) studied virtual-image reconstruction and optimal locations for TV views, for emittance reconstruction techniques. An Argonne consultant, E. Colton, was hired to review the FMIT beamline-optics design and to study higher order aberrations effects on the target spot. He found errors in the Gaussian input-beam codes for RAYTRACE (the code was not properly orienting the phase-space ellipse) and stated that the higher order aberrations were negligible on target. His studies were done with a PARMILA code that included third-order effects in quadrupoles. His studies will continue through the end of fiscal year 1980.

Poisson computer analysis has been completed for the 13 identical quadrupoles in the FMIT HEBT between the linac and the beam switching magnet. These quads produce 1.28-kg/cm gradient and 8.19-kg pole-tip field. The computer analysis produces the pole shape and the yoke dimensions, and verifies the current requirement and flux in the iron.

Similarly, the Poisson analysis has been completed for the 7 identical quadrupoles in the FMIT HEBT between the last bending magnet and the target. These quads produce 1.1193-kg/cm gradient and pole-tip field of 7.16 kg.

This same design will be used for the prototype HEBT; therefore, the computer analysis of all quadrupoles for the FMIT and prototype HEBT is complete.

2. Prototype HEBT. Beamline designs were revised as the latest RFQ and 5-MeV linac information became available. The prototype beamlines will be prototypical of the FMIT beamline in all aspects except for the prototype beamline's nonperiodic structure. Two quadrupoles will be the linac type-A1 design, and three will be identical to the FMIT "last-leg" quads (5-in. aperture, $\ell_{\text{eff}} = 30$ cm). The optics were redesigned to accommodate changes in the spot-size requirements on the beam stop. Input-beam parametric studies, misalignment, and tolerance studies were performed and the beamline mechanical design is underway.

3. RFQ POP Beamline. Final input-beam parametric and spectrometer studies were performed, and the beamline was used for the POP tests.

III. BEAM DYNAMICS

At the start of the period, a matching code was written and tested. This code matches an RFQ output beam to the DTL by assigning field-gradient

strengths to the first four input quadrupoles of the DTL. A smooth transition of the beam into the DTL is achieved by weighted fitting of four properties (rms waist, rms bust, max waist, max bust) of the beam in each cell to self-determined parabolas. Tests show that the matches are quite good.

The matching code was used to study the quadrupole-gradient requirements of the several RFQ designs. For each basic design, the output-beam size can be varied by flaring out the vanes in the accelerator section of the RFQ. Plots were made of the average quad gradient, the spread in gradient, and the maximum beam size in the DTL. An RFQ design and matching conditions were chosen for the FMIT RFQ.

Studies also were made of the effect on quadrupole matching gradients, when the drift length was varied between the RFQ and DTL, and the effect of changing the cutoff position of the end of the RFQ. The general conclusion was that a $B\lambda$ drift space was better than a longer one, and that although some improvement in beam size could be achieved by stopping the RFQ $1/8$ cell length from the usual cell end, the change in size was not significant.

A trip to LBL was made to observe and aid in the testing of the A2 quadrupole magnet. The tests confirmed an earlier prediction that increasing the A1 bore size to 2.92 cm would result in too small a maximum gradient in the A5 quad. (Subsequent measurements have shown the A1 design to be good.) As a result, the A2 quad was redesigned to increase its maximum gradient.

The need for better evaluation of particle loss in the DTL has led to the conversion of some versions of the PARMILA code to the Cray computer. The Cray allows many more particles to be followed. At present, the matching code, the DTL PARMILA, and three versions of PARMTEQ are running on the CRAY. (PARMTEQ is the version of PARMILA that simulates the RFQ).

Forty-thousand particle runs through the RFQ and DTL have provided satisfactory estimates of the losses to be expected near the input of the DTL. These losses are at energies too low to produce worrisome radiation, and therefore are of interest only for the magnitude of the power deposited in the first few drift tubes.

Even 40 000 particles are not enough to evaluate the higher energy losses further down the linac. This will require new codes that allow overpopulation of the input regions to the RFQ, from which losses arise.

H⁻ ION SOURCE, INJECTOR, and ACCELERATOR TEST-STAND STUDIES

STATUS OF RESEARCH

A. Ion-Source Research

During the first half of 1980, the following performance has been achieved for various surface plasma-source (SPS) configurations.

1. Accelerator Test-Stand (ATS) Source. An ATS source based on the general configuration of the Dudnikov device was designed, constructed, and tested. In this instance, the goal was to achieve an H⁻ pulsed beam having a symmetrical emittance* with $\epsilon_x = \epsilon_y < 0.04 \text{ } \pi\text{cm-mrad}$, and an output current (I_{max}) of about 20 mA, for use in the ATS injector. The measured performance of the ATS source is $I_{\text{max}} = 47 \text{ mA}$, $\epsilon_x = \epsilon_y = 0.035 \text{ } \pi\text{cm-mrad}$.

2. Rotating Ion-Source (RIS) Configuration. With a fixed anode, 0.5- by 10-mm emission slit and 1/2-mm anode web, pulsed operation of RIS has achieved a 104-mA maximum output current. The RIS performance can be compared with its performance before FY-80 of $I_{\text{max}} = 40 \text{ mA}$.

3. General SPS Research.

a. Anode Web Thickness Studies. Anode web thickness studies during the year resulted in a 160% increase in maximum current extracted from the RIS configuration. A preliminary understanding of the effect of anode web thickness on source performance was achieved as a result of a simple modeling of the H⁻ transport within the source. The anode web thickness effect was noted because of a 1-mm difference between the Dudnikov and RIS anode webs. The actual web thickness effect was subsequently investigated in the Dudnikov configuration, which was most easily modified, and later was incorporated in all three configurations (Dudnikov, RIS and ATS source).

b. RIS Gas-Feed Location. We believe that feeding the gas in a distributed manner across the arc region may improve performance; however, this seems to run counter to what has been observed in the Dudnikov configuration.

c. Extraction Geometry Studies. We did a cursory study of the extraction geometry with the primary intent of achieving a suitable extraction geometry for the ATS source. We pursued this only until a beam of the desired

*The emittance numbers reported here are those that contain 63% of the current in each direction.

intensity and synthetic emittance for the ATS source was achieved. Most of the investigation concerned circular emission and extractor apertures.

d. Cesium Generation Studies. Studies of the production of cesium vapor for injection into SPS devices were done on three separate cesium vapor sources; a cesium metal oven and mixtures of $2\text{Ti}+\text{Cs}_2\text{CrO}_4$ or $2\text{Ti}+\text{Cs}_2\text{Cr}_2\text{O}_7$ powder. In all three instances, the Dudnikov source configuration could be operated satisfactorily, although the source seems to be somewhat easier to operate with $2\text{Ti}+\text{Cs}_2\text{CrO}_4$ mixture. Usually the powdered ($2\text{Ti}+\text{Cs}_2\text{CrO}_4$ and $2\text{Ti}+\text{Cs}_2\text{Cr}_2\text{O}_7$) mixtures are packed into the source anode and thus the cesium production is self-regulating and dependent upon the anode operating temperature; that is, it is not directly under the control of the experimenter. The cesium metal oven, on the other hand, is controlled by the experimenter, but its response is slow, and there is no self-regulation, as in the case of the metal chromate and titanium mixtures.

We measured the cesium evolution rate as a function of the temperature of the $2\text{Ti}+\text{Cs}_2\text{Cr}_2\text{O}_7$ and $2\text{Ti}+\text{Cs}$ mixtures. The cesium evolution rate of the $2\text{Ti}+\text{Cs}_2\text{CrO}_4$ mixtures was about 3 times higher at the estimated anode operating temperatures (450°C) than for the $2\text{Ti}+\text{Cs}_2\text{Cr}_2\text{O}_7$.

e. Space-Charge Beam-Neutralization Studies. The intense beams of low-energy ions extracted from an SPS have sufficiently high space charge to seriously degrade the beam emittance, if the space charge of the beam is not at least partially compensated by ions produced from the background gas of the vacuum through which the beam is transported. Previous measurements showed that space-charge neutralization was not enhanced by addition of extra H_2 gas. This year, we found that heavy gases such as Ar, N_2 , Kr, CO improve the transmission of the negative beam from the source to a Faraday cup beyond the 90° source magnet. This effect arises from two competing processes: (1) better space-charge neutralization, which results in a lower emittance beam, and (2) fewer stripping collisions between the beam and neutralizing background gas. In the instances of Kr neutralizing gases, the transport efficiency ($i_{\text{source}}/I_{\text{transported}}$) was about 91%; whereas for H_2 gas, it was only 74%.

The energy of the electrons created in the beam plasma was measured for a variety of gases and was found to be about 25 eV. A round beam of 100 mA has a potential drop of about 500 V; therefore, this suggests about 5% residual space charge. Further study of this problem is planned.

f. Discharge Modeling. A simple discharge model was developed to explain the discharge voltage. A sustained discharge requires that $\gamma n = 1$, where γ is the secondary emission coefficient for electrons produced by bombarding ions, and n is the number of ion pairs produced by each electron in the H_2 gas. The model also describes the effect of the anode web thickness, discussed earlier, and predicts that only about 5% of the H^- produced in the source is ever extracted.

g. Miscellaneous. A calculational effort has been directed towards the H^- SPS emittance versus current threshold problem. An experimental analysis program that interfaced the electronic scanner current data to beam fraction was written. Emittance analysis is laborious using this technique, although it now seems likely that we will be successful in automating this scheme.

Other calculations done during this report period deal with the theoretical space-charge limit for extracting H^- ions through circular emission-extractor geometries.

B. ATS

1. ATS Injector. This injector is housed within a copper-screen room 4 m wide by 9 m long, and 5 m high; the room allows for the addition of a second shielding screen to be added at a later time, should that become necessary. All permanent seams of the screen room are continuously soft soldered, and closure openings (doors, etc.) are sealed by flexible rf finger stock. The enclosure interlocks and safety devices are installed.

The high-voltage supply for the injector is a 300-kV, 250-mA dc supply capable of continuous duty (that is, cw injector operation). This oil-filled supply, with a volume of approximately 10 m³, has been installed, connected to the injector dome, and tested without the injector accelerating column in place.

Utility power for the injector dome is provided by a 10-kVA isolation transformer that is installed and operational. The injector dome consists of a 3.5-m-long, 1.2-m-wide, 2-m-high insulated enclosure, supported by six 22-cm-diam PVC cylinders. Corona tests of the dome were conducted to 300 kV.

The dome encloses equipment at dome potential to operate the 20-kV beam transport, dome diagnostics, etc., and an internal high-voltage cage containing the equipment to operate the ion source. This internal cage operates at a potential of 20 kV, relative to the dome, and its utility power is provided by a 5-kVA isolation transformer located within the dome.

In all, the dome contains some 44 chassis that were either fabricated in-house or procured; they have been installed and are currently operational.

The ATS ion source described earlier has been installed and tested within the dome, and its cooling and vacuum systems are in operation.

The following ATS ion source beam diagnostics have been installed: Faraday cups at 90° and 0°, and a surface ionization gauge (SIG) as a cesium-flow gauge.

The 300-kV pulse regulator remains to be completed, but does not prevent operation of the injector. The 20-kV injector transport was installed and was made operational after water leaks in the quadrupole doublet, caused by shipping damage, were repaired. The injector accelerating column, its corona rings, and voltage divider are being installed. There are some light link chassis located at ground potential that are used for data acquisition from the dome and remote dome controls. These have been bench tested and installed, but are not yet operational.

The ground-potential vacuum pumping station located at the ground end of the accelerating column is operational.

Initial high-voltage tests of the entire injector system are occurring during the last weeks of FY-80.

2. ATS-Injector Transport. Two alignment monuments also have been permanently installed by drilling holes through the concrete floor and pouring independent concrete alignment support columns in the virgin tuff that underlies the ATL building. The monument tops are fitted with kinematic mounts, to allow accurate repositioning of the alignment instruments and targets for alignment checks.

The ATS-injector transport, and whatever accelerator structure is to undergo testing and development, are supported on roller-bushing stands that mount on 1-1/2-diam case-hardened support rails. These rails are aligned relative to the beam axis and are supported on a 7-m-long aluminum I-beam structure. Installation and alignment of this support structure is complete.

The support bases that mount on the alignment rails have been fabricated, as well as the supports for the injector ion optical elements, beam line and four diagnostic boxes. Fourteen diagnostic actuators are fabricated, but not yet assembled; 16 diagnostic actuator controls have been fabricated and installed in the instrument racks, but have not been wired to the actuators.

The eight electromagnetic quadrupole lenses that form the emittance-trimming section, and perform the matching into the linac, have been received and their field quality measured. The harmonic content was outside the specification. Optical comparator measurements of the mechanical pole locations indicate a systematic assembly error that probably results from an error in the manufacturer's assembly jig. For this reason, the lenses have not been mounted on the ATS, and we are trying to correct the problem without remanufacturing the lenses.

The ac power and cooling-water manifold that services the equipment supported on the alignment rails is installed.

3. RFQ Decision. Because of the decision to perform the initial ATS experiments with an RFQ structure, the overall ATS development was restructured to optimize the use of our resources. These changes included delaying the completion of the rf power source, ATS controls and data acquisition system, and the injector transport system. This was done to allow the RFQ design to be developed and then, during its fabrication, the delayed activities could be completed. We did not significantly alter the injector activities for the following reasons: (1) with an injector beam, we could implement, test, and develop the laser diagnostic, (2) with the injector beam, we could characterize the accuracy of the injector column and transport-system calculations. This is an area that has elicited a great deal of controversy in the past and deserves as much research time as practical without affecting the ATS primary function of studying rf linac structures.

With the RFQ decision, a great deal of previously accomplished ATS work was set aside; however, for completeness it is briefly described in sections below.

4. Buncher Design. A fundamental frequency buncher was electrically designed with the code SUPERFISH, and the mechanical design was initiated. This effort was terminated with the decision to proceed with an RFQ structure, but includes its own bunching system.

5. Periodic Quadrupole Transport. Construction of the beam transport between the buncher and the drift tube linac had been proposed in the form of a periodic quadrupole array. The concept was to extend the permanent-magnet (PM) lens structure of the linac through the upstream transport region, between the buncher and the linac entrance. This would allow the matching doublet to

be placed upstream from the buncher, rather than in the limited space between the buncher and the linac.

The PM lens system was designed using PANDIRA; quotes for the PMs were obtained. A considerable effort was expended to insure that a fabrication procedure would be followed that would eliminate errors in the fabrication of the PM pieces. The RFQ decision was made prior to placement of the magnet order; thus the order was not placed.

6. Drift-Tube Linac Design. The PM quadrupoles for the drift-tube linac were also designed; they were ordered and have been received. The drift tubes, their support stems, and cooling circuits were completely designed for the three-cell linac SUPERFISH (calculations to establish electric-field configurations); mechanical tolerance studies, and mechanical design were completed. In addition, the drift-tube ends that are pressed from stainless steel sheets were fabricated. A laser-welding fabrication procedure for drift-tube assembly was identified, because PM-loaded drift-tube assemblies cannot be fabricated with the standard furnace-brazing techniques.

The vacuum box for the drift-tube linac was also partially into preliminary design when the RFQ decision was made. In this instance, a large amount of the work can still be of use, as most of what has been described in the drift-tube structure will eventually follow the RFQ.

7. ATS Data-Acquisition and Control System. The ATS data-acquisition and control system will eventually provide many needed tasks and services. The system will monitor test-stand operating parameters such as quad currents and source voltages, etc. It will accept, through CAMAC module interfaces, emittance data giving real-time diagnostic information about the accelerator performance. The information is processed on-line. This information can be input into computer programs such as TRACE (currently being installed on the system) to determine how to adjust operating parameters to achieve desired results with the test stand. Certain control functions, in particular those dealing with emittance measurements, will be performed by the computer.

Our data-acquisition system revolves around a SEC-MIK-11 microcomputer, utilizing a DEC-LSI 11/2 microprocessor. This computer plugs directly into a CAMAC crate, providing a direct link between the computer and CAMAC. The rest of our very limited computer system contains a Data Systems Design Model DSD440 dual floppy disk, a Tektronix 4010 display terminal, and a Tektronix 4631 hard-copy unit.

We use the DEC RT-11 operating system software that is compatible with our computer hardware. Several persons now utilize the RT-11 system. This was facilitated by a 5-hour lecture series covering the RT-11 operating system, CAMAC, and the SEC-CAMAC software library.

We have demonstrated that our system can access CAMAC, handle CAMAC Look-At-Me (LAM) interrupts to the computer, make nonprocessor (NPR) data transfers between computer memory and disk storage, and permit a program-overlay structure. We have installed a Tektronix PLOT10 emulator (written at LASL) on the computer, to have real-time graphics capability. The computer codes written so far for the test stand have emphasized data acquisition.program-overlay structure.

Our CAMAC system currently contains the following hardware:

- Two CAMAC crates; one for the test stand and one for the laser diagnostics.
- One interface, to tie the two CAMAC crates together.
- Two Dataway displays, one for each crate, to show visually the status of the CAMAC lines.
- One manual input; this allows data to be input by hand through CAMAC, for test purposes.
- One 16-channel scanning A/D converter, to read dc voltages (such as quad power-supply voltages) .
- Two 24-bit input gates, to read the status of limit switches, interlocks, etc.
- One dual 15-channel stepping-motor controller, to run the emittance gear.
- One 48-channel charge integrating ADC, to read 48-emittance harp wires.
- One system processor, to handle the 48-channel ADC.

8. The rf Power System. All major components of the rf power system are on hand, including the klystron, solenoid, modulator tank and components, high-voltage power supply, capacitor bank, crowbar, control chassis, oscillator, amplifier chain, and the wave guide to transport the rf power from the klystron to the linac.

9. RFQ Design. Nine RFQ pole-tip designs have been studied for the ATS. The initial designs, although outperforming drift-tube linac designs, resulted in long structures (> 8 m), and required more rf power than is available from the existing klystron. The later designs were considerably improved, and we have chosen one that seems quite good. Although the pole-tip design was carried to 5 MeV, the structure to be built during FY-81 will terminate at 2 MeV, to be compatible with the klystron power limitations and provide a good test of the structure design. The preliminary design was frozen in mid-September, and we anticipate starting fabrication in October.

C. Theory

1. ATS Transport Calculations. Beam-dynamics calculations were performed for the ATS injector transport from the injector-column exit to the $2\beta\lambda$ drift-tube accelerator entrance. These were performed for currents appropriate to the $2\beta\lambda$ linac. The transport system, after the buncher, was designed to look very similar to the linac. The reason for this was twofold. First, the beam was kept small, thereby minimizing emittance growth from magnet aberrations. Secondly, we hoped that while the beam was in the process of being transported through a device that resembled the linac, a good "matched" distribution for the linac would evolve. The geometry is pictured in Fig. 74.

$$E_0 = 250 \text{ KEV}$$

$$E_F = 566 \text{ KEV}$$

$$F = 440 \times 10^6 \text{ Hz}$$

INITIAL EMITTANCES

$$100\% = 0.0205 \text{ CM-MRAD}$$

$$90\% = 0.0129 \text{ CM-MRAD}$$

$$\text{RMS} = 0.0032 \text{ CM-MRAD}$$

Fig. 74.
Test stand linac.

A calculation of some interest was the effect of chromatic aberrations that would occur in the period transport between the buncher and the linac entrance. The concern here was that the beam energy spread introduced by the buncher would cause an unacceptable emittance growth in the periodic system. The beam-dynamics simulations indicated that this was not the case. Unfortunately, these results are no longer relevant, because of the RFQ decision.

2. Buncher Optimization. Until the recent advent of the RFQ, traditional longitudinal beam matching into a linear accelerator was accomplished by using one or more rf cavities resonating at the fundamental linac frequency or one of the harmonics. It appeared to us that, by making a judicious choice of buncher-cavity frequencies, amplitudes, and spacing, we could produce any longitudinal phase-space distribution required to match into a linac. We have written a computer code to do the parameter optimization. The program input is the desired matched distribution in energy versus phase at a given point in time, the number of buncher rf cavities, and the individual frequencies of these cavities. The computer program then determines the optimum rf field amplitudes in the individual cavities, plus the cavity spacings.

The desired longitudinal phase-space distribution is compared, using a least-squares procedure, with that obtained by tracing particles through the buncher system, using some nominal buncher parameter set. These parameters are varied to determine their effect on the least-squares sum. A new set of buncher parameters is calculated to minimize the least-squares sum, and the iterative procedure is repeated until a stable solution is obtained. We used this procedure to obtain several good possibilities for buncher systems for the 250-keV, $2\beta\lambda$ structure for the ATS. This effort was terminated at the time of the RFQ decision.

3. $2\beta\lambda$ Linac Studies. We designed a linac to accelerate an initial 250-keV dc beam to 566 keV. A $2\beta\lambda$ structure was chosen because it permits much stronger transverse focusing at this low injection energy and high frequency. In Fig. 75, we show the output current from the linac as a function of input current to the buncher. Figure 75 shows a current limit of 20 mA, as expected. For an input current of 10 mA, we obtain a beam-transmission efficiency of 81% through the entire structure and a 45% rms-emittance growth.

Fig. 75.

Output current and output emittance vs input current.

ating gradient configuration is reached. The final distribution function is periodic with the structure period; that is, the distribution is matched to the final configuration. Computer simulations show that it is possible to match into highly non-linear focusing forces by producing a large beam matched to an accelerator operating near the $2\sigma_x + \sigma_z = 360^\circ$ resonance, which is excited by the first harmonic of the rf coupling forces. These calculations do not include space-charge effects. We expect the procedure to work similarly when the three-dimensional space-charge calculation is included in the particle-tracing code. This procedure is discussed in more detail in a report by W. P. Lysenko.⁶⁸

We believe that the adiabatic transition that occurs in an RFQ structure is responsible for its excellent performance. It is worthy of note that the detailed matching theory was highly instrumental in providing the impetus to build the proof-of-principle RFQ.

5. Random Errors. With the periodic, no-space-charge version of the HOT code, the effects of random misalignments of cell elements from the central axis were investigated. Nonlinear focusing forces, such as the rf coupling forces and the axial nonlinearity, lead to forces proportional to the dependent variable, whose strength varies randomly from cell to cell. Such

4. Detailed Matching.

A numerical procedure was developed for generating phase-space distributions matched to nonlinear periodic focusing systems. This procedure uses a version of the particle-tracing code HOT, which starts in a smooth-focusing configuration, for which a matched distribution can be calculated by the RZED79 code. Such a distribution is followed in the tracing code while adiabatically deforming the focusing forces until an alter-

diffusion effects have been studied theoretically, with the conclusion that the emittance is expected to increase exponentially in time. Simulations confirmed this theory in our examples for the ATS drift-tube linac; but it also was found that particle losses may be expected, even before any appreciable emittance increase from this mechanism has occurred. The losses in the simulations were caused by coherent bunch motion induced by the random errors.

An RFQ structure is undoubtedly superior to a drift-tube linac in this regard, because it is not likely to have errors that vary randomly from cell to cell. As explained in the previous section, even large nonlinearities can be matched, as long as their strength varies slowly (or not at all) from cell to cell.

6. Three-Dimensional Space-Charge Calculations. A three-dimensional space-charge routine is being developed for use in various particle-tracing codes. The space-charge potential is expressed as a nonorthogonal expansion in some convenient set of functions. The unknown coefficients are determined by the requirement that the Poisson equation and the associated boundary conditions are satisfied. [Because we choose a finite (hence incomplete) set of functions, the fit is not exact.] This method requires the calculation and inversion of a matrix that depends on the region and on the set of expansion functions chosen. At each time step in the particle tracing simulation, it is necessary to compute only a simple source vector to multiply by the fixed matrix, thus obtaining the desired expansion coefficients. A report by W. P. Lysenko and E. A. Wadlinger⁶⁹ discusses this method in more detail. We are presently working on a version of this method that does not do general boundary conditions, but will do RFQ problems efficiently.

7. Analytical Beam-Dynamics Theory. The theory of emittance growth caused by mismatch has been developed and placed on a rigorous basis. Starting from the full three-dimensional time-dependent Vlasov equation, with arbitrary time-dependent external forces, a multitime-scale analysis yields approximate equations for both the slowly varying and rapidly fluctuating parts of the match. In particular, the rapidly fluctuating part of the match satisfies a linear partial-differential equation.

The equation for the time evolution of a perturbation about the match (that is, a mismatch), has been derived and is shown to reduce to a good

approximation of a simplified linearized Vlasov equation. The short-time behavior of this Vlasov equation has been solved exactly, and these exact solutions explain the phenomenon of rapid emittance growth observed in the simulations.

A systematic expansion of the longer time behavior has been developed and solved. The solutions are capable of explaining the time behavior of the emittance because, in particular, explicit emittance formulas result. Formulas for the asymptotic value of the emittance have been derived and compared to simulations. The effects of mismatches, because of both current fluctuations and rf, have been explicitly evaluated. The predicted rf mismatch emittance growth agrees in detail with the results of PARMILA simulations. Current fluctuations are found to be not very important, in qualitative agreement with previous simulations. Of course, the analytic theory allows examination of arbitrary kinds of mismatch.

D. Ion Optics

We have constructed a quadrupole magnet-field measuring system for measuring the harmonic content of PM-quadrupole lenses. The system was constructed because existing equipment within the Laboratory cannot be used with the small-bore PM lenses planned for use with the 2BX drift-tube accelerator. The heart of the system consists of a Tektronix 4051 programmable calculator that controls the field-measuring coil, accepts the measurement data, performs the data reduction and outputs the completed analysis. The mechanical equipment, in-house-constructed interface equipment, and the software have been completed. Final checkout will be completed when a commercial interface module has been repaired by the vendor.

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