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ABSTRACT

This report covers the activities of Los Alamos National Laboratory's Accelerator Technology Division during the first 6 months of calendar 1981. We discuss the Division's major projects, which reflect a variety of applications and sponsors. The varied technologies concerned with the Proton Storage Ring are continuing and are discussed in detail. For the racetrack microtron (RTM) project, the major effort has been the design and construction of the demonstration RTM. Our development of the radio-frequency quadrupole (RFQ) linear accelerator continues to stimulate interest for many possible applications. Frequent contacts from other laboratories have revealed a wide acceptance of the RFQ principle in solving low-velocity acceleration problems. In recent work on heavy ion fusion we have developed ideas for funneling beams from RFQ linacs; the funneling process is explained. To test as many aspects as possible of a fully integrated low-energy portion of a Pion Generator for Medical Irradiation (PIGMI) accelerator, a prototype accelerator was designed to take advantage of several pieces of existing accelerator hardware. The important principles to be tested in this prototype accelerator are detailed. Our prototype gyrocon has been extensively tested and modified; we discuss results from our investigations. Our work with the Fusion Materials Irradiation Test Facility is reviewed in this report.

PROTON STORAGE RING

SUMMARY AND STATUS

The Proton Storage Ring (PSR) staging building, a 12 500-sq-ft laboratory structure 100 m SE of the Accelerator Technology (AT) Division central office building, is complete. Beneficial occupancy should occur in July. Preparations are being made to move all PSR equipment-development programs from their present location in SM-40 to the staging building by the end of that month.

Title II design of the PSR tunnel and equipment building has been initiated by the project architect-engineer (AE). A comprehensive review of the Storage Ring radiation-shielding requirements has resulted in a moderate increase in shield thickness specifications.

Several areas were addressed by the Medium Energy Physics (MP) Division at Los Alamos. A prototype direct-extraction H^- ion source has been fabricated and initial tests have begun. During the next reporting period the ion source will be installed on the H^- beam test stand so that current-intensity and beam-quality measurements can be made. A conceptual layout of the new LAMPF switchyard configuration has been produced. It includes a 2-m-long space for a kicker magnet that directs H^- beam pulses to Line D. Preliminary investigations into independent steering for intense H^- and H^+ beams in the linac were made.

The Ring-injection dipole magnets have been reconfigured into a set of five identical units; the design is nearly ready for vendor quotations. The theoretical and experimental investigation of the magnetic H^- stripping process to be used for injecting beam into the Ring is now complete; a paper on this topic was presented at the March 1981 Particle Accelerator Conference, Washington, DC, and is included in this report.

A fast high-current programmable power supply based on power field-effect-transistor (FET) technology is being developed for the injection-line pulsed steering magnets. Tests with a prototype circuit demonstrated that desired currents (300 to 400 A) can be reached with the needed frequency response (10 to 100 kHz). This circuit, which uses feedback to provide precise control of the pulse shape, shows promise for other PSR pulse-driver applications, including the orbit bump magnets, and switchyard and injection-line kickers.

Design of the main Ring dipole magnets has been completed; requests for quotation on fabrication of 11 magnets (1 prototype and 10 production units) have been sent to 11 US companies and 3 European firms. After careful review of the beam-clearance requirements in the extraction-kicker straight sections, the aperture specifications for the 20 Ring quadrupoles have been set at 7 in. Conceptual design has been initiated.

The 2.8-MHz buncher design was examined, and a system was recommended based on a ferrite-loaded quarter-wave resonator whose frequency can be rapidly adjusted (during injection) by varying the bias magnetic field applied to the ferrite. Another recommendation was to drive the resonator with a relatively low-impedance rf source (100 to 1000 Ω). The combination of these two design principles will provide a buncher system that is capable of responding appropriately to the effects of beam loading.

During this reporting period ferrite rings obtained from the old Brookhaven Alternating Gradient Synchrotron (AGS) accelerating cavities were tested to determine whether their characteristics meet the needs of the 2.8-MHz buncher. Results to date are not conclusive.

The conceptual design of the 603.75-MHz buncher has been formulated. The system is based on eight side-coupled (LAMPF-type) cavities driven through magic tees with appropriate phase relationships to allow safe dumping of reflected power. The rf power (110 kW) is to be provided by a commercially manufactured TV transmitter package. As in the case of the 2.8-MHz buncher, rapidly changing beam loading is a very important consideration. Present plans call for fast mechanical tuning of the cavity resonant frequency, using a speaker-cone arrangement. However, there is some doubt that sufficiently rapid frequency response can be attained, and other methods using biased low-loss ferrite will be investigated within the next few months. Quotations for the rf power source, a dual 55-kW television transmitter operating at 603.75 MHz, have been solicited.

First-order beam optics for the extraction transport system have been completely worked out. A solution has been found that can deal with the large momentum dispersion in the extracted beam and the large off-momentum function at the Ring extraction point. Details of the solution, calling for eighteen 6-in.-aperture quadrupoles, are given in a paper (included here) that was presented at the March 1981 Particle Accelerator Conference, Washington, DC.

The short-bunch extraction-kicker¹ modulator was tested successfully at full voltage (50 kV) and pulse rate (720 pps) during this period. Component lifetime tests will be conducted after delivery of a new EG&G 5-in. thyratron. Construction of the long-bunch kicker modulator is near completion.

Work is continuing on development of a higher voltage modulator whose design is based on fast-switching magnetic cores, rather than thyratrons.

The conceptual design of the PSR Instrumentation and Control system has been formulated, and work has begun on some of the basic software building blocks. The central computer has been specified (VAX 11/750), and an order has been placed; delivery is expected in July or August.

ENGINEERING AND CONSTRUCTION

The Preliminary Safety Analysis Report has been completed and approved. Title II design on the PSR tunnel and equipment building has started.

The heating-ventilating and air-conditioning systems were re-examined resulting in a simpler and less expensive system. The PSR tunnel width was increased from a nominal 4.88 m to 5.64 m to accommodate future local radiation shielding and to simplify implementation of remote-handling techniques. Layout of utilities such as compressed air, deionized water, convenience electrical outlets, electrical-power and control-wiring routing, etc., was finished and transmitted to the AE. Design work began on the neutral and tune-up beam stops and on the PSR extraction tunnel. Surplus cooling towers, heat exchangers, and water pumps for the PSR deionized water system are on site and will be incorporated into the AE's system design.

INJECTION-LINE SKEW-DIPOLE MAGNETS

We had planned two skew-dipole magnets in the injection line: an upper one at the intersection with Line D and a lower one at the Ring interface. Calculations on the lower magnet revealed it would weigh over 50 tons, far too heavy to transport with available equipment. It was then decided to split the lower magnet into three separate magnets and the upper one into two. A single

design has been adapted for the five magnets required. Computer design is complete and drawings are nearly finished. A bid package will be sent to potential fabricators in July.

INJECTION STEERER ELECTRONICS

R&D work on a feedback arrangement to control the current through the vertical steerer has continued during this reporting period. The feedback concept (Fig. 1) permits the development and control of complex current waves in the steerer magnet. Current levels of ~ 400 -A peak are needed to produce the fields necessary for beam steering.

Power FETs have been used to fabricate the system shown in Fig. 1. Three 50-A peak-rated devices have been used in a model pulse-follower arrangement. A 7-A commercial operational amplifier was used to supply gate drive, and standard integrated-circuit amplifiers and devices were used to perform summing and differencing for the model device. Peak currents of >300 A have been achieved with the necessary time and amplitude programming. The model FET follower was configured as a unipolar device, but additional work with both N- and P-Channel FETs has indicated a bipolar power amplifier can be constructed.

A bipolar unit consisting of 10 N-Channel and 30 P-Channel devices was designed and fabrication was begun. This power amplifier can deliver at least 400-A peak into a load having an inductance that matches the proposed steerer magnet ($\approx 0.5 \mu\text{H}$) and will be used to investigate overall performance factors such as rise time, bandwidth, peak power, and duty-cycle effects. It will be very useful in qualifying protective mechanisms and circuits and will help determine the best design for the current transport lines to the steerer.

Figure 2 shows a typical current wave for the steerer. This figure shows a current level of 110-A peak delivered to a $0.5\text{-}\mu\text{H}$ magnet through the three-FET model device.

RING BENDING MAGNETS

All layouts, drafting, checking, engineering, and physics calculations for the main dipole-bending magnets have been completed.

operate well. Because we have had so much trouble with the low-power amplifiers, an in-house development effort has been started. Preliminary results on the 1-W amplifiers are encouraging.

The personnel and equipment protective system is patterned after that at LAMPF. All associated modules have been built and tested. The largest project was to design and build a high-voltage enclosure and foil tester for the crowbar unit. This unit is now 90% complete.

The WR-430 waveguide system for the initial klystron testing and cavity testing at Los Alamos has been delivered, except for the 500-kW circulator that is scheduled for delivery in January 1982. Installation of this system is complicated because most of the waveguide is water-cooled. Tap water will be used because the aluminum waveguide is not compatible with the deionized water system. The high-power waveguide loads require large water flows, and the circulator water must be maintained to within $\pm 2^{\circ}\text{C}$ for proper operation.

The demineralized water system will not be ready before November 1981, primarily because of the long lead time needed to procure the required 400-gpm pump. Efforts to expedite delivery of this component are under way, and an alternate source is being investigated. The permanent water system has been designed and all parts are on order. The local-water manifold for the rf-cavity test stand also has been designed and parts have been ordered.

CONTROL SYSTEM

General Configuration

Driven by the twin constraints of a large number of elements to be monitored and controlled and the need for independent development of various control system elements both at Los Alamos and at NBS, a system configuration has gradually evolved in which distributed intelligence plays a key role. The host computer (a PDP-11/44) will be used to do complex data reduction and graphics displays, and will be linked to the primary control station, which is the central control console. Located ~400 ft from the control station, and physically adjacent to the accelerator itself, will be three secondary stations, functionally divided into injector, rf, and magnet control stations. The secondary stations will contain the actual control elements of the system, for

example, Analog to Digital Converters (ADCs), Digital to Analog Converters (DACs), stepping-motor controllers, etc. Each secondary station will contain a data base comprising the units under its control. An image of each of these three secondary data bases will be maintained in the primary control station. Actual control of the system normally will be effected from the primary console, through fast links to the secondary stations. However, during the project's developmental phase it will be necessary to operate each secondary station separately from the primary. This dictates local intelligence for each separate station of the system. We also decided to configure the primary station as a development system and to equip it with sufficient software tools to carry through the project's requirements.

Secondary-Primary Link

Various schemes for linking the primary and secondary stations have been considered and tested, including the Synchronous Data Link Control (SDLC) serial method. This method was eventually discarded because of its complexity, cost, and software overhead. No commercial Multibus board was available that offered this protocol. This necessitated using a custom board, to be developed at Los Alamos or at some other Laboratory (with the associated software and hardware problems), or discarding the method altogether. The latter choice was deemed the wiser, although Computrol now produces a Multibus board with the SDLC protocol, which we may yet use for the primary-host link to the PDP-11/44. Because this board is so complex, there are better options available for the primary-secondary link.

In any communications link, the fundamental choice is between serial and parallel transmission. The serial link offers the advantages of fewer wires, hence lower cost. Noise problems are easier to eliminate but at the cost of decreased speed and serial-to-parallel conversion at each end of the link. The parallel link is intrinsically simpler, because no data conversion occurs at either end, and the transmission speeds are much greater. Loath to design our own Multibus link board, we investigated available commercial boards that implement serial links, and we found them all wanting in one respect or another. The optical couplers available for such commercial boards were so slow (typically less than 2400 baud) that extensive modification of the boards was necessary to bring them up to the performance standard required by our

system. The commercial boards, Universal Synchronous Asynchronous Converters, are limited (for asynchronous transmission) to 9600 baud and below. Reasoning that a well-designed custom board was preferable to a modified commercial board, we designed our own parallel link, which turned out to be simple enough to allow all secondary binary (Input/Output) read-and-control circuitry to be on the same Multibus board. We eliminated the speed problem with the optical couplers by replacing them with differential line drivers and receivers. The physical link between the secondary and primary stations is now an 18-conductor cable of No. 22 wire.

Each secondary station will be linked separately to the primary in a star configuration. The link boards for both the primary and secondary stations have been designed, prototyped, and tested. Under worst-case conditions, the system permits error-free transmission of an 8-bit byte every 10 μ s across the link. Were higher speeds ever needed, it would be simple to add a Direct Memory Access (DMA) controller and block transfer data at higher rates--an option, incidentally, that would be precluded by a serial scheme.

Secondary Station

The secondary station consists of a video terminal with keyboard and a power supply for the Multibus crate. The 12-slot Multibus crate contains two single-board computers (SBCs), the custom-panel interface, core memory for the data base, ADC and DAC boards as needed, and custom stepping-motor driver boards as needed. The custom panel, with two infinite-turn knobs and interrupting push button, provides the main control for the secondary station.

Two SBCs were used in the secondary station to divide, and thus simplify, the software tasks. Despite apocryphal assertions to the contrary, a single SBC is quite limited in the speed with which it can perform a large number of tasks; the contradictory demands of immediate interrupt service and rapid data-base update argue convincingly for separate SBCs for these two tasks. The simple processor (\$500), which updates the data base and provides the DAC control signals on a continuous basis, operates independently from the rest of the system and eliminates the need for executive software control of these functions. The remaining SBC is an Intel iSBC 80/24, which updates the local display from the data base and services interrupts from the control panel and from the primary data-link request line. When the primary station requests

data from the secondary or ships a control signal to it, the request is handled with top priority by the secondary station, thus permitting knob control from the primary station. Any knob response time greater than ~ 100 ms leads to operator annoyance; this response time has been our design criterion for link response. Local control is effected through the two control knobs and push-button switches, effectively eliminating arcane dialogue through the keyboard. The left-hand control is used for scrolling through the data base to select the active line, which is controlled by the right-hand knob. Both control knobs drive the software through interrupts, guaranteeing timely response without the need for a repetitive sync pulse or a wait loop. The eight push buttons along the top of the control panel select the function desired by the operator. Generally, these push buttons effect the display of information, but two of them permit the operator to enter and execute a special interpretive code in the secondary station. This capability is discussed in more detail in the section on software. Below the function buttons, the four push buttons form a status register that selects the desired units display. Thus, from the secondary-station control panel, the operator can select the data-base segment he desires to display, in whatever units he desires, and can control the output to whatever setting he selects. Data-base entries are made through the keyboard; otherwise, the keyboard generally is not used.

Many stepping motors are used in the control system to effect changes in the phase and amplitude of various rf signals and to control water-system valves, etc. The control of these stepping motors is provided through a custom Multibus board that contains logic to control four stepping motors per board. The actual control element is a CY500 chip that can be programmed by the SBC for independent control of the stepping motor. Limit-switch logic for each motor prevents overshoot on the control and provides a fiducial for calculation of the control function. In this sense, each CY500 is effectively a coprocessor to the SBC. The board has worked well and has been produced on a commercial printed-circuit board.

Software Development

Adding a dual floppy-disk drive and controller to the secondary-station system effectively turned it into a software-development system. However, this advantage was purchased at the cost of much agony and irritation in getting the

system up and running, because the manufacturer was unable to supply the promised software. After the necessary software drivers were written and debugged, the system functioned as hoped, running the Control Program for Microcomputers (CP/M) operating system and providing editors, assemblers, and compilers as promised. Currently, we have compilers for FORTRAN, BASIC, C, and PASCAL; additional software is very inexpensive. Much of the display secondary software has been written, which permits knob control of the data base at the secondary station. An interpreter is currently being written that will provide the operator/engineer with local "programming" capability to the extent of loop control, etc. This interpreter is roughly half complete. The drivers for the ADCs and DACs have been written.

To date, the operating software has been written in Intel 8085 assembly-language code, but the C compiler is up and running, and we anticipate higher level code development for the primary station. The codes to update the data base have been blocked out, and the secondary-station executive has been flow charted extensively.

Host Computer

The PDP-11/44 minicomputer has been delivered to NBS and installed in the RTM control-room area. Installation of this computer, including the vendor software, was completed in June. It has a moderately fast CPU with a floating-point processor and 8-kbyte cache memory, a 256-kbyte main memory expandable to 1024-kbyte, two 10-Mbyte disk drives, two-256 kbyte cassette drives, and a 120-character/second console terminal. The software supplied by the vendor consists of a multiuser-disk operating system, utilities, assembler, and optimizing FORTRAN compiler. A telephone link between the PDP-11/44 and the NBS Univac computers is being set up so that program and data files used for RTM design calculations may be transferred for use on the minicomputer.

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RADIO-FREQUENCY QUADRUPOLE LINEAR ACCELERATOR

SUMMARY

Our development of the radio-frequency quadrupole (RFQ) linear accelerator continues to stimulate interest for many possible applications. Frequent contacts from other laboratories have revealed a wide acceptance of the RFQ principle in solving low-velocity acceleration problems. We have completed final RFQ beam-dynamics designs for Los Alamos programs and for the European Organization for Nuclear Research (CERN) new injector system. In addition, we have made preliminary beam-dynamics designs to assist several other Laboratories in making decisions concerning RFQ use.

FINAL BEAM-DYNAMICS DESIGNS

Final designs have been completed for two RFQ accelerators. These are for accelerator technology development at Los Alamos and for a new injector system for CERN. Table VI summarizes the RFQ parameters; the rf power was estimated using an approximate formula for the four-vane resonator. Results from the formula were multiplied by 1.5 to account for actual copper losses and for losses in the coaxial manifold that feeds rf power into the four-vane resonator. Finally, the beam power was added to obtain the peak-power values listed in the table.

For the Los Alamos program, we have designed an RFQ to accelerate 100 mA of hydrogen ions from 0.10 to 2.0 MeV in 2.89 m.¹ The main emphasis was to limit to a very small value the radial emittance growth during acceleration. With a 110-mA beam into the RFQ, multiparticle beam-dynamics simulation programs have estimated this growth to be a factor of from 1.20 to 1.29.

For CERN we have developed an RFQ to accelerate a 100-mA beam of protons from 50 to 520 keV in 1.38 m.² This RFQ has been accepted by our CERN collaborators; based upon its characteristics, they have produced mechanical designs for their 200-MHz four-vane resonator. The vanes will be shipped to Los Alamos in late July, and we will then use the numerically controlled (NC) mill to machine the pole-tip contours.

TABLE VI

RFQ DESIGN PARAMETERS

	<u>Los Alamos</u>	<u>CERN</u>
Ion	H^-	H^+
Frequency (MHz)	425	202.56
Input energy (MeV)	0.10	0.05
Output energy (MeV)	2.00	0.52
Nominal current (mA)	100	100
Transmission efficiency (%)	91.4	93.6
Output emittance ^a	0.021	0.05
Length (m)	288.6	138.2
Peak rf power (kW) ^b	1020	304

^aRMS normalized area/ π in cm-mrad units.

^bIncludes power required for the rf manifold and for the beam.

PRELIMINARY BEAM-DYNAMICS DESIGNS

After the successful proof-of-principle (POP) test, there has been a rapidly increasing interest in the RFQ. We continue to be asked by many Laboratories to provide guidance for RFQ use in existing or proposed accelerators. We include here some of the new RFQ design examples that have been generated in response to these requests.

RFQ for Polarized H^- Injector at AGS

In response to a collaboration from ANL and Brookhaven National Laboratory (BNL), we have generated RFQ design examples that would be suitable for a polarized H^- injector into the 200-MHz Alvarez linac at the BNL AGS. The characteristics of the most attractive design example, called BNL2, are listed in Table VII. The 22-MV/m peak surface field corresponds to ~ 1.5 times the

concluded that the best method for countering the beam loading is to provide for fast tuning of the rf-cavity resonant frequency over a range of about ± 100 kHz.

During the past 6 months a buncher-system conceptual design has been developed that includes mechanical tuning of the rf cavity at low audio frequencies. The cavity wall will be deformed by a loudspeaker-type arrangement, in synchronism with the beam injection/extraction cycle. During a large part of the cycle, the rf drive will be improperly matched to the cavity/beam system, and significant power will be reflected. The improper matching is taken care of by driving each set of cavities (on either side of the Ring) through a magic tee (or short-slot hybrid). With suitable adjustment of connecting waveguide lengths, reflected power from the cavities can be made to return to the fourth port (rather than to the generator) where a high-power resistive load is connected.

A problem with this design approach is that the cavity tune does not accurately follow the rapidly changing beam-loading situation at injection. This inaccuracy could cause the beam to be accelerated to a higher energy, an intolerable condition. Mechanical tuning at up to 20-kHz frequencies will be needed to achieve accurate tracking, which may be hard to accomplish. An alternative scheme might be to use ferrites for fast electronic adjustment of cavity inductance. Feasibility depends on finding a suitable high-frequency ferrite material that does not have prohibitive losses. This approach will receive close attention during the coming 6 months.

PULSE-POWER SYSTEMS FOR THE PSR

Several types of pulse-power modulators are integral parts of the injection line and the extraction line for the PSR.

The most difficult pulse-power system to develop is the modulator for the extraction-line deflection system that kicks the protons from the steady-state Ring trajectory through a septum to the extraction line. Two modes of PSR operation require two types of extraction-kicker modulators. The short-bunch mode requires a modulator to provide simultaneous positive and negative 50-kV pulses of 50-ns duration, 720 times per second. These specifications place requirements on pulse-power components that exceed the ratings of available

units. Thus, the system has been redesigned to include two stages of sequential deflection.

The reliability limitations at voltages greater than 50 kV for the thyratrons available may be, in principle, circumvented by using magnetic pulse compression of a low-voltage, low-power pulse. However, magnetic systems have not been developed to the operating range required by the PSR extraction system. At present, the initial stages of this development are under way. The magnetic pulse-compression scheme using magnetic switching offers the possibility of building a one-section extraction kicker to operate at voltages of positive and negative 100 kV, with higher reliability and longer life than thyatron switched units.

The long-bunch modulator also must generate positive and negative 50-kV pulses, but of 400-ns duration and at a repetition rate of 120 times per second. Two sequential extraction-kicker stages must be used because of the 50-kV thyatron output-switch limitations. The long-bunch-modulator development is a subset of the short-bunch development, with less severe requirements. Thus a magnetic pulse-compression system also can function as a long-bunch modulator.

The following sections describe the progress and present status of the pulse-power system being developed for the PSR.

THYRATRON EXTRACTION MODULATOR

The short-pulse modulator to drive the extraction kicker was operated for 3.6×10^7 shots at the design repetition rate and voltage of 720 pps and 50 kV for a total of 14 h. The lifetime was encouraging. The primary switch tube failed at the end of this test and was replaced with an EEV CX1171. Initial testing has begun with the new tube; indications are that the tube is not switching as rapidly as required. Lower impedance drivers may cure the problem.

The Blumlein circuit was modeled, using the NET-2 circuit analysis program, to determine the effect of the switch-tube inductance on the Blumlein operation. The results shown in Fig. 4 indicate there will be two undesirable after-pulse aberrations of significant magnitude that will be generated because of the inherent inductance of the switch tube. Various schemes are being

* AFTER-PULSE SIMULATION

Fig. 4.
Blumlein output with 30-nH switch inductance.

considered to short out the extraction system, after the main pulse passes by, to reduce after-pulse aberrations.

Initial high-voltage testing of the long-pulse modulator was performed using SF_6 insulative gas to check for serious problems before oil immersion; it was then tested in oil. Malfunction of the EG&G trigger chassis has prevented further operation. The initial testing did indicate that with the RG-218 output cable there was an undesirable pulse tilt caused by the skin resistance of the inner conductor. This problem can be eliminated by using a different output transmission line.

MAGNETIC PULSE-COMPRESSION SYSTEMS

An evaluation has been made of lumped-element magnetic pulse-compression systems for the PSR extraction kicker and for the isotope-separation laser driver. An analytical study was completed that developed the scaling relations for magnetic energy losses, magnetic switching times, and geometrical design considerations. The analytical study also detailed a computer program that was developed to calculate the same parameters based on Maxwell's equations. The analytical results (Fig. 5) and computer code are in general agreement as to the extent of losses, etc. In addition, a circuit model for use in network analysis programs was developed. The third computer activity was the development of a magnetic pulse-compression system design code that includes all the stray circuit elements. The code designs, for each type of magnetic pulse-compression circuit, a complete multistage circuit and includes magnetic and resistive losses to determine overall system efficiency, power gain, and cost. The total cost includes the cost of fabrication, capacitors, magnetic cores, and miscellaneous hardware. One important result of the system design code is the importance of resistive losses in the overall system efficiency (Fig. 6).

Fig. 5.
Calculated losses in the pulse-compression system.

Fig. 6.
Energy losses per 500-J output laser driver.

Without resistive losses, a multistage magnetic pulse-compression system can be designed that is 85 to 90% efficient. However, resistive losses can reduce the system efficiency to between 60 and 70%.

Another area of progress is the fabrication of racetrack magnetic cores using amorphous steel (METGLAS). A winding technique and special mandrel have been developed to produce a quality core with interlaminar Kapton insulation. The annealing of an amorphous steel core was completed with the assistance of the Applied Photochemistry Division of Los Alamos, where a special furnace was built. The annealing cycle, to 365°C, created problems with an original aluminum mandrel, which has been replaced with a stainless steel version.

A test tank has been fabricated to conduct initial switching and loss tests next quarter.

NEUTRALIZATION OF H⁻ BEAMS BY MAGNETIC STRIPPING*

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Summary

The stability of H⁻ beams passing through strong magnetic fields has been relevant to accelerator transport problems and, recently, to neutral beam preparation techniques. We have measured the H⁻ electron detachment rate as a function of rest-frame electric field and provide parameters for a theoretical lifetime expression. We discuss the limitations imposed on H⁻ transport by magnetic stripping, and neutral-beam preparation in emittance growth, magnetic fields, and beam energies. Application techniques are also briefly discussed.

Introduction

An H⁻ ion beam passing through a transverse magnetic field B with velocity bc is subject to a rest-frame electric field $E = \gamma cB \times B$. This electric field gives rise to a finite ion lifetime because of the field-induced ion-continuum degeneracy and consequent field dissociation. For ions with energies of hundreds of MeV, the $H^- \rightarrow H^0 + e^-$ dissociation rate can be significant in magnetic fields of the magnitude used for beam transport. This same effect can be put to practical use for neutral-beam preparation.^{1,2}

Stripping Rate

In a recent experiment at LAMPF the electric field dissociation rate was measured over five decades of ion lifetime.³

An 800-MeV H⁻ beam from the LAMPF linac was well collimated and attenuated to countable levels ($\sim 10^4$ s⁻¹) by apertures and thin foils. It then was passed through a special magnet with a region of linearly increasing field, a short constant-field region, and a region where the field decreased rapidly to zero. The magnet could be oriented so that either the linearly increasing or the steeply increasing field was first encountered by the beam. Ions were deflected by the magnetic field until stripped to neutrals. Thus the spectrum of angular deflections could be measured and analyzed to determine the stripping rate. Angular deflections were determined after passing through a 5-m drift space with a multiwire proportional chamber. A scintillation counter telescope and appropriate spatial and temporal cuts of the data were used to improve the signal-to-noise ratios.

The results of the LAMPF experiment span the range from 3 ps to 3 μ s. Combined with the results of G. Stinson, et al.,⁴ the data span the range from 3 ps to 100 μ s. L. Scherk⁵ has expressed the rest-frame lifetime τ of the H⁻ ion as

$$\tau = (A_1/E) \exp(A_2/E), \quad (1)$$

where $E = \gamma cB$ is the ion rest-frame transverse electric field. Experimental results fit this form well; for the combined data sets,
 $A_1 = 2.47 \cdot 10^{-6}$ V·s/m ($\pm 4\%$)
 $A_2 = 4.49 \cdot 10^3$ V/m ($\pm 0.25\%$).

*Work performed under the auspices of the US Department of Energy.

Beam Transport

It has long been recognized that the field stripping of ions sets practical limits on the magnetic fields used for beam transport of H⁻ ions. The dissociation-rate measurements of Stinson et al.³ were made as part of the TRIUMF H⁻ ion cyclotron design effort. The LAMPF measurement² extends the data to rates that were previously unmeasured and confirms the theoretical form predicted by Scherk.⁵

Loss rates in H⁻ beam-transport lines can be expressed as the fraction of the ion beam neutralized when passing through a length in a specified transverse magnetic field. If the ion mean lifetime is given by Eq. (1), then the fractional loss rate is given by

$$\frac{df}{ds} = -f/(\beta\gamma\tau) = (fB/A_1) \exp[-A_2/(\beta\gamma cB)], \quad (2)$$

where f is the unneutralized fraction of the original ion beam and s is the longitudinal coordinate along the beam. The quantity $\beta\gamma\tau$ then represents a stripping length. Figure 1 is a plot of contours of constant loss rate, as a function of ion kinetic energy and bending radius. The figure shows that energetic H⁻ ion accelerators require large bending radii in their transport lines to avoid H⁻ stripping spills.

Fig. 1. Beam-neutralization rate isocontours, as a function of H⁻ ion kinetic energy and bending radius. Contours are for fractional loss rates of 10^{-6} m⁻¹, 10^{-5} m⁻¹, and 10^{-4} m⁻¹.

Neutral-Beam Preparation

Stripping Criteria

The LAMPF H⁻ stripping-rate measurements² were motivated in part by the desire to prepare an 800-MeV neutral hydrogen beam with acceptable emittance increase, caused by the stripping process. Such a beam could be injected into the 800-MeV proton

accumulator ring, now under construction at the Los Alamos National Laboratory, by drifting it through bending and focusing magnets in the ring lattice.¹ This injection method would avoid the substantial ion optical engineering problems associated with the application of a single-step, charge-changing injection method at 800 MeV.

Because of the distribution in the locus of neutralization implied by Eq. (2), an angular spread, as well as a net angular deflection, is induced in the stripped beam. In general, a practical stripper magnet will be designed to accomplish virtually complete stripping in the magnet fringe field. A sufficient criterion for such stripping by a magnet with asymptotic peak field B_0 and maximum fringe gradient B'_m is given by

$$\delta x_{TC} \ll B_0/B'_m, \quad (3)$$

with t_0 evaluated from Eq. (1) at $B = B_0$. Adequate or necessary conditions depend on the field configuration and may be evaluated by numerical integration of Eq. (2). Assuming complete ionization in the magnet fringe, the angular growth is a monotonically decreasing function of the field gradient at which detachment occurs. Neutralization in a linearly increasing field results in an angular distribution, which is closely approximated by a Gaussian distribution with rms angular width σ_0 which decreases with the field gradient B' . This dependence is shown in Fig. 2 as contours of constant rms angular spread for a beam with negligible initial divergence, in a plot of kinetic energy versus inverse field gradient. The energy range spanned by the plot provides approximate limits for which the beam-neutralization technique can be applied. At higher energies, beam transport without substantial detachment losses becomes difficult; at the lower range of energies, reasonable beam divergences are not achievable with practically realizable fields and gradients. Figure 2 shows also the contours of field B_0 at which the peak in the angular distribution originates.

Fig. 2. Isocontours of angular width $2\sigma_0$, and magnetic field B_0 , corresponding to peak rate in angular distribution as a function of beam energy and inverse gradient for a stripping field with constant gradient B' .

Stripper-Magnet Design

A possible stripper-magnet configuration is suggested in the inset of Fig. 3; a second set of (unenergized) pole pieces with the same gap G as the high-field dipole is positioned at a distance D from the magnet. Field solutions obtained by conformal mapping (assuming infinitely permeable pole-piece material) are shown in Fig. 3 for three values of D/G . The maximum field gradient along the midplane axis is given by

$$B'_m = \frac{B_0 \pi}{2G} \quad (4)$$

at a field $B_0/2$ for $D = 0$. As D is increased to G , B'_m decreases by a factor of 0.62 at $0.61 B_0$. For the limiting case of large D (that is, a dipole magnet), B'_m is reduced by a factor of two from Eq. (4), at $0.70 B_0$. In practical magnets, these figures are approximately valid if fields and materials are such that the relative permeability in all parts of the magnet are sufficiently high. The gradients may be enhanced in this configuration by energizing the neutral poles in the direction opposite B_0 .

Fig. 3. Analytical results for axial field of magnet shown in inset, with right-hand pole pieces energized to an asymptotic field B_0 .

Angular Distribution and Beam Emittance

An example of an angular distribution is given in Fig. 4 for a perfectly collimated 800-MeV H^- beam

Fig. 4. Angular distribution of a perfectly collimated 800-MeV ion beam neutralized in the field of Fig. 3 for $D = G = 1$ cm and $B_0 = 2$ T. The rms width $\sigma_0 = 0.37$ mrad.

passing through an ideal magnet, with $B_0 = 2T$ and $D = G = 1$ cm. Such simulations with similar configurations agree well with experimental results and can be used for magnet design. Alternatively, Fig. 2 presents a guide for field specification. The field extent δB over which the gradient should remain high can be estimated from

$$\delta B = \frac{B_0 \rho_0 \sigma_0}{B_s} \quad (5)$$

where B_0 is the beam rigidity. Equation (5) gives the extent of field on either side of B_s , so that 68% of the particles are stripped in $2\delta B$ centered around B_s .

The ion loss-rate expression, Eq. (2), can be numerically integrated for trajectories through a magnet. Figure 4 shows an angular distribution obtained by this method for a beam with initial zero divergence. Such calculations agree well with experimentally observed distributions and can be closely fitted to Gaussian forms. This form permits determination of beam emittance growth in analogy to incoherent thin-target scattering. Characterizing an incident beam of arbitrary distribution and finite rms emittance ϵ by the usual (rms) transport parameters q_{11} , q_{22} , and r_{21} , the angular widths combine quadratically; that is, the post-magnet angular matrix element σ'_{22} is given by

$$\sigma'_{22} = \sigma_{22} + \sigma_0^2 \quad (6)$$

The ratio of the new emittance ϵ' to ϵ can be expressed as

$$\frac{\epsilon'}{\epsilon} = \left(1 + \frac{\sigma_0^2}{\epsilon^2} \right)^{1/2} = \left[1 + \frac{\sigma_0^2}{\sigma_{22}(1 - r_{21}^2)} \right]^{1/2} \quad (7)$$

The two forms of Eq. (7) provide alternate parameterization and are related through the expression for ϵ in the beam matrix elements. Minimization of the relative emittance growth is obtained for smallest spot size at the stripper magnet.

Beam Manipulation

H^- beams are commonly manipulated by producing H^+ or H^0 beams, using stripping foils. The neutral beams may then be passed through magnets without deflection and stripped by a further foil to H^+ .

Magnetic stripping presents an alternative to this technique, with virtually 100% efficiency--assuming that the emittance growth in stripping is tolerable. Additionally, magnetic stripping can be done with very small nuclear depolarization (in contrast to foil stripping) and may be particularly useful in polarized beam manipulation.⁶ For applications where partial stripping is required or sufficiently high fields are not attainable for fringe field stripping, a wiggler magnet configuration may be used to limit beam angular spread.

Conclusion

High energy H^- ion beams will continue to be used in existing and future accelerators. The H^- ion field-stripping rate is now known over a sufficiently wide range of values to calculate transport-line loss rates with good accuracy. It is also possible to calculate the quality of neutral beam that can be prepared by field stripping of ion beams. This has potential applications for charge-charging beam injection and for sharing beam between several lines.

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LOS ALAMOS PROTON STORAGE RING EXTRACTION SYSTEM*

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Summary

The unprecedented peak and average proton currents and extraction rates from the Proton Storage Ring (PSR) under construction at the Los Alamos National Laboratory present new problems in beam extraction. Activation caused by beam spill must be minimal to permit hands-on maintenance. Timing requirements are uncommonly stringent. Solutions to these problems are outlined below.

Introduction

The Proton Storage Ring¹ will be part of the upgraded Weapons Neutron Research (WNR) spallation neutron source. The 800-MeV negative hydrogen ion beam from the LAMPF linac will be accumulated by a novel charge-changing injection technique² and extracted for delivery to the neutron production target. The purpose of the PSR is to change the temporal structure of the LAMPF beam to structures more suitable for time-of-flight neutron measurements while still maintaining high peak and high average neutron fluxes.

Two operating modes are provided. A short-bunch high-frequency (SBHF) mode (for basic nuclear physics research with fast neutrons) accumulates and stores six 1-ns bunches of 10^{11} protons. The bunches circulate at 60-ns intervals. Accumulation occurs for 108 μ s every 8.3 ms with individual bunches extracted at 1.4-ms intervals. This mode presents the most stringent timing requirements of the extraction system.

A long-bunch low-frequency (LBLEF) mode (for condensed matter research with thermal and epithermal neutrons) accumulates a single 270-ns bunch of 5.2×10^{11} protons in 750 μ s every 83 ms. The circulating proton beam is extracted promptly after accumulation. Beam spill allowances for the PSR are set by the LBLEF mode's high currents: 46-A peak circulating current, 105-mA average circulating current, 100- μ A average extraction line current. At the space-charge limit for 46 A circulating current, the beam emittance is $\epsilon_x = 0.7$ cm $\cdot$ mmrad and $\epsilon_y = 2.0$ cm $\cdot$ mmrad.

Figure 1 shows the circulating current beam profile in the middle of a straight section. The beam core is determined by the PSR lattice parameters and momentum spread ($\delta p/p = 4 \times 10^{-3}$). The beam halo, which largely determines beam spill in the PSR and extraction line, is mainly due to the injected beam emittance and beam scattering in the injection stripping foil.

Extraction Kicker

In the SBHF mode the Landau damping time for coherent transverse motion of the bunch is of the order of microseconds. Thus if the extraction of one bunch perturbs the remaining circulating bunches, that coherent perturbation will rapidly become an incoherent growth in beam emittance. A 10% afterpulse ringout in the kicker for a single pass of the beam would double the beam emittance. The extraction timing budget shown in Fig. 2 specifies a 2% afterpulse ringout.

*Work performed under the auspices of US Department of Energy.

Fig. 1. Beam profile including effect of full-momentum bite ($\delta p/p = 0.054$), in middle of straight section, LBLEF mode. For any monoenergetic component of beam $\epsilon_x = 0.7$ cm $\cdot$ mmrad, $\epsilon_y = 2.0$ cm $\cdot$ mmrad, $n_b = 1.92$.

Fig. 2. Pulse for kickers. Amplitude is ± 50 kV across 50 Ω . Risettime plus jitter is less than 29 ns; flat top less twice jitter interval is greater than 31 ns; falltime, jitter, plus ringout to 2% level is less than 29 ns.

Parallel-plate transmission-line electrodes will be used to generate a backward-wave TEM pulse to deflect the circulating beam in the PSR past the extraction septum into the extraction line. This unconventional choice of kicker "magnet" is dictated by the stringent timing and afterpulse ringout requirements for SBHF operation.

Figure 3 shows the parallel-plate transmission-line geometry. The electric field amplitude at the beam is $E = 2V_0/d$ where d is the electrode separation and V_0 is the pulse voltage. For a TEM field $B = Ec$ and the force on a proton with velocity moving opposite to

the pulse is $F = q(E + BcB) = qBcB(1/B + 1)$. For computational purposes an effective kicker magnetic field B_{eff} is used: $B_{eff} = (2V_0/cd)(1/B + 1)$. Values of 50 G to 100 G can be achieved for the PSR parameters ($V_0 = 50$ kV, $\beta = 0.84$, $d = 0.075$ m to 0.14 m).

The pulse power supplies for providing the ± 50 -kV pulses to the kickers are somewhat unconventional (transformer-coupled, pulse-charged power supplies, ferrite-isolated double-Blumlein pulse-forming networks) and have been described in detail elsewhere.³

Fig. 3. Kicker electrode geometry. Pulses propagate opposite to beam bunches; symmetric push-pull excitation results in virtual ground at mid-plane. Matched terminations minimize reflections.

Figure 4 shows the placement of the kickers in the PSR. The 4-m kicker length is set by the timing budget. The kicker aperture is set by the requirement that the center of the beam be at least 3.75 cm from the electrode surface. A conventional current-sheet septum magnet is used. Because of the need to replace the septum with minimum difficulty, none of the current carrying elements are in vacuum.

Extraction-Line Configuration and Constraints

After passage through the septum magnet, the beam is directed onto the WNR spallation target through a transport line whose configuration is determined by LAMPF line D, an existing low-current transport

Fig. 4. Beam envelopes. Note placement and apertures of kickers and septum. Because kicker "magnets" contain no ferrite, they can pass through quadrupoles to include maxima of B_x . One period of PSR lattice is 9.022 m long.

system. The relation of the PSR to line D and the WNR target is shown in Fig. 5. The existing architectural and optical structure of line D imposes constraints on the line design. In particular the point of intersection of the line labeled A in Fig. 5 with line D (sections B-F) is fixed by structural considerations involving the existing line D tunnel. A skew magnet system M1 (15° bend) and M3 (19° bend) is used to orient the beam along section B. From section B the beam path is steered 30° horizontally by magnet M4 through section C and thence through three 30° magnets (M5, 6, and 7) for a vertical approach to the target, T.

Beam spill throughout the transport line is limited by requiring a minimum acceptance of 5 cm·mrad (that is, apertures no less than three times the beam core). The problem of matching the beam to the 7.5-cm aperture of existing magnets M4-M7, as well as the dispersion induced by these magnets, dominates the constraints on beam optics. Additionally, the beam is to be focused within a 2-cm-diam area on the target. The line is required to carry beams containing varied charge densities, with peak currents of 46 A in the LBL mode but must be tuned with low peak currents. Hence space-charge effects have a first-order influence on line optics.

Beam Optics

In addition to having a substantial momentum spread, the extracted beam is described by an initial dispersion in the x (horizontal) direction of magnitude comparable to the vectors bounding the undispersed beam envelope. Specifically, the initial dispersion vector is [0.85 cm, 2.73 mrad] at the extraction point in the LBL mode, for the conditions of Fig. 1. Figure 6 shows an acceptable solution for the extraction-line optics. The first set of four quadrupoles after the lower skew magnet M1 match the extracted beam to a periodic 90° FODO configuration; four quadrupoles are required to accommodate a range of ring tunes and are arranged at optimum separations for this purpose.

The solution in sections B and C is dominated by the requirement of matching to the 90° vertical bend and target. A first-order solution cancels horizontal dispersion at M4 and sets the conditions for a narrow waist through M4 as well as a waist in the 90° bend. A small y dispersion (local vertical) arises from the skew configuration and becomes large in the 90° bend. Solutions that match to the target and cancel the y dispersion in the bend magnets or at the target lead to unacceptably large beam envelopes; an optimum solution, incorporating a partial contribution of dispersion to the target spot, has been obtained with acceptable beam sizes at all points.

Addition of space charge to the beam drastically changes the nature of the solutions. Final optimization makes the target spot size a monotonically increasing function of beam current and emittance. Acceptable spot and envelope sizes are achieved for currents from 0 to more than 70 A. A tuning algorithm for the line has been partially devised to exploit the sensitivities of beam sizes to lens strengths as viewed on beam profile monitors located at critical points in the line.

Other options to the line configurations were considered. In particular, a phase-space rotator would prove useful in manipulating dispersion. Such a device (that is, a solenoid or quadrupole rotator) has proven impractical for our application in terms of device size or beam spreading during the rotation process.

Fig. 5. PSR extraction line configuration. The transport line to existing line D is labeled "A." Beam from P1 follows path ABCD to target T. Line section E bypasses the ring; section F leads to an alternate target. Magnet M2 switches beam to a tuneup beam dump.

Fig. 6. An extraction line solution for 46-A beam current including dispersion. Beam envelopes are shown for the geodesic horizontal (x) direction and local vertical (y) direction versus distance along the beam trajectory. Horizontal-focusing quadrupole singlets are shown as boxes beneath the line in the lower part of the figure; vertical-focusing quads are shown above the line.

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THE NBS-LOS ALAMOS RACETRACK MICROTRON

SUMMARY

In June 1979, the National Bureau of Standards (NBS) and the Los Alamos National Laboratory jointly submitted to the Division of Nuclear Physics, Department of Energy, an original, unsolicited proposal, "Research on CW Electron Accelerator Using Room-Temperature RF Structures." This proposal was accepted by DOE in August 1979, with initial funding to NBS in September 1979 and to Los Alamos in October 1979.

Even at the present early stage of the project, it is already clear that our work is having a major impact on progress toward developing a national high-energy, high-current, high duty factor, electron accelerator. Three groups are preparing designs and proposals for such facilities: the Massachusetts Institute of Technology (MIT)-Bates Linear Electron Accelerator Group report to DOE/NSF Nuclear Sciences Advisory Committee (February 1980); "Facilities Status Report and CW Recirculator Design Study," the Argonne National Laboratory (ANL) report¹; the Southeastern Universities Research Association (December 1980), "Proposal for a National Electron Accelerator Laboratory." Two of the three (ANL and Bates) are studying accelerator designs that employ beam recirculation. Both groups are relying heavily on the NBS-Los Alamos project for the design and development of crucial components and subsystems, including the disk-and-washer (DAW) rf structure, and the entire 5-MeV cw linac injector. We are maintaining close contacts with all three groups, keeping them informed of our progress and results, sharing technical information, and maintaining an awareness of their requirements.

The major effort on the project in the first half of 1981 has been (and will continue to be for two more years) the design and construction of the demonstration racetrack microtron (RTM). The conceptual design of the RTM was completed in the first half of 1980. Important parameters of the machine include 5-MeV injection energy obtained by use of a cw linac, 15 passes through the microtron with a 12-MeV energy gain per pass, 185-MeV final beam energy, and a design cw current capability of 550 μ A. Figure 7 shows the layout of the RTM. During the first half of 1981, detailed designs of major subsystems

design had a measured $Q = 29\,000$ for a six-cell, $\beta = 1$ cavity, indicating an effective shunt impedance $ZT^2 = 90\text{ M}\Omega/\text{m}$. Although this is less than the $100\text{ M}\Omega/\text{m}$ we had hoped for, it is certainly adequate for our needs. These results have led to a final design for the 2.4-m-long preaccelerator structure, which is now under construction. Changes in the DAW design from the original concept include the use of two tee supports (instead of four) for each pair of washers and an increased diameter of the structure (Fig. 8). One effect of these changes is to increase the structure's shunt impedance. Another effect is to reduce the frequencies of a set of transverse modes below that of the accelerating frequency. This set of modes could have interfered with the accelerating mode in a structure with a small diameter and a large number of cells. Figure 8 illustrates the complete preaccelerator structure.

Fig. 8.
Disk-and-washer preaccelerator structure.

Even though the DAW does not have as high a shunt impedance as was originally expected, it does have the advantage of a higher shunt impedance (~ 10 to 15%) than an equivalent side-coupled structure. Another advantage of the DAW is the high cell-to-cell coupling factor ($\sim 50\%$). This high coupling factor makes fabrication easier because each cell does not have to be individually tuned. Also, it will make the structure more stable under the high heating loads imposed by the rf power in cw operation. The structure also has more stored energy than a side-coupled or an on-axis coupled structure; therefore, it will be more stable under heavy beam loads.

THE RADIO-FREQUENCY SYSTEM

The RTM's rf system comprises the following six subsystems: the high-voltage power supply, the 500-kW klystron, the low-level rf system, the personnel and equipment protection system, the WR-430 waveguide system, and the demineralized water system. We discuss each subsystem below.

Two 65-kV, 16.5-A power supplies have been delivered, one to NBS at Gaithersburg, Maryland and one to Los Alamos. Installation is in progress on both supplies. A crowbar enclosure and tester was designed and is $\sim 90\%$ complete. When these power supplies were tested at the vendor's plant, the crowbar circuits did not function properly. The vendor agreed to modify these circuits, as required, at Los Alamos.

Two VKS-8270 klystrons, rated for 500 kW at 2380-MHz, have been built by the vendor. The first klystron developed output window problems and has been rebuilt. Both klystrons have passed acceptance tests for gain, output power, bandwidth, and dynamic gain. One klystron has been received at Los Alamos but has not yet been installed.

The master oscillator module for the accelerator has been designed and built. The other low-level components, such as voltage-controlled phase shifters and variable attenuators, and the 1- and 75-W amplifiers were delivered to Los Alamos. The vendor for the 10-W amplifiers has been unable to meet our specifications and is many months late in delivery of these parts. The 1-W amplifiers failed after only a few hours of operation and were returned to the vendor for repair under warranty. The 75-W amplifiers have been tested and

operate well. Because we have had so much trouble with the low-power amplifiers, an in-house development effort has been started. Preliminary results on the 1-W amplifiers are encouraging.

The personnel and equipment protective system is patterned after that at LAMPF. All associated modules have been built and tested. The largest project was to design and build a high-voltage enclosure and foil tester for the crow-bar unit. This unit is now 90% complete.

The WR-430 waveguide system for the initial klystron testing and cavity testing at Los Alamos has been delivered, except for the 500-kW circulator that is scheduled for delivery in January 1982. Installation of this system is complicated because most of the waveguide is water-cooled. Tap water will be used because the aluminum waveguide is not compatible with the deionized water system. The high-power waveguide loads require large water flows, and the circulator water must be maintained to within $\pm 2^{\circ}\text{C}$ for proper operation.

The demineralized water system will not be ready before November 1981, primarily because of the long lead time needed to procure the required 400-gpm pump. Efforts to expedite delivery of this component are under way, and an alternate source is being investigated. The permanent water system has been designed and all parts are on order. The local-water manifold for the rf-cavity test stand also has been designed and parts have been ordered.

CONTROL SYSTEM

General Configuration

Driven by the twin constraints of a large number of elements to be monitored and controlled and the need for independent development of various control system elements both at Los Alamos and at NBS, a system configuration has gradually evolved in which distributed intelligence plays a key role. The host computer (a PDP-11/44) will be used to do complex data reduction and graphics displays, and will be linked to the primary control station, which is the central control console. Located ~400 ft from the control station, and physically adjacent to the accelerator itself, will be three secondary stations, functionally divided into injector, rf, and magnet control stations. The secondary stations will contain the actual control elements of the system, for

example, Analog to Digital Converters (ADCs), Digital to Analog Converters (DACs), stepping-motor controllers, etc. Each secondary station will contain a data base comprising the units under its control. An image of each of these three secondary data bases will be maintained in the primary control station. Actual control of the system normally will be effected from the primary console, through fast links to the secondary stations. However, during the project's developmental phase it will be necessary to operate each secondary station separately from the primary. This dictates local intelligence for each separate station of the system. We also decided to configure the primary station as a development system and to equip it with sufficient software tools to carry through the project's requirements.

Secondary-Primary Link

Various schemes for linking the primary and secondary stations have been considered and tested, including the Synchronous Data Link Control (SDLC) serial method. This method was eventually discarded because of its complexity, cost, and software overhead. No commercial Multibus board was available that offered this protocol. This necessitated using a custom board, to be developed at Los Alamos or at some other Laboratory (with the associated software and hardware problems), or discarding the method altogether. The latter choice was deemed the wiser, although Computrol now produces a Multibus board with the SDLC protocol, which we may yet use for the primary-host link to the PDP-11/44. Because this board is so complex, there are better options available for the primary-secondary link.

In any communications link, the fundamental choice is between serial and parallel transmission. The serial link offers the advantages of fewer wires, hence lower cost. Noise problems are easier to eliminate but at the cost of decreased speed and serial-to-parallel conversion at each end of the link. The parallel link is intrinsically simpler, because no data conversion occurs at either end, and the transmission speeds are much greater. Loath to design our own Multibus link board, we investigated available commercial boards that implement serial links, and we found them all wanting in one respect or another. The optical couplers available for such commercial boards were so slow (typically less than 2400 baud) that extensive modification of the boards was necessary to bring them up to the performance standard required by our

system. The commercial boards, Universal Synchronous Asynchronous Converters, are limited (for asynchronous transmission) to 9600 baud and below. Reasoning that a well-designed custom board was preferable to a modified commercial board, we designed our own parallel link, which turned out to be simple enough to allow all secondary binary (Input/Output) read-and-control circuitry to be on the same Multibus board. We eliminated the speed problem with the optical couplers by replacing them with differential line drivers and receivers. The physical link between the secondary and primary stations is now an 18-conductor cable of No. 22 wire.

Each secondary station will be linked separately to the primary in a star configuration. The link boards for both the primary and secondary stations have been designed, prototyped, and tested. Under worst-case conditions, the system permits error-free transmission of an 8-bit byte every 10 μ s across the link. Were higher speeds ever needed, it would be simple to add a Direct Memory Access (DMA) controller and block transfer data at higher rates--an option, incidentally, that would be precluded by a serial scheme.

Secondary Station

The secondary station consists of a video terminal with keyboard and a power supply for the Multibus crate. The 12-slot Multibus crate contains two single-board computers (SBCs), the custom-panel interface, core memory for the data base, ADC and DAC boards as needed, and custom stepping-motor driver boards as needed. The custom panel, with two infinite-turn knobs and interrupting push button, provides the main control for the secondary station.

Two SBCs were used in the secondary station to divide, and thus simplify, the software tasks. Despite apocryphal assertions to the contrary, a single SBC is quite limited in the speed with which it can perform a large number of tasks; the contradictory demands of immediate interrupt service and rapid data-base update argue convincingly for separate SBCs for these two tasks. The simple processor (\$500), which updates the data base and provides the DAC control signals on a continuous basis, operates independently from the rest of the system and eliminates the need for executive software control of these functions. The remaining SBC is an Intel iSBC 80/24, which updates the local display from the data base and services interrupts from the control panel and from the primary data-link request line. When the primary station requests

data from the secondary or ships a control signal to it, the request is handled with top priority by the secondary station, thus permitting knob control from the primary station. Any knob response time greater than ~ 100 ms leads to operator annoyance; this response time has been our design criterion for link response. Local control is effected through the two control knobs and push-button switches, effectively eliminating arcane dialogue through the keyboard. The left-hand control is used for scrolling through the data base to select the active line, which is controlled by the right-hand knob. Both control knobs drive the software through interrupts, guaranteeing timely response without the need for a repetitive sync pulse or a wait loop. The eight push buttons along the top of the control panel select the function desired by the operator. Generally, these push buttons effect the display of information, but two of them permit the operator to enter and execute a special interpretive code in the secondary station. This capability is discussed in more detail in the section on software. Below the function buttons, the four push buttons form a status register that selects the desired units display. Thus, from the secondary-station control panel, the operator can select the data-base segment he desires to display, in whatever units he desires, and can control the output to whatever setting he selects. Data-base entries are made through the keyboard; otherwise, the keyboard generally is not used.

Many stepping motors are used in the control system to effect changes in the phase and amplitude of various rf signals and to control water-system valves, etc. The control of these stepping motors is provided through a custom Multibus board that contains logic to control four stepping motors per board. The actual control element is a CY500 chip that can be programmed by the SBC for independent control of the stepping motor. Limit-switch logic for each motor prevents overshoot on the control and provides a fiducial for calculation of the control function. In this sense, each CY500 is effectively a coprocessor to the SBC. The board has worked well and has been produced on a commercial printed-circuit board.

Software Development

Adding a dual floppy-disk drive and controller to the secondary-station system effectively turned it into a software-development system. However, this advantage was purchased at the cost of much agony and irritation in getting the

system up and running, because the manufacturer was unable to supply the promised software. After the necessary software drivers were written and debugged, the system functioned as hoped, running the Control Program for Microcomputers (CP/M) operating system and providing editors, assemblers, and compilers as promised. Currently, we have compilers for FORTRAN, BASIC, C, and PASCAL; additional software is very inexpensive. Much of the display secondary software has been written, which permits knob control of the data base at the secondary station. An interpreter is currently being written that will provide the operator/engineer with local "programming" capability to the extent of loop control, etc. This interpreter is roughly half complete. The drivers for the ADCs and DACs have been written.

To date, the operating software has been written in Intel 8085 assembly-language code, but the C compiler is up and running, and we anticipate higher level code development for the primary station. The codes to update the data base have been blocked out, and the secondary-station executive has been flow charted extensively.

Host Computer

The PDP-11/44 minicomputer has been delivered to NBS and installed in the RTM control-room area. Installation of this computer, including the vendor software, was completed in June. It has a moderately fast CPU with a floating-point processor and 8-kbyte cache memory, a 256-kbyte main memory expandable to 1024-kbyte, two 10-Mbyte disk drives, two 256 kbyte cassette drives, and a 120-character/second console terminal. The software supplied by the vendor consists of a multiuser-disk operating system, utilities, assembler, and optimizing FORTRAN compiler. A telephone link between the PDP-11/44 and the NBS Univac computers is being set up so that program and data files used for RTM design calculations may be transferred for use on the minicomputer.

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RADIO-FREQUENCY QUADRUPOLE LINEAR ACCELERATOR

SUMMARY

Our development of the radio-frequency quadrupole (RFQ) linear accelerator continues to stimulate interest for many possible applications. Frequent contacts from other laboratories have revealed a wide acceptance of the RFQ principle in solving low-velocity acceleration problems. We have completed final RFQ beam-dynamics designs for Los Alamos programs and for the European Organization for Nuclear Research (CERN) new injector system. In addition, we have made preliminary beam-dynamics designs to assist several other Laboratories in making decisions concerning RFQ use.

FINAL BEAM-DYNAMICS DESIGNS

Final designs have been completed for two RFQ accelerators. These are for accelerator technology development at Los Alamos and for a new injector system for CERN. Table VI summarizes the RFQ parameters; the rf power was estimated using an approximate formula for the four-vane resonator. Results from the formula were multiplied by 1.5 to account for actual copper losses and for losses in the coaxial manifold that feeds rf power into the four-vane resonator. Finally, the beam power was added to obtain the peak-power values listed in the table.

For the Los Alamos program, we have designed an RFQ to accelerate 100 mA of hydrogen ions from 0.10 to 2.0 MeV in 2.89 m.¹ The main emphasis was to limit to a very small value the radial emittance growth during acceleration. With a 110-mA beam into the RFQ, multiparticle beam-dynamics simulation programs have estimated this growth to be a factor of from 1.20 to 1.29.

For CERN we have developed an RFQ to accelerate a 100-mA beam of protons from 50 to 520 keV in 1.38 m.² This RFQ has been accepted by our CERN collaborators; based upon its characteristics, they have produced mechanical designs for their 200-MHz four-vane resonator. The vanes will be shipped to Los Alamos in late July, and we will then use the numerically controlled (NC) mill to machine the pole-tip contours.

TABLE VI

RFQ DESIGN PARAMETERS

	<u>Los Alamos</u>	<u>CERN</u>
Ion	H^-	H^+
Frequency (MHz)	425	202.56
Input energy (MeV)	0.10	0.05
Output energy (MeV)	2.00	0.52
Nominal current (mA)	100	100
Transmission efficiency (%)	91.4	93.6
Output emittance ^a	0.021	0.05
Length (m)	288.6	138.2
Peak rf power (kW) ^b	1020	304

^aRMS normalized area/ π in cm-mrad units.

^bIncludes power required for the rf manifold and for the beam.

PRELIMINARY BEAM-DYNAMICS DESIGNS

After the successful proof-of-principle (POP) test, there has been a rapidly increasing interest in the RFQ. We continue to be asked by many Laboratories to provide guidance for RFQ use in existing or proposed accelerators. We include here some of the new RFQ design examples that have been generated in response to these requests.

RFQ for Polarized H^- Injector at AGS

In response to a collaboration from ANL and Brookhaven National Laboratory (BNL), we have generated RFQ design examples that would be suitable for a polarized H^- injector into the 200-MHz Alvarez linac at the BNL AGS. The characteristics of the most attractive design example, called BNL2, are listed in Table VII. The 22-MV/m peak surface field corresponds to ~ 1.5 times the

TABLE VII

RFQ DESIGN PARAMETERS

	<u>BNL2</u>	<u>OAK5</u>	<u>N141</u>	<u>TBR1</u>	<u>TEX8</u>
Ion	H ⁻	H ⁺	¹⁴ N ⁺	³ H ⁺	² H ⁺
Frequency (MHz)	201.25	40	25	150	11
Input energy (MeV)	0.02	0.20	0.10	0.20	0.0007
Output energy (MeV)	0.75	5.0	14.0	5.0	0.020
Nominal current (mA)	0.1	2000	150	330	0.1
Transmission efficiency (%)	100	91	88	95	97
Output emittance ^a	0.011	0.81	0.055	0.074	0.026
Length (m)	123.4	14.4	22.4	7.0	2.4
Peak rf power (kW) ^b	66	16 300	2690	5000	1.0

^aRMS normalized area/ π in cm-mrad units.

^bIncludes power required for the rf manifold and for the beam.

Kilpatrick limit. The 20-keV injector energy is chosen to match the 20-keV output energy of the ANL polarized H⁻ source. Although the nominal beam current is 0.1 mA from the polarized ion source, this design could provide good performance with the high-intensity H⁻ source as well. For example, the PARMTEQ simulation for a 30-mA H⁻ input beam current predicts a transmission of over 96%.

RFQ for High-Intensity Oak Ridge Accelerator

We have generated an RFQ design, in response to a request by Oak Ridge, to evaluate the maximum proton charge per micropulse that could be accelerated to 200 MeV in a single linear-accelerator channel. Table VII lists the characteristics of this design, called OAK5. The motivation behind this request by Oak Ridge is to evaluate the feasibility of replacing the existing electron-accelerator neutron source (ORELA) with a (p,n) source to gain more neutron intensity. The RFQ would serve as an injector into an Alvarez linac.

RFQ for Plasma Heating by Positive Light Ions

An RFQ design for plasma heating, called N141, was generated at the request of BNL. It accelerates positive nitrogen-14 ions to 1-MeV/nucleon and uses a peak surface field of 20 MV/m at 25 MHz. This design was used to help evaluate the feasibility of an alternate plasma-heating scheme that uses charged light ions. Table VII summarizes the parameters and performance characteristics.

RFQ for Tritium-Breeding Accelerator

At the request of BNL an RFQ design was generated to evaluate the feasibility of an accelerator system to breed plutonium using high-energy protons. This design is called TBR1 and is summarized in Table VII. The peak surface field is 26.4 MV/m, which is ~ 2 times the Kilpatrick limit at 150 MHz. The output beam from this RFQ would be injected into an Alvarez linac for acceleration to higher energy.

RFQ for Cyclotron Axial Beam Buncher

An RFQ design, called TEX8, was made to demonstrate how an RFQ could be used as an axial injector for a cyclotron.³ Table VII shows the characteristics of this RFQ. In this design example, 90% of the beam is bunched to within $\pm 15^\circ$ in phase.

The RFQ acceleration structure would be driven by an rf voltage source as a capacitive load consisting of four metal vanes mounted on insulators. By use of an accel-decel extraction system and an electrostatic lens, an ion beam from existing ion sources could be focused into the entrance of the four vanes at an energy of 0.4 to 1 keV/nucleon. The four vanes of the RFQ structure would then focus the beam through the structure, accelerate the ions to the required injection energy for the cyclotron (10 to 15 keV/nucleon), and adiabatically compress the ions into small bunches suitable for use in the cyclotron accelerating system.

If the RFQ is powered at the same frequency as the cyclotron and the exit end of the structure is located near the axial inflector of the cyclotron, almost all of the continuous ion beam extracted from the ion source can be

injected into the cyclotron within the rf phase acceptance of the cyclotron. This RFQ should provide an increase of 2 to 5 times the current captured by the cyclotron compared to that captured by the commonly used single-gap buncher system. In addition, the very small energy spread of the ions leaving the RFQ should improve the beam transport through the cyclotron during acceleration.

PROGRESS IN RFQ DESIGN TECHNIQUES

Pole-Tip Geometry Errors

For the Fusion Materials Irradiation Test (FMIT) prototype RFQ, we have studied the accuracy with which RFQ vanes must be positioned longitudinally with respect to each other. If errors in longitudinal positioning are present, they will alter the electric potential distribution and the corresponding electric fields. To investigate this type of error, we constructed a model⁴ to calculate the potential of a three-dimensional distribution of point charges that simulate an RFQ. From this study we concluded that if the vanes were positioned relative to each other longitudinally, with an accuracy of 0.13 in., there would be very minimal effect upon the performance.

Radial errors were also studied by scaling a POP RFQ error study.⁴ We concluded that if the radial position of the FMIT RFQ pole tips were accurate to ~ 0.03 in., there would be no appreciable degradation of the beam parameters. The sideways positioning of the vanes is expected to be accurately determined by rf tuning procedures used to balance the fields in the four quadrants.

Field Enhancement at Vane Gaps and Ends

Good performance of an RFQ accelerator requires that it be designed with high surface electric fields. These field levels are sufficiently near the electric breakdown limit that care must be taken not to further enhance the surface fields. In making long RFQ vanes it is often necessary to machine two or more lengths and fit them together. We have studied the electric-field enhancement produced by small gaps between two adjacent vane sections.⁵ The two-dimensional electrostatics program CHARGE was used in a manner that closely

approximated the three-dimensional problem. We used a variety of vane separations and radii of curvature on the corners of the vane ends. However, under the best circumstances the surface fields were enhanced by a factor of from 1.2 to 1.3. In most cases this is unacceptable, and the vane sections must be joined with no gap between them. This study also showed that rounding the corners of vane ends, where no other metal surfaces are nearby, will suitably control the field enhancement.

Improvements in RFQ Design Programs

A new computer code, called Initial Matching Section (IMS), has been written for generating matched-beam input parameters for the radial-matching section in RFQ designs. The smooth-approximation solutions are used, together with a simple space-charge model consisting of a uniform charge distribution within a cylinder, to obtain approximate values of the average β -function over an rf period. A matched-beam ellipse within the RFQ is then obtained by successive iterations for each of a set of equally spaced rf phases. Then for each phase, the corresponding matched ellipse at the output of the radial-matching section is transported backward through the radial-matching section, using the usual transport-matrix formalism. In this procedure, the radial-matching section is divided into a large number of segments, and each segment is represented by a transport matrix. An average over rf phases is then made for the resultant beam-ellipse parameters at the input to the radial-matching section. Thus, we obtain the required values of α and β for the dc input beam, which will optimize the RFQ acceptance. The inclusion of this program in the RFQ design procedure has greatly reduced the time required to simulate with PARMTEQ the performance of a given design.

THE I-R 100 AWARD

The Los Alamos National Laboratory has been granted the 1981 I-R 100 Award for development of the RFQ linac structure. This award is given to a hundred significant newly developed products by the publication Industrial Research and Development. The award will be presented on September 24, 1981 at the Museum of Science and Industry, Chicago, Illinois. The RFQ POP resonator will be on

exhibit at the Museum September 25 through October 18. After that, the RFQ will be placed on permanent exhibit in the Los Alamos Bradbury Science Museum.

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HEAVY ION FUSION

SUMMARY

Recently, proposals to investigate the feasibility of heavy ion induced fusion for commercial power production have generated interest in large linear-accelerator systems. The low-velocity part of these systems tends to be one of the serious overall limitations. The RFQ, which can be constructed in a special manner for low frequencies, appears to offer an attractive solution to this low-velocity problem.

In recent work on heavy ion fusion we have developed ideas for funneling of beams from RFQ linacs; the funneling process is explained below. We have also begun preliminary studies of RFQ resonant cavities.

RFQ DESIGNS

The 12.5-MHz Xenon RFQ Designs

- We have used improvements in our design algorithms to generate a new design, which we refer to as HIF5. The parameters and performance characteristics for this design are presented in Table VIII. The peak surface field assumed was 20 MV/m. This example shows that at 12.5 MHz a beam current of 50 mA can be bunched and accelerated in a single channel, provided that the peak surface field of 20 MV/m can be obtained and provided that the injection energy is at least 300 keV. More details of this design were reported at the 1981 Particle Accelerator Conference.¹

A second Xenon RFQ design, called ANL6, was done at the request of ANL for a possible second low-velocity accelerator for their heavy ion fusion accelerator program. The parameters and performance are presented in Table VIII. This design example assumed a more conservative peak surface field of 17.5 MV/m.

TABLE VIII
RFQ DESIGN PARAMETERS

	<u>HIF5</u>	<u>ANL6</u>	<u>HIF6</u>
Ion	Xe ⁺¹	Xe ⁺¹	Xe ⁺¹
Frequency (MHz)	12.5	12.5	2.7
Input energy (MeV)	0.30	0.25	0.30
Output energy (MeV)	10.0	3.0	10.0
Nominal current (mA)	50	30	275
Transmission efficiency (%)	93	97	98
Output emittance ^a	0.011	0.009	0.09
Length (m)	27.7	15.5	14.2

^aRMS normalized area/ π in cm-mrad units.

The 2.7-MHz Xenon RFQ Designs

A computer program (CURMAX), which chooses the design frequency to maximize the beam current in an RFQ, was used to generate a Xe⁺¹ RFQ with maximized beam current. Table VIII lists the parameters and performance for this design, called HIF6. A peak surface field of 20 MV/m was assumed. The increased beam current and the reduced length, as compared with the HIF5 design, result from lowering the frequency from 12.5 MHz to an optimized value of 2.7 MHz. This result shows that significant improvements should be possible in the low-beta linac if the frequency can be lowered from the values previously considered.

Low-Frequency Structures

For frequencies below ~20 MHz, the four-vane RFQ cavity radial dimensions become so large that problems arise in fabrication. An initial study of

RFQ resonant-cavity structures has been made to identify those that are more attractive for low-frequency applications. A preliminary conclusion of this initial work is that both the spiral-resonator structure and a modified split-coaxial structure warrant further quantitative study to evaluate their size, mechanical properties, and power efficiency. A lumped-circuit model was used to compare the properties of a variety of transverse-electric-mode resonators. The application of this model for various types of transverse-electric-mode RFQ cavities of a fixed frequency suggests an approximate inverse relation between the required power and radial dimensions.

FUNNELING OF ION BEAMS

In the rf linear-accelerator approach to heavy ion fusion, an essential component is a device to combine charged-particle beams. To produce a final beam of high energy and high current, the linear-accelerator system must start with multiple low-frequency linacs each having a low-current beam. Pairs of these beams can then be combined into single beams that are suitable for further acceleration in a linac operating at twice the frequency. This process, called funneling, combines two bunched beams by deflecting interlaced micro-structure pulses until they are collinear. Time-varying deflection systems are required, and (in principle) funneling can be accomplished with no emittance increase, so that the radial brightness of the final beam is doubled after each funneling operation. By repeating this process, a single final beam of the required intensity and energy can be produced.

In the funneling process many requirements must be met. While the two beams to be combined are undergoing suitable deflections to make them collinear, the radial focusing must be maintained, and the beams must not be allowed to debunch. A new approach has been suggested^{*} that uses the RFQ as a deflector. The RFQ pole-tip shape is modified to generate an electric dipole field that produces a first-order transverse force on the beam pulses. While

^{*}This information was supplied by G. N. Minerbo, Los Alamos National Laboratory, Accelerator Technology Division, Group AT-1, "Notes on Funneling Systems," January 16, February 12, February 17, 1981.

the beam is being deflected, the bunching and focusing functions of the RFQ are maintained. After the two beams are deflected toward each other, another deflection is required to make them collinear. We are examining other special forms of the RFQ structure to see if they are also suitable for this purpose.

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PIGMI PROTOTYPE-ACCELERATOR PROGRAM

SUMMARY AND STATUS

To test as many aspects as possible of a fully integrated low-energy portion of a Pion Generator for Medical Irradiation (PIGMI) accelerator, a prototype accelerator was designed to take advantage of several pieces of existing accelerator hardware. The prototype design includes a 30-keV injector coupled to an RFQ that in turn injects beam at 1.5 MeV into a drift-tube linac (DTL) having a 4.2-MeV final energy. The important principles to be tested in this prototype accelerator include the following items.

1. Beam matching into the RFQ at 30 keV, using a single einzel lens.
2. High-surface-field (2 times the Kilpatrick limit) operation of an RFQ.
3. Resonant rf-power coupling between an RFQ and a DTL.
4. Beam matching between an RFQ and a DTL.
5. Operation of a permanent-magnet loaded DTL at high electric-field gradients.
6. Verification of the engineering, fabrication, and assembly procedures for all accelerator components. The engineering design has been completed and fabrication of all of the accelerator components initiated.

PIGMI 30-kV INJECTOR

A new duoplasmatron ion source and 30-kV proton injector for the PIGMI prototype accelerator were constructed and tested. The new duoplasmatron uses the same filament, intermediate electrode, plasma aperture, and expansion-cup geometry as the previous source, but has a much smaller anode housing and a more simple packaging of the magnetic coil and water-cooling. The magnetic circuit was scaled down to give the same magnetic field between the intermediate electrode and anode with only a small increase in the number of ampere turns in the coil. The initial tests of this duoplasmatron were completed on the MP-Division ion source test stand. For these tests, the accelerating voltage was 112 kV with a 30-kV extraction voltage across a 1.27-cm extraction gap. The source ran successfully at 60 Hz with a 300- μ s pulse width at 33-mA

extracted current. Under standard LAMPF operating conditions, the source produced a 25-mA beam with an $\sim 90\%$ proton fraction. The normalized emittance under these conditions was 0.04π cm·mrad with a 2% threshold on the measured data.

The focus electrode and extractor electrode shapes for the 30-kV injector were designed with the computer code SNOW¹. The 1.5-cm-gap design gave a 34-mA convergent beam with a 30-kV energy. Because the beam energy is so low, a standard unipotential three-element einzel lens was designed to focus the beam from the injector into the PIGMI RFQ accelerator. Figure 9 shows the optics of the final design for the extraction and the transport systems.

Figure 10 shows the layout of the ion source and the transport system within the injector. A turbomolecular pump located near the ion source efficiently pumps the ion-source gas load. The low-energy-transport chamber houses the einzel lens, the insertable diagnostics, and the steering magnets. This chamber is designed to bolt directly to the accelerator (Fig. 10) and will be pumped by the accelerator vacuum system. This arrangement, coupled with the small apertures between the various regions, will allow differential pumping and a large pressure difference between the accelerator and the ion source.

The equipment cabinet (Fig. 11) is a self-contained system for operating the injector. The complete high-voltage region has been enclosed in an interlocked and grounded cabinet. This cabinet contains the high-voltage isolation transformer, the power supplies for the steering magnets, the turbomolecular pump, and the einzel lens. In addition, the master timing circuit for the injector and accelerator, the oscilloscope for monitoring the ion-source arc, the injector ionization-gauge controller, and the interlock monitor also are located in the cabinet.

Fig. 9.
Beam profile for the PIGMI injection system.

Fig. 10
PIGMI 30-kV injector assembly.

Fig. 11
Ion source and associated equipment.

The entire injector and beam-transport system has been assembled and successfully tested. The typical operating parameters for the system are listed below.

Arc voltage	120 V	Gas flow	1.0 cc/min
Arc current	20 A	Arc chamber pressure	180 microns
Arc magnet current	0.9 A	Column pressure	6×10^{-6} torr
Filament current	30 A	Einzel-lens voltage	0 to 32 kV

The injector, operated at 60 Hz with a 75- μ s pulse width, produced a 25-mA beam at a potential of 31 kV. The current increased to 30 mA at 33 kV, indicating that the extraction gap should be shortened by a small amount to obtain the required current at 30 kV. Emittance scans made at 31 keV with a 25-mA

beam yielded a normalized emittance of 0.039π cm•mrad for about 96% of the beam, a value in excellent agreement with the emittance measured on the MP-Division ion-source test stand. After 1 day of operation, the plasma oscillations on the beam and arc current observed in the earlier tests disappeared; operation then became stable and reproducible.

PIGMI PROTOTYPE RFQ

The POP RFQ accelerator tested in February 1980 was designed with removable vane tips. To take advantage of the successfully tested RFQ resonator and manifold cavity, new vane tips having the same length were designed to be installed in the existing resonator. The geometry of these vanes was designed to accept a 30-keV dc beam with a nominal 32-mA current, then bunch and accelerate it to a final 1.5-MeV energy. A vane length of 110.78 cm was chosen to fit within the existing resonator cavity. A maximum surface field of 40.6 MV/m, corresponding to ~ 2 times the Kilpatrick limit at 440 MHz, was based on previous experiments with the POP RFQ in which fields in excess of this value were obtained. The design parameters for the prototype RFQ are summarized below.

Frequency	440 MHz
Ion	H^+
Number of cells	171
Length	110.78 cm
Vane voltage	69.92 kV
Average radius, r_0	0.233 cm
Final radius, a_f	0.139 cm
Initial synchronous phase, ϕ_i	-90°
Final synchronous phase, ϕ_f	-30°
Estimated peak rf power	193 kW
(including RFQ, manifold, and beam)	
Nominal current limit	67 mA
Nominal acceptance at 32 mA	0.10π cm•mrad (normalized)

The radial, phase, and energy profiles as calculated by the beam dynamics program PARMTEQ are shown in Fig. 12.

New copper vane tips were machined for installation into the POP resonator. Meanwhile, in preparation to receive the vane tips, the POP cavity was chemically cleaned to remove braze blush or other surface oxides. This treatment apparently spoiled the Q of the cavity enough to make it unusable; thus, plans to make beam tests of the prototype accelerator were abandoned.

PIGMI PROTOTYPE DTL

The prototype DTL accelerates beam from 1.5 to 4.135 MeV in 61 cm. The DTL section has 12 cells and an axial electric-field gradient of 6 MV/m. Each drift tube is designed to contain a 1-in.-long permanent-magnet-quadrupole lens having a 20-kG/cm magnetic gradient.

All engineering and design work has been completed for the prototype DTL, and fabrication of all components is in progress. The tank was fitted with a strongback bolted along the bottom to support the drift tubes. The bottom was precision bored to accept the drift tubes before being shipped to be copper plated. The drift-tube cooling jackets were completed and leak checked; final assembly now is in progress.

All samarium/cobalt magnet pieces to make fifteen 1-in. quadrupoles have been received and sorted. Two magnet assemblies have been completed and their field quality measured, using a rotating coil and frequency analyzer. The field quality of these first two assemblies is very good. Because beam tests of the DTL are not now planned, assembly of the remaining magnets has been postponed, and the drift tubes will be assembled empty.

Fig. 12
Beam profiles for the PIGMI DTL.

A waveguide feeds rf power into the RFQ manifold. We have designed a resonant cavity between the manifold and the DTL tank to couple power into the DTL. This coupling cavity has been fabricated and is ready for low-power tests.

DAW COLD-CAVITY ASSEMBLIES

Cold-cavity assemblies of DAW structures for $\beta = 0.5, 0.6, 0.7,$ and 0.8 were designed for tests at 2300 MHz. Each assembly consisted of ten washer pairs, a mockup of a coaxial bridge coupler, and the end terminations. These assemblies have been fabricated and assembled.

RFQ CONTACT TESTS

In second-generation RFQ resonators it is important to improve and broaden our ability to make rf contact joints between the vanes and the inner surface of the resonator housing. Four RFQ resonators were fabricated to test a variety of rf contact designs. One of these had the four vanes brazed to the outer wall, and this resonator served as a reference for Q-value measurements. Two other rf-joint designs have been constructed and tested. One had a clamping arrangement for various types of deformable wires. The other had a groove containing a copper-plated C-seal. The C-seal allows the vanes to have a certain range of tilting and radial movement. Both the wire-seal and the C-seal designs had acceptable Q-values when compared with the brazed resonator. Other rf-joint designs are now being fabricated for future testing.

RFQ VANE-TIP FABRICATION

In theory, RFQ pole tips have well-defined shapes as specified by the lowest order potential function. In practice, the pole tips conform to the theoretical surface in position and radius of curvature at the midplane but have circular cross sections to facilitate their manufacture by computerized NC milling machines. A generalized procedure has been developed for machining

vane tips for structures of any frequency. Because of the various RFQ projects within AT Division, a state-of-the-art milling machine has been leased by the Division to fabricate vane tips. The procedure developed for machining the PIGMI vane tips has since been successfully used to machine vanes for three additional projects at three different frequencies.

PIGMI APPLICATIONS

During the past 5 yr of the PIGMI program at Los Alamos, all accelerator technologies required to build a practical pion-treatment facility have been developed or identified. Likewise, there have been on-going clinical trials with pions in at least three major scientific research centers in the world. All clinical trials in the world to date still represent a statistically insignificant quantity of data on which to base conclusions concerning the effectiveness of pion therapy in cancer treatment. Most medical authorities concur that its effectiveness cannot be judged until there are medically dedicated pion-producing facilities at one or more major medical centers. To date, no monies have been identified to pursue the construction of such a facility.

ACCELERATOR FOR RADIOISOTOPE PRODUCTION

Nuclear medicine provides cost-effective, noninvasive, dynamic-function information, clinically useful in diagnosing human diseases. Accelerator-produced nuclides (for example, ^{201}Tl , ^{67}Ga , ^{111}In , ^{123}I , etc.) are gaining in importance in nuclear medicine, and by 1983 there will be a total of 22 accelerators in industry and at medical institutions in the United States devoted to medical radionuclide production. However, some useful nuclear reactions require energies exceeding those available from these accelerators. Some large accelerator facilities (LAMPF; Brookhaven Linac Isotope Producer; Negative Ion Cyclotron Facility in Vancouver, British Columbia, called TRIUMF) are producing usable amounts of difficult-to-obtain radionuclides (^{68}Ge , ^{77}Br , ^{82}Sr , ^{127}Xe , etc.); however, it is doubtful that these research facilities can routinely supply large amounts of the short-lived nuclides ($T_{1/2} \approx 10$ days) to the medical community.

A proton accelerator that could deliver 200 μ A or more at a 70-MeV energy would be a valuable asset to the nuclear-medicine community. The PIGMI technology can be readily applied to a design of an accelerator for radioisotope production.

The size, cost, and parameter range for a linear accelerator designed to be competitive in the radioisotope market are dictated to a great extent by the availability of commercial rf sources. The PIGMI design is based on a readily available 440-MHz klystron designed for military radar. In addition to the rf power supply that would include two or more klystrons, the accelerator would include three additional major components: a 30-keV proton injector, a 2-m-long RFQ structure to bunch and accelerate beam to 2.5 MeV, and a permanent-magnet quadrupole-loaded DTL. Each of these accelerator components has been designed, built, and tested at Los Alamos under the PIGMI program.

Because most of the rf power in linear accelerators is dissipated in the structure itself, a relatively small amount of power actually goes into accelerating beam. Once the power requirement is met for exciting the structure, however, all additional available power can be put to use accelerating protons. Although linear accelerators are well known for their ability to accelerate high beam currents, they tend to be very inefficient at low currents. The lowest practical average current compatible with the PIGMI design is 500 μ A. At 70 MeV, this amounts to 35 kW on target.

The construction and operating costs of such an accelerator are dominated by two of its components: (1) the power and duty factor available from the klystrons and (2) the length of the DTL structure. The installed cost for the DTL (including salaries) is estimated to be \$66 K/m, whereas the installed cost for the rf power is estimated to be \$385 K per klystron stand, or about the equivalent of 7 m of linac structure. The power requirement is proportional to the design electric accelerating gradient so that short linacs require large amounts of power, but longer structures tend to be more economical to operate.

A 500- μ A 70-MeV PIGMI accelerator designed to optimize construction costs would be 20 m long and would have an installed cost (accelerator only) of \$2.6 M. The total ac power required to operate the linac would be 650 kW. The peak beam current would be an adequate 18 mA. At the expense of increasing the initial cost, a linac can be designed to operate at a reduced power level by increasing both the structure length and the peak beam current. An accelerator design requiring only 375 kW of ac power would be 27 m long and would

have an installed cost of \$3.0 M. The peak beam current would be 28 mA. A specific design would depend upon siting considerations and the relative cost of power and venture capital.

In the second design, if one klystron should fail there would be enough reserve power in the remaining two to continue operation at the 200- μ A level. In addition, by using all three klystrons there would be enough reserve power to accelerate a total of 2 mA of beam, thus providing a maximum capability of 140 kW on target without increasing the peak beam current.

PIGMI TECHNOLOGY TRANSFER

As part of its charter, the PIGMI program has attempted to transfer into industry much of the accelerator technology developed during the program. Representatives from thirty-one companies attended a Technology Transfer Briefing held in February. Presentations by the AT-Division staff on various aspects of PIGMI technology included the following topics.

The RFQ Linear Accelerator	Linac-Structure Fabrication
Applications of the RFQ	Injector Systems
The rf Power Sources	Applications of PIGMI Technology
The PIGMI and RFQ Accelerator Test Facility	

The industry representatives were invited to visit our laboratory facilities to see systems built and tested under the PIGMI program. They also were invited to take advantage of the offer to transfer technology through a variety of programs already established by Los Alamos for that purpose. These mechanisms include cooperative or collaborative programs, assignment of industrial staff members to Los Alamos programs, technical seminars by the Laboratory staff for industrial audiences, Laboratory subcontracts, and technical-assistance programs.

REFERENCE

1. J. E. Boers, "SNOW - A Digital Computer Program for the Simulation of Ion Beam Devices," Sandia National Laboratories report SAND 79-1027 (August 1980).

THE GYROCON RADIO-FREQUENCY GENERATOR PROJECT

SUMMARY AND STATUS

The Los Alamos prototype gyrocon was extensively tested and modified during the reporting period. The first tests produced essentially no rf output power, with several hundred kilowatts of beam power. Subsequent investigations revealed that the beam was well centered on its mechanical axis but was diverging in the deflection cavity. The input cavity was multipactoring severely, and the cathode was slowly losing its emission capability. A phosphor screen was designed and built to replace the conical bender solenoid. The gyrocon was modified by closing the vacuum valve between the electron gun and the deflection cavity (Fig. 13) and by removing the conical bender magnet. An insertable titanium evaporator was built and installed to replace the bender solenoid. This evaporator could be rotated with the system under vacuum, so the whole deflection cavity could be coated with a thin titanium film. Then the evaporator was replaced by the phosphor viewing screen, which was located where the lowest point of the conical bender normally is located. The gyrocon was then operated with the viewing screen in place. By this time, the cathode was capable of emitting only 2 A, rather than the design value of 9 A. The 15-cm-diam screen, which had

Fig. 13.
Cross section of the prototype gyrocon.

a copper aperture plate in front of it, was completely illuminated by the dc beam, indicating that the beam diameter was much too large. When the screen was moved vertically, the beam was found to be diverging.

Two of the Los Alamos electron-gun codes were run to simulate this experiment; for beam currents below 5 A, the beam was overfocused and formed a crossover in front of the deflection cavity. Thus, the beam is quite divergent in the region beyond the deflection cavity. Experimentally, higher currents in the gun-focus coil intensify the image at the screen. The gun-focus coil is air-cooled, rather than water-cooled like the other coils. While we were noting the beneficial effects of large gun-focus-coil currents, this coil overheated and shorted out. When rf power was applied to the deflection cavity, the beam (as a whole) made small rotations, but the deflection diameter was less than the beam diameter. Once beam dynamics were understood, it was clear that a major rebuild of the gyrocon was required. The electron gun would be replaced and a larger gun-focus coil would be made and installed in place of the shorted coil. As a final experiment before the rebuild, the screen was removed, and the bender coil was replaced. The gyrocon was operated briefly, and 5 to 10 W of output power were measured with a 100-kW beam power. The deduction was made that the output loops were too lightly coupled to the output cavity and would be corrected during the rebuild.

The gyrocon was taken apart completely and rebuilt as outlined above. The new gun-focus coil was water-cooled and had three times as many turns as the original one. A careful check of the original design data uncovered a factor of 2.5 that was used in the original gun calculations, but that had been neglected in the translation of the calculated results into laboratory values. Thus, the original gun-focus coil was designed for only 40% of the magnet field that was actually required, and the failure of the coil was understandable.

The rebuilt gyrocon was conditioned by running the drive power into the deflection cavity for a few days. Then the view screen tests were started and annular deflections were noted on the screen. By adjusting the phase and amplitude of the rf drive, the deflection beam would go from an ellipse to a circle to an ellipse with the major and minor axes interchanged. The dc beam could be easily focused to an intense 1-cm-diam spot on the screen with the new gun-focus coil. The electron-gun emission was not constant and was still below the design value. Thus, it appears that gas evolution from the unbaked parts of the gyrocon is poisoning the cathode. The phosphor screen was removed, and

the conical bender magnet was installed. Under these conditions, as much as 200 to 300 W were produced at each of the output couplers with 170 kW of beam power.

CONCLUSION

The present problems are that the output cavity is multipactoring, the beam current still is low, significant power at the first several harmonics is produced, and the output cavity is still too lightly coupled to the waveguide. Waveguide tuners were made and experimentally located to significantly increase the coupling to the output cavity. We ran the output cavity in an attempt to condition it against multipactor. The long-term solution to the electron-gun problem is either to bake the gyrocon or to purchase an electron gun with an impregnated, rather than an oxide-coated, cathode. The bake alternative is impractical because of the large size of the prototype gyrocon. The second option is too expensive for the present fiscal year but is being investigated for the future. The experimental work designed to increase the rf power is continuing.

FUSION MATERIALS IRRADIATION TEST FACILITY

STATUS

The status of the Fusion Materials Irradiation Test (FMIT) project is being reviewed by the Executive and Congressional branches of the US Government. The level of funding for FY82 is uncertain as of June 1981. In addition, scope of the project was decreased from a January 1981 total estimated cost of \$125.5 M to \$105 M. These actions resulted in a delay in the start of construction of the FMIT facility, eliminated one test cell from the facility, and reconfigured the high-energy beam-transport (HEBT) system.

In spite of these difficulties, the design of the FMIT prototype accelerator (FPA) injector, RFQ, rf power system, beam-diagnostic system, drift tubes, and control system continued with acceptable delays in the schedule. The design of the FMIT linac tank was started and soon will be ready for procurement.

The FPA building program supported a wide range of development and testing activities and continued the installation of the utilities that will be required for the rf-power-amplifier tests. The building's cooling-water system was installed; three of the four cooling loops were hydrostatically tested. The first part of the Phase C electrical power system was completed. The rf equipment platform was erected, and installation of some equipment racks and power distribution gear was completed. The steel for the 10-ton bridge crane was received from the manufacturer; the design was quality-assurance approved. Installation of utilities and structural supports for the rf-power-amplifier test stand is in various stages of completion.

Construction of the office building at Los Alamos is proceeding smoothly.

ACCELERATOR

Injector

Operational tests began on the prototype injector; the newly designed spherically convergent extractor electrodes were included on this test.

Results from these tests were encouraging in that it was possible to consistently achieve stable operation at full design current and voltage (250 mA at 75 kV). Beam quality (as observed visually) appeared to be quite good, and beam divergence was less than expected. In a nonfocused 110-cm drift length immediately out of the extractor, the full 250-mA beam diverged from an initial <0.8-cm diam to ≤ 2.6 -cm diam. This datum, taken by itself, would indicate that the visible core of the ion beam had a normalized emittance not greater than 0.03π mrad $\cdot$ cm and a space-charge neutralization of at least 99%. This success with the spherically convergent extractor design led us to conclude that this method has significant advantages over the planar-Pierce design concepts used previously. Although test results with planar-Pierce extractors had been favorable at lower values of beam perveance, attempts to extend this type of extractor to higher perveance proved futile. Figure 14 is a scaled drawing of the successful extractor geometry.

Tests have continued with the cusp-field ion source. Two new models (one of stainless steel and the other of copper) are presently in use, incorporating modifications to permanent-magnet placement, wall cooling, brazing of seams, filament feed-through placement, gas feed, and physical dimensions. Although operation has been satisfactory, several improvements expected with the stainless-steel source were not realized and cooling was only barely adequate. The new copper source chamber has delivered consistently good performance and has completely eliminated the recurring vacuum-leak problems of the original copper unit.

Rather severe problems developed with the use of the extractor high-voltage power supply, which is rated at 125 kV and 250 mA and uses a

Fig. 14.
Electrode geometry of the high-perveance 75-kV extractor with spherically convergent beam.

motor-driven variable transformer at the ac input. In the input circuit, 50-kV vacuum tubes are used as series-pass elements to reduce ripple and to maintain 0.01% regulation, while minimizing energy stored in the output capacitors. The power supply is physically separated into three units: a power cabinet, a high-voltage tank, and a control chassis. Although the supply operated flawlessly when first delivered and when operating into a resistive load, changes in the physical configuration and in extraction-load characteristics have caused severe problems, especially in ground-loop coupling. Sensitivity to noise pickup in the reference signal was noted. A tendency to open-loop oscillation was traced to an electrostatic feedback path within the high-voltage tank. Undesirable phase shifts in the external feedback circuits were responsible for intermittent problems when load parameters were varied. It was necessary to use a higher speed shutoff on the input circuit to reduce the damage caused to other circuits during spark-down transients.

During the early design phases of the low-energy beam-transport (LEBT) subsystem, a series of beam-simulation runs made with the TRACE computer code revealed an undesirable sensitivity to changes in input-beam parameters. This prompted a redesign of the 90° analyzing magnet under the injector to avoid the introduction of an asymmetry in the LEBT beam and to better match into the RFQ. The new design included a nonparallel pole face ($n = 0.5$) and carefully tailored edge angles to provide optimum focusing. New pole tips were designed using the POISSON and MIRT computer codes. The design produces a wedge shape for $n = 0.5$ and radial gradient of 51.86 G/cm within 0.2 to 0.4% over the center 8 cm of the pole. The pole tips were machined and installed, then the effective field was mapped and trimmed by cutting the pole entrance and exit ends. Additional trimming of the edge angles is in progress.

The RFQ Linac

The RFQ progress has centered around development programs and vendor identification and qualification. The major procurement items consist of the core tank, manifold tank, and vanes.

The development programs proceeded quite successfully. Of particular importance was the development of a technique to provide a cold weld at the rf joint between the vane base and the tank; however, the cold weld causes difficulties should disassembly be required. Tests showed that Q values equivalent

TABLE VII

RFQ DESIGN PARAMETERS

	<u>BNL2</u>	<u>OAK5</u>	<u>N141</u>	<u>TBR1</u>	<u>TEX8</u>
Ion	H ⁻	H ⁺	¹⁴ N ⁺	³ H ⁺	² H ⁺
Frequency (MHz)	201.25	40	25	150	11
Input energy (MeV)	0.02	0.20	0.10	0.20	0.0007
Output energy (MeV)	0.75	5.0	14.0	5.0	0.020
Nominal current (mA)	0.1	2000	150	330	0.1
Transmission efficiency (%)	100	91	88	95	97
Output emittance ^a	0.011	0.81	0.055	0.074	0.026
Length (m)	123.4	14.4	22.4	7.0	2.4
Peak rf power (kW) ^b	66	16 300	2690	5000	1.0

^aRMS normalized area/ π in cm² mrad units.

^bIncludes power required for the rf manifold and for the beam.

Kilpatrick limit. The 20-keV injector energy is chosen to match the 20-keV output energy of the ANL polarized H⁻ source. Although the nominal beam current is 0.1 mA from the polarized ion source, this design could provide good performance with the high-intensity H⁻ source as well. For example, the PARMTEQ simulation for a 30-mA H⁻ input beam current predicts a transmission of over 96%.

RFQ for High-Intensity Oak Ridge Accelerator

We have generated an RFQ design, in response to a request by Oak Ridge, to evaluate the maximum proton charge per micropulse that could be accelerated to 200 MeV in a single linear-accelerator channel. Table VII lists the characteristics of this design, called OAK5. The motivation behind this request by Oak Ridge is to evaluate the feasibility of replacing the existing electron-accelerator neutron source (ORELA) with a (p,n) source to gain more neutron intensity. The RFQ would serve as an injector into an Alvarez linac.

RFQ for Plasma Heating by Positive Light Ions

An RFQ design for plasma heating, called N141, was generated at the request of BNL. It accelerates positive nitrogen-14 ions to 1-MeV/nucleon and uses a peak surface field of 20 MV/m at 25 MHz. This design was used to help evaluate the feasibility of an alternate plasma-heating scheme that uses charged light ions. Table VII summarizes the parameters and performance characteristics.

RFQ for Tritium-Breeding Accelerator

At the request of BNL an RFQ design was generated to evaluate the feasibility of an accelerator system to breed plutonium using high-energy protons. This design is called TBR1 and is summarized in Table VII. The peak surface field is 26.4 MV/m, which is ~ 2 times the Kilpatrick limit at 150 MHz. The output beam from this RFQ would be injected into an Alvarez linac for acceleration to higher energy.

RFQ for Cyclotron Axial Beam Buncher

An RFQ design, called TEX8, was made to demonstrate how an RFQ could be used as an axial injector for a cyclotron.³ Table VII shows the characteristics of this RFQ. In this design example, 90% of the beam is bunched to within $\pm 15^\circ$ in phase.

The RFQ acceleration structure would be driven by an rf voltage source as a capacitive load consisting of four metal vanes mounted on insulators. By use of an accel-decel extraction system and an electrostatic lens, an ion beam from existing ion sources could be focused into the entrance of the four vanes at an energy of 0.4 to 1 keV/nucleon. The four vanes of the RFQ structure would then focus the beam through the structure, accelerate the ions to the required injection energy for the cyclotron (10 to 15 keV/nucleon), and adiabatically compress the ions into small bunches suitable for use in the cyclotron accelerating system.

If the RFQ is powered at the same frequency as the cyclotron and the exit end of the structure is located near the axial inflector of the cyclotron, almost all of the continuous ion beam extracted from the ion source can be

injected into the cyclotron within the rf phase acceptance of the cyclotron. This RFQ should provide an increase of 2 to 5 times the current captured by the cyclotron compared to that captured by the commonly used single-gap buncher system. In addition, the very small energy spread of the ions leaving the RFQ should improve the beam transport through the cyclotron during acceleration.

PROGRESS IN RFQ DESIGN TECHNIQUES

Pole-Tip Geometry Errors

For the Fusion Materials Irradiation Test (FMIT) prototype RFQ, we have studied the accuracy with which RFQ vanes must be positioned longitudinally with respect to each other. If errors in longitudinal positioning are present, they will alter the electric potential distribution and the corresponding electric fields. To investigate this type of error, we constructed a model⁴ to calculate the potential of a three-dimensional distribution of point charges that simulate an RFQ. From this study we concluded that if the vanes were positioned relative to each other longitudinally, with an accuracy of 0.13 in., there would be very minimal effect upon the performance.

Radial errors were also studied by scaling a POP RFQ error study.⁴ We concluded that if the radial position of the FMIT RFQ pole tips were accurate to ~ 0.03 in., there would be no appreciable degradation of the beam parameters. The sideways positioning of the vanes is expected to be accurately determined by rf tuning procedures used to balance the fields in the four quadrants.

Field Enhancement at Vane Gaps and Ends

Good performance of an RFQ accelerator requires that it be designed with high surface electric fields. These field levels are sufficiently near the electric breakdown limit that care must be taken not to further enhance the surface fields. In making long RFQ vanes it is often necessary to machine two or more lengths and fit them together. We have studied the electric-field enhancement produced by small gaps between two adjacent vane sections.⁵ The two-dimensional electrostatics program CHARGE was used in a manner that closely

approximated the three-dimensional problem. We used a variety of vane separations and radii of curvature on the corners of the vane ends. However, under the best circumstances the surface fields were enhanced by a factor of from 1.2 to 1.3. In most cases this is unacceptable, and the vane sections must be joined with no gap between them. This study also showed that rounding the corners of vane ends, where no other metal surfaces are nearby, will suitably control the field enhancement.

Improvements in RFQ Design Programs

A new computer code, called Initial Matching Section (IMS), has been written for generating matched-beam input parameters for the radial-matching section in RFQ designs. The smooth-approximation solutions are used, together with a simple space-charge model consisting of a uniform charge distribution within a cylinder, to obtain approximate values of the average β -function over an rf period. A matched-beam ellipse within the RFQ is then obtained by successive iterations for each of a set of equally spaced rf phases. Then for each phase, the corresponding matched ellipse at the output of the radial-matching section is transported backward through the radial-matching section, using the usual transport-matrix formalism. In this procedure, the radial-matching section is divided into a large number of segments, and each segment is represented by a transport matrix. An average over rf phases is then made for the resultant beam-ellipse parameters at the input to the radial-matching section. Thus, we obtain the required values of α and β for the dc input beam, which will optimize the RFQ acceptance. The inclusion of this program in the RFQ design procedure has greatly reduced the time required to simulate with PARMTEQ the performance of a given design.

THE I-R 100 AWARD

The Los Alamos National Laboratory has been granted the 1981 I-R 100 Award for development of the RFQ linac structure. This award is given to a hundred significant newly developed products by the publication Industrial Research and Development. The award will be presented on September 24, 1981 at the Museum of Science and Industry, Chicago, Illinois. The RFQ POP resonator will be on

exhibit at the Museum September 25 through October 18. After that, the RFQ will be placed on permanent exhibit in the Los Alamos Bradbury Science Museum.

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HEAVY ION FUSION

SUMMARY

Recently, proposals to investigate the feasibility of heavy ion induced fusion for commercial power production have generated interest in large linear-accelerator systems. The low-velocity part of these systems tends to be one of the serious overall limitations. The RFQ, which can be constructed in a special manner for low frequencies, appears to offer an attractive solution to this low-velocity problem.

In recent work on heavy ion fusion we have developed ideas for funneling of beams from RFQ linacs; the funneling process is explained below. We have also begun preliminary studies of RFQ resonant cavities.

RFQ DESIGNS

The 12.5-MHz Xenon RFQ Designs

We have used improvements in our design algorithms to generate a new design, which we refer to as HIF5. The parameters and performance characteristics for this design are presented in Table VIII. The peak surface field assumed was 20 MV/m. This example shows that at 12.5 MHz a beam current of 50 mA can be bunched and accelerated in a single channel, provided that the peak surface field of 20 MV/m can be obtained and provided that the injection energy is at least 300 keV. More details of this design were reported at the 1981 Particle Accelerator Conference.¹

A second Xenon RFQ design, called ANL6, was done at the request of ANL for a possible second low-velocity accelerator for their heavy ion fusion accelerator program. The parameters and performance are presented in Table VIII. This design example assumed a more conservative peak surface field of 17.5 MV/m.

TABLE VIII
RFQ DESIGN PARAMETERS

	<u>HIF5</u>	<u>ANL6</u>	<u>HIF6</u>
Ion	Xe ⁺¹	Xe ⁺¹	Xe ⁺¹
Frequency (MHz)	12.5	12.5	2.7
Input energy (MeV)	0.30	0.25	0.30
Output energy (MeV)	10.0	3.0	10.0
Nominal current (mA)	50	30	275
Transmission efficiency (%)	93	97	98
Output emittance ^a	0.011	0.009	0.09
Length (m)	27.7	15.5	14.2

^aRMS normalized area/ π in cm·mrad units.

The 2.7-MHz Xenon RFQ Designs

A computer program (CURMAX), which chooses the design frequency to maximize the beam current in an RFQ, was used to generate a Xe⁺¹ RFQ with maximized beam current. Table VIII lists the parameters and performance for this design, called HIF6. A peak surface field of 20 MV/m was assumed. The increased beam current and the reduced length, as compared with the HIF5 design, result from lowering the frequency from 12.5 MHz to an optimized value of 2.7 MHz. This result shows that significant improvements should be possible in the low-beta linac if the frequency can be lowered from the values previously considered.

Low-Frequency Structures

For frequencies below ~20 MHz, the four-vane RFQ cavity radial dimensions become so large that problems arise in fabrication. An initial study of

RFQ resonant-cavity structures has been made to identify those that are more attractive for low-frequency applications. A preliminary conclusion of this initial work is that both the spiral-resonator structure and a modified split-coaxial structure warrant further quantitative study to evaluate their size, mechanical properties, and power efficiency. A lumped-circuit model was used to compare the properties of a variety of transverse-electric-mode resonators. The application of this model for various types of transverse-electric-mode RFQ cavities of a fixed frequency suggests an approximate inverse relation between the required power and radial dimensions.

FUNNELING OF ION BEAMS

In the rf linear-accelerator approach to heavy ion fusion, an essential component is a device to combine charged-particle beams. To produce a final beam of high energy and high current, the linear-accelerator system must start with multiple low-frequency linacs each having a low-current beam. Pairs of these beams can then be combined into single beams that are suitable for further acceleration in a linac operating at twice the frequency. This process, called funneling, combines two bunched beams by deflecting interlaced microstructure pulses until they are collinear. Time-varying deflection systems are required, and (in principle) funneling can be accomplished with no emittance increase, so that the radial brightness of the final beam is doubled after each funneling operation. By repeating this process, a single final beam of the required intensity and energy can be produced.

In the funneling process many requirements must be met. While the two beams to be combined are undergoing suitable deflections to make them collinear, the radial focusing must be maintained, and the beams must not be allowed to debunch. A new approach has been suggested^{*} that uses the RFQ as a deflector. The RFQ pole-tip shape is modified to generate an electric dipole field that produces a first-order transverse force on the beam pulses. While

^{*}This information was supplied by G. N. Minerbo, Los Alamos National Laboratory, Accelerator Technology Division, Group AT-1, "Notes on Funneling Systems," January 16, February 12, February 17, 1981.

TABLE IX

TEMPERATURE SENSOR COMPARISON OVER TEMPERATURE RANGE OF 60° to 120°F

<u>Sensor</u>	<u>Type-T Thermocouple</u>	<u>Platinum RTD</u>	<u>Thermistor</u>
Accuracy (interchangeability)	±2°F	±0.2°F	±0.2°F
Sensitivity at sensor	0.02 mV/°F	0.2 mV/°F	30 mV/°F
Long-term stability below 180°F	1 to 2°F/yr	0.01% over 5 yr	±0.2°F/yr
Cost per channel	\$ 300	\$ 325	\$ 225
Linearity	Fair	Good (with bridge)	Good (with bridge, over FMIT temp. range)
Sensing-element dimensions	0.1-in.	0.1 in. by 1.0 in. (Too long)	0.1-in. bead

A system-simulation study was performed for the rf amplifier cooling loop to define a controller algorithm, the system stability margins, and how stability is affected by attempts to achieve tighter control over temperature. This information will be used two ways: first as input to the development of facility-control software, later as a guide for tuning the system during start up. A simple digital controller was identified with a 2-s update rate that outputs a variable duty-cycle pulse, providing speed control of an ac motor-driven valve. The controller is of the form

$$\frac{\text{pulse width}}{U} = G_1 E_1 + G_2 \left(\frac{E_1 - E_2}{U} \right) + G_3 \left(\frac{E_1 - 2E_2 + E_3}{U^2} \right) ,$$

where E_i are successive samples of control error, G_i are arbitrary gains, and U is update rate. With this controller the simulated cooling system met

all performance requirements and can be easily adjusted in the field to correct for differences between the simulation and test hardware.

A paper³ on the dc power system for FMIT deuteron accelerator has been written.

A design review of the FMIT accelerator vacuum system was held and the FMIT vacuum system design of a combination of ion pumps and cryogenic pumps was approved.

The last 20 ft of the HEBT was mocked up in the vacuum laboratory to conduct performance tests on the security valve system and also on the Helicoflex 6-in. collar, flange clamp, and aluminum-lined seal. A rotating-vane security valve closed in 43 ms with 15 ms required for sensing. The total closing time was 58 ms as checked with an oscilloscope. The noise of the valve closure was audible but no noticeable vibrations or movements were observed. A second valve of an explosive guillotine type closed in 25 ms. The guillotine valve would require design modifications to flanges, as well as to opening and closing operations, to be applicable to the HEBT beam pipe. The desired closing time is <10 ms. However, the required closing time is a function of valve location and also permissible beam-pipe contamination if there is target burn-through. The first type of valve is commercially available at \$22 K and can have five-hundred closures before replacement of seals is needed. The guillotine valve will require development; it is less expensive at \$5 K but would have to be serviced after each closure. The current HEBT layout drawing depicts both types of protection valves in the beam pipe.

The Helicoflex clamp and seal arrangement performed very well. Two seals were used during the experiment. Using Seal 1 and no lubricant on the clamp, the required sealing torque was recorded at 60 ft lbs. Initially the outside diameter of the seal ranged from 0.265 to 0.267 in. After six resealing cycles, the seal was compressed to an outside diameter of from 0.222 to 0.235 in. The seal was leak tight after each cycle, even though the flanges were not parallel. A heat tape was placed over the flange and turned on. No noticeable leak was found, using the isolation bag technique around the flanges and seal with a mass-spectrometer leak detector having a sensitivity of 8.73×10^{-11} atm-cc/s (for helium). Seal 2 was taken through eight resealing cycles and checked the same as Seal 1. Dry molybdenum-based lubricant was used on the clamp/flange interface. The required torque started at

10 ft lbs and ended with the eighth cycle being 28 ft lbs, with the recorded seventh cycle compressing the seal to a range of 0.247 to 0.252 in. diam.

The necessary P&ID were prepared for both FMIT and the FPA; these diagrams depict the pumps, valves, and instrumentation required for vacuum-system operation. The P&ID for the FPA then was used to develop the logic to be implemented on the programmable controller, a solid-state device used to replace relays, counters, and timers for sequencing vacuum operations, which may communicate with the FCS computer.

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