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Accelerator Technology Program

January—September 1983

Compiled by

R. A. Jameson

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ACCELERATOR TECHNOLOGY PROGRAM

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ABSTRACT

This report presents highlights of major projects in the Accelerator Technology Division of the Los Alamos National Laboratory. The first section deals with the Fusion Materials Irradiation Test Facility's 2-Mev accelerator on which tests began in May, as scheduled. Then, activities are reported on beam dynamics, inertial fusion, structure development, the racetrack microtron, the CERN high-energy physics experiment NA-12, and LAMPF II.

The Proton Storage Ring is discussed next, with emphasis on the computer control system, diagnostics interfacing, and theoretical support. Other sections summarize progress on a portable radiographic linac, developments on the klystron code, and on permanent magnets. Activities of the Theory and Simulation Group are outlined next, followed by discussion of the oscillator experiment and the energy-recovery experiment in the free electron laser project. The last section reports on the accelerator test stand.

An unusual and very satisfying activity for the Division was the hosting of the 1983 Particle Accelerator Conference in Santa Fe, March 21-23, 1983. The conference had the largest attendance ever, with 895 registrants, 61 invited papers, and 521 contributed papers.

FUSION MATERIALS IRRADIATION TEST FACILITY

STATUS

The effort to provide joint international funding for construction and operation of the Fusion Materials Irradiation Test (FMIT) Facility is continuing under the auspices of the International Energy Agency. If the funding agreement is concluded early in 1984, as expected, the FMIT Facility is scheduled to begin full-scale operation at the start of 1990. Funding for the development of the lithium target, remote handling, and experimental systems at the Hanford Engineering and Development Laboratory and for the development of the accelerator system at Los Alamos is being provided by the United States during this interim period.

At Los Alamos we completed the installation and began testing the 2-MeV accelerator in May 1983, as scheduled. Initial operation used an unmatched dc beam from the 75-keV injector into the radio-frequency quadrupole (RFQ) accelerating structure. The rf power was applied in 7-ms, 5-Hz pulses at power levels from 100 to 400 kW. A high-energy beam-transport system (HEBT) equipped to measure the beam energy and current followed the RFQ. This preliminary characterization of the 2-MeV accelerator's performance verified that the energy gain and transmission efficiency were as predicted by computer simulations. Thus, the technical integrity of the design was established for FMIT's 35-MeV accelerator's low-energy section. Present efforts are directed toward cw operation of the RFQ and are hampered only by the considerable amount of outgassing that is occurring as the average rf power level is increased.

The design and procurement of the drift-tube linac (DTL) components required to raise the output energy from 2 to 5 MV and to allow testing the match of the RFQ beam into the linac are funding limited, as are the activities related to the 35-MeV accelerator design.

ACCELERATOR

Injector

At the end of December 1982, a new set of extractor electrodes was installed in the FMIT injector. These electrodes were designed by iterating

between a shape optimization routine and a beam performance code. Theoretically, the new electrodes would reduce the effective phase space of the beam by nearly a factor of 3. In actual practice, the emittance was improved by a factor of 2. With the new electrodes, the FMIT injector has delivered up to 120 mA of H_2^+ beam onto the beamstop, a substantial improvement over the old system that could deliver only 80 mA.

A solenoid optimization code is now being used with high-current beams. Reductions in spherical aberration of about a factor of 2 have been achieved. The amount of improvement is quite dependent on coil placement, and more work will be required to determine the best coil positions. A vectorized elliptic integral routine has been written that speeds computation considerably. An interesting spin-off of this work is its applicability in design studies for a meson bottle to be incorporated in a Los Alamos neutrino-source proposal.

In an attempt to eliminate the clumsy (possibly unreliable) mechanical iris assembly, we investigated the possibility of controlling the beam current by injecting a heavy gas into the source plasma. This injection increases the effective mass of the extracted beam and hence, under matched perveance conditions, the beam current. We found that very small amounts of argon (the first gas tried) were extremely effective; in fact, the current decreased by several orders of magnitude with the addition of minute amounts of argon. Several gas mixtures with varying hydrogen-to-argon mixture ratios were tried to achieve a range of control, but none worked satisfactorily. We are now evaluating a mixture of neon and hydrogen. We believe that argon was difficult to use because it is ionized more easily than hydrogen and thus became the primary constituent of the plasma rather than a small contaminant. Neon has a much smaller ionization cross section than hydrogen and should prove to be a better mixing gas. In any case, we also discovered that simply increasing the hydrogen gas flow could achieve a factor of 4-to-5 reduction in the H_2^+ , down to approximately 20 mA into the RFQ.

During this reporting period, much effort was devoted to upgrading and repairing the high-voltage power supply (HVPS). The high-voltage diode arrays were replaced with newer diodes having better characteristics. This replacement alone reduced the unregulated ripple voltage from 800 to ~400 V. Several modifications to the regulation circuit also have been made and have resulted in substantially better performance of the HVPS. Regulated ripple voltages are

now typically 50 V or less, compared with 100-250 V previously obtained under the best of conditions.

Several 75-kV inductors have been tried between the HVFS and the equipment dome and extractor to reduce the destruction of electronics during arc downs. The first inductor was about 4 mH and arced over between the three layers of windings. The second unit tried was a ferrite core inductor in oil. Although it had no arcing problems, it failed to give the required protection at high current because of saturation (despite use of core gaps). A third, 75-kV, inductor has been designed and should be completed by the end of September. It is a 17-mH air-core inductor of single-layer design that should not arc over and should preserve its high inductance, independent of current.

FMIT RFQ

The FMIT 80-MHz RFQ was successfully tuned. The dipole component of field was held to less than 3%, and the field was tilted 5% in favor of the high-energy end. A new technique for tuning the RFQ ends was developed that eliminates the need for capacitive end tuners. Tuning is accomplished by varying the inductance of the end terminations with an adjustable shorting strap from the vane protrusion to the vane base at the wall. Once the appropriate size and position for the inductive tuners were determined, they could be removed and replaced with no change in field distribution.

Mechanical Design

Mechanical design effort for the FMIT project was centered on assembly of the 2-MeV prototype beamline. Fabrication and copper-plating of the RFQ major components were completed by outside contractors. These components were received, inspected, and prepared for assembly. Assembly and tuning of the RFQ proceeded on schedule with a minimum of problems and a maximum of dedication by the individuals involved. Before RFQ assembly, the 2-MeV HEBT was assembled in unified stages. A mini-HEBT was used for injector/low-energy beam-transport (LEBT) tests. As the RFQ neared completion, the 5-MeV linac tank that was in place for rf tests was removed. The 2-MeV HEBT, installed following the RFQ, included a prototypic beamstop. An important feature of the HEBT is that it is a check of the 25-cm quadrupole magnet design for the 35-MeV HEBT.

As the operation phase of the 2-MeV prototype commenced, mechanical design efforts were redirected to a variety of projects. Work on design packages for

the 5-MeV beamline was resumed. The drift-tube girder assembly, RFQ-to-linac "bell housing", and the downstream tank closure designs were reviewed and updated. A drift-tube model to test alignment procedures was begun. A program to test graphite bonding in the beamstop is in progress.

For the FMIT 35-MeV designs, work progressed on the linac tank's final drawing package. Also, an update and preliminary design package for the HEBT wall module was completed.

The post couplers in the FMIT prototype 2- to 5-MeV DTL reach resonance when they are too far from the drift tube to couple effectively. A scheme is now being tested that involves capacitively loading slightly extended post couplers to resonate in the three-quarter-wavelength mode.

Mechanical design effort for other projects consisted of developing the RFQ vane-tip machining program, free electron laser (FEL) beamline design, and the accelerator test stand (ATS) DTL. Vane-tip machining procedures were revised to achieve a greater degree of precision and, in subsequent vane machining, the revision was a team effort between AT Division and the Mechanical Fabrication Division's Shop 43; a factor-of-10 improvement in vane precision resulted.

Beam Diagnostics

A major redesign of timing and the digitizing electronics for the linear photodiode arrays was completed. The optical measurement of beam profiles by imaging emergent light from the beam region through a fiber-optic bundle onto a microchannel-plate intensifier and Reticon photodiodes has been reported.¹ The new design incorporates microprocessor control to synchronize timing of the light integration period with the passage of a single beam pulse. The system now may be remotely erased, gains adjusted, and integration times changed; Fig. 1 is a block diagram of the physical arrangement of input elements.

A Reticon camera head was designed, assembled, and used on the HEBT beamline for the first 2-MeV RFQ beam. A CAMAC-based control unit provides beam profiles to the LSI-11/23 microcomputer of the diagnostic system. A third unit of the Reticon system is the display module that has been installed at the central control console to provide real-time beam-profile displays for the operator. The digitizing electronics are contained in a 19- by 28- by 30-cm package at the beam pipe. Several new computer programs have been implemented to accommodate data acquisition for this new system.

Fig. 1.

The imagescope-to-photodiode sensor elements are shown with the input lens represented by the four small squares on the ends of the four imagescopes: bundles of optical fibers arranged to maintain spatial coherence. MCP is an abbreviation for microchannel plate. The linear photodiode arrays are called by their commercial name of Reticon. The electronics digitizes the beam profiles and transmits the data over a fiber-optic link.

A single line of a TV beam profile has been made available to the operator console as a real-time indicator of beam width and position. A new electronic module has been designed and built to allow CAMAC selection of the individual TV line to be displayed. A preliminary set of fiducial lights has been installed at one of the TV camera locations. The two lights [small light-emitting diodes (LEDs)] show both the scale of the beam image and the physical center of the beam pipe. TV cameras have been mounted on the RFQ at two of the view ports to provide full views of the beam at the vane entrance.

An electron accelerator at Argonne National Laboratory was used to check the impulse response of three electromagnetic sensors: the capacitive pick-up loops, the Pearson 80-MHz current transformer, and a beam-position monitor. These devices were installed on the HEBT to detect accelerated beam from the RFQ. Three capacitive loops measure flight time of a beam bunch between their separated positions, with the second loop (proceeding downstream) serving to

establish a time window for the beam bunch at the third loop. The energy of the beam, derived from the time of flight, has been measured to a few per cent. Information from this system is presented to the control room. A bench test of the energy-measurement system showed better than 200-ps resolution out of a 40-ns simulated flight time.

Further processing of the output signal from the capacitive loops may infer characteristics of the longitudinal distribution of the beam. A comprehensive package of computer programs has been assembled to allow Fourier transform techniques to be applied to these signals. A design effort using micro-strip circuit-board techniques is now producing a preliminary version of a capacitive pickup with greatly reduced size. Both mechanical and electrical designs are complete for a halo feeler system. Design is under way for the electronic read-out of the 80-MHz current transformer.

The rf System

We have successfully demonstrated the multiple-loop rf drive concept on the FMIT prototype DTL cavity with a dummy drift-tube in place.

Two 600-kW rf amplifier systems, each with its own rf drive loop for coupling rf power into the cavity, were used in the test. The configuration for the test used the two high-power rf systems, one acting as the master system and the other as the slave, along with the required phase-and-amplitude feedback control systems. The slave system had an amplitude controller that caused the slave to track the master in output power. The output power of the master was determined by the cavity amplitude controller that matched the cavity field to a set-point value for the desired field. This controller adjusted the output of the master system and, consequently, the slave system until the cavity field reached the set-point value. In addition to the amplitude controllers, each rf system had a phase controller that maintained zero phase shift through each system, regardless of operating parameters over the full operating-power range of zero to 600 kW. Phase control is essential to ensure that the two rf systems are driving the cavity in phase. Failure to do so results in high voltage standing wave ratios (VSWRs) in each amplifier's output drive line, thereby dramatically affecting the gain of each final amplifier, preventing control of the cavity field to the tolerance required for proper accelerator operation.

The system was taken to maximum power; each amplifier system contributed 600 kW for a total of 1.2 MW of peak rf power at 80 MHz. The pulse width was 300 μ s, and the pulse repetition frequency was 120 pps for a 3.6% duty factor and an average power of 43 kW. The output VSWR seen by each amplifier was reduced to approximately 1.2 with the cavity at resonance and the phase-and-amplitude feedback controllers operating in the closed-loop configuration.

Step-function disturbances were introduced into each control loop to measure the system response. With each amplifier delivering 150 kW to the cavity (the required power level to maintain the cavity field without beam loading), a step disturbance was applied to the cavity amplitude-control loop on the master rf system. If the loop were open, the step disturbance would drive the output of each system to about 500 kW (450 kW is the power required per system at full beam loading), which would produce a 100% increase in cavity field. The cavity amplitude controller maintained the cavity field to within 0.3% of the set-point value once the initial transient damped away. During this 50- μ s transient, the maximum overshoot in cavity-field amplitude is 7%. The FMIT specification requires a $\pm 1\%$ tolerance on the steady-state cavity field.

The phase controllers on each rf system were tested with a step disturbance equivalent to a 45° phase shift applied to each controller. The phase controller held the phase shift through each system to within 0.25° of the steady-state value. During the 10- μ s transient at the beginning of the disturbance, the maximum phase overshoot is about 11° . The FMIT specification requires a $\pm 1^\circ$ tolerance on phase control. System performance was observed over a 4-h period with hands off. No change in system performance was observed during this run.

After we completed the multiple-loop drive tests, we placed the RFQ on the beamline and, for simplicity, used one high-power rf system to supply the RFQ rf power. It took some experience to learn how to condition a structure this large. To break through multipactoring at turn-on, it was necessary to drive the structure with about 600 kW to establish the cavity fields. After 20-30 μ s at 600 kW, the incident power was reduced to 300 kW for the remainder of the rf pulse. As soon as the tank was conditioned to 10-ms pulse length at 350 kW, the beam turn-on was initiated. An oscillation with a 5-ms period in the drive VSWR from 1.7 to about 3 was observed. As the duty factor was increased to 10%, this oscillation disappeared. The oscillation still occurs

when operating in the pulse mode and, to all indications, seems to be a thermal effect that affects RFQ tuning because the oscillation damps out after several seconds of cw operation.

To increase the pulse length beyond 10 ms, we had to frequency modulate the rf source on a millisecond time scale to track the RFQ's frequency variations during the pulse. If this were not done, the VSWR protection circuit would trip off the rf drive for pulses longer than 10 ms. The slug tuners on the manifold tank are inadequate for this purpose because of their low response time.

The rf conditioning has been in progress for 8 wk in an attempt to achieve cw operation at full field (350 kW). Because of vacuum outgassing, output power was limited to about 100 kW.

We have observed that the power balance between the RFQ core tank and manifold tank varies with power level. It has been suggested this variation probably is due to temperature changes in one or both structures; these temperature changes cause frequency tuning errors that, in turn, affect the power balance. This effect will be investigated by purposely changing core and manifold temperatures independently and observing the effect on the power balance through the rf monitor loops.

Facility Control System

The FMIT 2-MeV accelerator is controlled by a distributed computing system consisting of a DEC PDP 11/60 and several LSI 11/23 microcomputers. Each 11/23 is installed in a CAMAC crate and provides for data acquisition and control of related groups of accelerator functions. Each can stand alone with its own operator's console. Most operations, however, are conducted from the central control room where the 11/60 controls a much more sophisticated console with interactive graphics terminals providing two-way communications with the remote microprocessors.

During the reporting period, the above control system has become almost completely operational, although not much central control-room operating experience has been gained because accelerator operations still are confined to start up and testing of individual systems that can be dealt with through the individual microcomputers.

Four of these microcomputer/CAMAC subsystems are now in daily use.

- The cooling control systems monitor and regulate accelerator temperature through four different cooling loops, manipulating nine different motor-driven valves. The water temperature of critical rf cavities is regulated to within $\pm 0.3^{\circ}\text{F}$ as measured by an array of thermistors.
- The magnet control system regulates the current in all focusing and steering magnets in response to operator commands. The beam observations that the operator uses to make steering and focusing decisions come from the diagnostics subsystem.
- The diagnostics-control subsystem provides communication between various noninterceptive beam sensors and the control room. It also communicates with a signal processing computer that reduces beam-data arrays.
- The injector-control subsystem provides for data acquisition and remote control of the ion source, HVPS, and the various devices along the low-energy beamline, including the vacuum system.

These systems have all worked well during initial operations, but as the accelerator comes on-line and we get more experience with control-room operations, they will continue to evolve.

Vacuum

A process control setter for our ion-gauge and thermocouple-gauge controllers has been designed and tested and is being built into a final unit. It can be used to adjust the process-control pressure set points accurately without the use of an ion gauge, thermocouple gauge, or vacuum. It will be most useful in an operational sense when a defective ion-gauge control unit requires replacement. The process controls on a spare control unit can be set quickly, and the replacement can be installed without malfunctioning of the vacuum control system or requiring that the system pressure be changed to set the process controls.

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BEAM DYNAMICS

NEW RFQ RADIAL MATCHING SECTION

The function of the entrance radial matching section is to provide an efficient transition between an incoming beam having time-independent characteristics and a beam in the RFQ that is matched to the time-dependent focusing system. Using a new, relatively simple, potential function,¹ it is possible to design matching sections that perform extremely well over distances (from the cavity end wall to the end of the matching section) between 2.5 and $5 \beta\lambda$. The vane-tip geometry, as specified by the potential function, has a rounded end with a finite gap to the end wall. A major benefit is to ease the task of matching in the LEBT region. A convergent beam is required as input into the radial matching section, and a common difficulty has been in getting the final focusing lens in the LEBT close enough to the RFQ. A shorter radial matching section requires a less convergent beam and, consequently, allows for the final lens to be farther from the RFQ entrance.

One problem associated with RFQ linacs that has received little attention is the effect on the beam caused by the exit fringe fields between the end of the vane tips and the exit wall of the cavity. When machining the vane tips, we abruptly terminate at the end of the last cell, except that corners are rounded to prevent excessively high surface-electric fields. For beam-dynamics purposes in the past, we have assumed the fields to be zero after the end of the last cell. As far as the quadrupole fields are concerned, this is analogous to approximating real quadrupoles by hard-edged quadrupoles. In the interest of obtaining a more accurate treatment, we have developed a multipole expansion² that allows a treatment of both longitudinal and transverse exit fields.

Also, because of the finite phase spread in the beam, particles exit at slightly different times in the periodic focusing cycle. Consequently, there will be some effective growths in the transverse emittances. It is possible to almost eliminate these emittance growths by using a new exit radial matching section,² which can be described by the same multipole expansion.

SPACE-CHARGE CALCULATION FOR RADIAL MATCHING SECTIONS

The standard space-charge subroutine used in PARMTEQ, as well as in other multiparticle simulation programs, is not well suited to the beam conditions

in the radial matching section, namely, a highly convergent, continuous beam. To prevent artificial debunching that is due to the space-charge calculation, a continuous beam is handled by assuming that an arbitrary (but specified) number of identical beam pulses are located on either side of the pulse being followed. This assumption is reasonable in most transport systems, in DTLs, and in RFQ linacs (except for the radial matching section) where the beam is almost periodic. However, in the radial matching section, the downstream end of the beam pulse can have a significantly smaller radius than the upstream end.

To treat this problem, a new space-charge calculation³ has been developed for PARMTEQ that assumes a continuous beam throughout the radial matching section with circular cross section and a charge distribution that depends on radius and the longitudinal coordinate but is independent of azimuth.

MATHEMATICAL DETAILS OF MACHINING RFQ VANE TIPS

The mathematical details involved in going from an RFQ design to a machined vane tip have been documented.⁴ It is assumed that a three-axis milling machine is used. The adjustments required to compensate for the finite size of the cutting tool and for subsequent copper-plating are included.

Constraints on the longitudinal step size and on the cutter size used for machining the vane tips are taken into account.

Usually the objective is to calculate the parameters required to machine a desired vane-tip geometry. However, it is also possible to go in the reverse direction; that is, given a sequence of circular arcs and straight line segments through which a cutting tool is moved, one can calculate the corresponding coordinates on the surface of the vane tip being machined.

EMITTANCE-GROWTH STUDIES IN THE RFQ

We have used PARMTEQ to study transverse emittance growth in an RFQ design for protons.⁵ Our conclusions are the following. The rf-defocus effect does not play a major role in emittance growth for this RFQ. The observed emittance growth is caused by space-charge forces. There is no evidence from this RFQ study that unstable collective modes of oscillation have made a significant contribution to the emittance growth. The strongest effect observed so far that seems related to emittance growth is that of bunch length. Our tentative conclusion is that for this RFQ, the transverse

emittance growth is probably associated with tune-spread effects caused through the space-charge forces by beam bunching.

A possible direction for further study is to try to isolate the mechanism in more detail, perhaps by studying the behavior of the bunch at different radii and different longitudinal positions. Once the mechanism is better established, we would hope to use this knowledge to modify either the parameter profile of the RFQ or the input distribution, or both.

FRACTION OF BEAM VERSUS EMITTANCE FOR n-DIMENSIONAL ELLIPSOID DISTRIBUTIONS

The fraction of the beam contained within a given emittance depends on the particle-distribution function. In our simulation codes, we commonly use a "waterbag" distribution for the input coordinates. A waterbag distribution is one in which the particle coordinates are chosen to uniformly fill an n-dimensional ellipsoid. In practice, we use either 4 or 6 for n, but in principle any integer could be used.

For such distributions, it is possible to calculate a variety of useful properties. For example, the rms emittance in any phase plane is $1/(n + 2)$ times the total emittance. The fraction of the particles contained within the rms emittance depends on n.

Calculations were made to determine the fraction of particles versus emittance for n-dimensional ellipsoid distributions.⁶ For $n = 6$, about 33% of the particles lies within the rms emittance in one transverse plane, but only about 8% lies simultaneously within the rms emittance in both transverse planes. For $n = 4$ through ∞ , approximately 87% lies within four times the rms emittance in a single transverse plane, and approximately 76% is simultaneously within four times the rms emittance in both transverse planes. These results are useful for estimating the transmission of a beam of specified emittance through a system of focusing lenses with a limited acceptance.

PARMELA BENCH-MARK CALCULATION

A comparison was made between measurements and calculations, using the electron multiparticle code PARMELA to test whether the PARMELA code does a reasonable job in calculating emittance growth.⁷ Data were obtained from a short transport line following an electron gun. Emittance measurements on a 5-A electron beam had been made using a pepper pot located about 60 cm downstream from the gun.

The PARMELA calculations were in close agreement with the results of the measurements.

DESERTRON INJECTOR-LINAC CONCEPTUAL DESIGN

A 2.5-GeV proton injector-linac design was generated^{8,9} for the proposed high-energy Desertron accelerator. The injector linac was patterned after the PIGMI accelerator and consists of an RFQ, a DTL, and a coupled-cavity linac (CCL). The RFQ and DTL were designed for a frequency of 440 MHz, and the CCL was designed at 1320 MHz. Permanent-magnet quadrupoles were used for focusing in the DTLs and CCLs. A preliminary cost-optimization study resulted in a 125-MeV transition energy between the DTL and the CCL. The resulting output beam parameters as determined by a PARMILA simulation were within the desired specifications. Lack of equipartitioning was identified as the probable cause of the transverse emittance growth that did occur in the CCL, which might be reduced in a more complete study.

CONCEPTUAL DESIGN FOR THE OAK RIDGE HEAVY ION LINAC INJECTOR

A 10-MeV/nucleon injector-linac design was generated for the proposed Oak Ridge heavy ion facility,¹⁰ and a preliminary cost estimate was made. The injector linac consists of a 25-MHz RFQ, which accelerates the beam to 0.20 MeV/nucleon; a 25-MHz π - π Wideroe, which accelerates the beam to a stripper at 1.2 MeV/nucleon; and, finally, a 100-MHz Alvarez DTL. The linac can accelerate almost 10 electrical milliamperes of $^{238}\text{U}^{+5}$ from a PIG source to the stripper, where a final charge state of +40 is obtained that is accelerated to full energy.

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ACCELERATOR INERTIAL FUSION

MULTITURN INJECTION STUDY

The rf-linac/storage-ring systems use an rf-linac accelerator to produce a low transverse-emittance beam of relatively low current at the desired final energy. The current is increased by stacking the beam in the transverse phase space of storage rings using multiturn injection. This stacking process unfortunately results in dilution, an increase in the effective phase-space area occupied by the beam. The available phase-space area for a heavy ion fusion (HIF) driver is limited by the target size and the beam-optics aberration limits imposed by the final focusing system. As a consequence, the multiturn injection must be designed in a way to minimize the phase-space dilution. The multiturn injection must also be designed to avoid large beam losses in the storage rings because such beam losses could lead to high material temperatures and consequent vaporization, which could degrade the vacuum and cause further beam losses for heavy ions. We have completed some initial multiturn injection studies¹ for an HIF storage-ring system using a new computer simulation program called MISAR, which includes transverse space-charge effects. The initial results for six-turn injection suggest that a transverse phase-space dilution of about 3 may result for stacking in both transverse planes of a storage ring when space-charge effects are included. However, the effects of machine resonances must be studied, and better statistical accuracy is needed so that beam-halo loss limitations on the septum can be accounted for more accurately.

RFQ PARAMETER STUDY FOR HEAVY IONS

A study was made of RFQ designs for six singly charged ions ranging from neon to uranium.² These results can be used in the overall design of an rf-linac/storage-ring accelerator driver for HIF. The rf frequency was varied within the range 6.25 to 60 MHz. The RFQ designs were made with the help of the two RFQ design programs CURLI and RFQUIK, and the resulting designs were studied with the multiparticle simulation program PARMTEQ to obtain the output transmission and emittances. The beam current used for each design was based on the value of the current limit calculated by CURLI. Somewhat arbitrary choices were made for some parameters, and (in a final design) these choices could be adjusted to optimize the performance.

INITIAL STUDY OF AN rf-LINAC/STORAGE-RING ACCELERATOR FOR HTE

The HIF accelerator research program calls for a high-temperature experiment (HTE) in which a high temperature (50- to 100-eV) solid-density plasma would be created. The HTE would require the construction of an accelerator that would allow a verification of the design procedures and principles to be used in an actual megajoule driver suitable for a reactor. Our approach³ has been to apply the same principles that were used at previous HIF workshops to synthesize first-order designs; then, a crude cost estimate was made for each design, based on assumptions about cost per unit length for linacs, rings, and beamlines. This approach allowed us to select those designs that give a minimum cost as candidates for further study.

Our procedure for this initial study has been to make a systematic, parameter variation of the input parameters for six ions, three charge states, and three ranges to obtain minimum cost configurations. In a complete study, this would only be a first step, which would correspond to identifying the regions of parameter space that give interesting solutions. Further studies and more detailed design work would be necessary to evaluate the performance of the more interesting solutions and to refine both the technical assumptions and the cost assumptions. The following conclusions can be drawn from this study: Only the ions with mass greater than or equal to that of xenon consistently yield the lowest cost solutions. Lowest cost solutions are obtained for several charge states and ranges, but solutions for singly charged ions and ranges of about 0.01 g/cm^2 have the smallest number of storage rings and beamlines, which may help to reduce the complexity of the system. The cost appears to be rather sensitive to the transverse, available dilution factor and the geometric aberration factor and much less sensitive to the maximum storage-ring tune shift and the chromatic aberration factor. In some cases, modest cost reductions were obtained by introducing 2×2 final beam splitting. Generally, major cost reductions did not occur when either the storage-ring or the final beamline space-charge limits were relaxed. The initial relative cost assignments were very crude; therefore, an important next step to continue this study would be to subject several of the most promising design configurations to a more detailed and more reliable cost study that would yield conclusions about actual dollar values. In addition, because the transverse, available dilution factor has an important influence on the overall cost, we recommend a simulation of the performance for the most promising designs in a way that gives a prediction

for the transverse emittance dilution. Such a simulation study could provide the basis for choosing an adequate value of the available dilution factor, but one that would not give an excessive cost penalty. Furthermore, such a simulation study could be used as a test of the assumptions used in this initial parameter study.

INITIAL STUDY OF A SYNCHROTRON/STORAGE-RING ACCELERATOR FOR THE HTE

If high duty factor is unimportant for the HTE, then a synchrotron can be used for acceleration rather than an rf linac. In general, the system would consist of a low-energy rf-linac injector, a synchrotron to accelerate the ion beam to full energy, and storage rings to accumulate the accelerated beam. The storage rings can be sequentially filled by transferring beam from the synchrotron and repeating the process until all storage rings are filled. Then the beam in each storage ring is bunched, extracted, and delivered to the target. An analysis of the system was carried out⁴ in a similar way as for the rf-linac/storage-ring system described above. Lowest cost solutions were generated for six ions, three charge states, and four ranges. The lowest cost solutions and also those that have fewest component rings and beamlines correspond to $q = 1$ and high mass such as xenon, mercury, or uranium. We find that relaxing the geometric aberration constraint has a significant impact on lowering the cost and also on lowering the number of component rings and beamlines, a result that is not unexpected. Other parameters that were seen to be important were synchrotron maximum tune shift (synchrotron space-charge limit), transverse, available dilution factor, and target temperature.

SPIRAL-RESONATOR RFQ

A spiral-resonator RFQ was made for operation at 11.7 MHz. Measurements on the Q and effective shunt impedance were made, and the structure was found to be very promising as an accelerator of heavy ions. Disagreements between RFQ shunt-impedance measurements made at Los Alamos and at Frankfurt were resolved. The difficulty turned out to be a matter of definition of terms.

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ACCELERATOR STRUCTURE DEVELOPMENT

RFQ RESONANT COUPLERS

Several schemes for resonantly coupling the RFQ to the coaxial manifold were tested. One technique was resonating the slot with an added capacitance. Another was to create two inductive stubs in a large opening. The stubs were resonated by using capacitive plates between them. Both techniques yielded similar coupling factors and both required rather large loading capacitance to achieve resonance. A third technique involved using resonant loop couplers. The resonating capacitance was much smaller because of the loop self-inductance, and the coupling was somewhat higher than for the other two methods. From the rf point of view, these techniques are basically equivalent, and a choice should be made based on mechanical-engineering considerations.

Up to now we have had no success in tuning more than one slot. However, we have not yet tried the resonant slots in combination with shorting rings. Doing this should simplify the tuning process considerably.

RFQ ANALYSIS

A method for determining the approximate RFQ gap error as a function of longitudinal position was developed. This technique estimated the gap error independently of the end tuning conditions. An extension of this theory resulted in a method to calculate gap asymmetry from field measurements on three modes. This method was not as successful, probably because higher order dipole modes were strongly mixed with the quadrupole mode. The use of shorting rings reduces the necessity for the asymmetry calculation, but the shunt-capacitance effect of the rings is not now taken into account. The theory will be modified to allow for this.

RFQ SHORTING RINGS

Periodic vane-to-vane shorting rings were installed, first on the cloverleaf cold model and then on the ATS RFQ. In both instances, the azimuthal symmetry of the fields was dramatically improved. The mode spectra were measured and were qualitatively the same as predicted by the transmission-line model. No attempt was made to develop a quantitative comparison. In the case of the ATS RFQ, it was found that the shunt capacitive effect lowered the operating frequency too much and produced pronounced dips in the field between

sets of rings. As a compromise, one-half of every set of rings was removed, reducing the capacitive loading by half while still yielding sufficient azimuthal improvement.

Two other RFQ improvements were tried: the so-called yin-yang and the double-dipole connections wherein some subset of vane ends are shorted to the end walls. The effect was found to be essentially the same as installing a partial set of vane-to-vane shorting rings at the ends. The results were no real improvement in the azimuthal symmetry and no change at all in the longitudinal distribution of the quadrupole mode fields.

SAI MODEL

Studies were made of a rectangular RFQ model for Science Applications, Inc. (SAI). This unique RFQ has several interesting properties. Difficulties in tuning the model are ascribed to the somewhat primitive construction techniques used. But, in the "thin" direction, the vane-to-vane shorts consisted of a rod between opposing walls. In the "fat" direction, vane-to-vane shorts were successfully made by bringing out connections to the long vanes through the adjacent walls and going around the short vane, rather than through it.

These external rings provide an opportunity to connect some sort of external manifold to the structure. Several manifold schemes have been tried, so far without success.

DISK-AND-WASHER TESTS

A disk-and-washer (DAW) cavity belonging to Argonne National Laboratory was tested there by exciting the cavity with high-current beam pulses. It was found that a wide variety of modes could be readily excited and that potential beam-deflecting modes could be identified by their position sensitivity. An attempt will be made to estimate the relative shunt impedance of some deflecting modes from the data obtained in this experiment.

Highlights of other accelerator-structure developments are discussed with their various projects.

RACETRACK MICROTRON (RTM)

ACCELERATING SYSTEM

Following our decision last September to abandon the DAW rf structure for the RTM project, a water-cooled side-coupled structure (SCS) was designed, modeled, built, and tested. The SCS has proved to be highly successful in all respects. It exceeds design specifications on shunt impedance (82.5 M Ω /m observed versus 80 M Ω /m goal), on voltage gradient (2.0 versus 1.5 MeV/m), and on power-dissipation capability (49 versus 28 kW/m). Following these successful tests, we have proceeded with construction of the remaining rf structures. The capture section is now complete and ready for final testing under power, and machining has begun on the "8-m section" for the microtron. The 8-m section actually consists of two center-fed, 4.1-m structures because the cell-to-cell coupling of the SCS is too small for a single power feed in an 8-m section.

A 2.7-m side-coupled linac has been built as part of the injector that is designed to accelerate the electron beam from 1 to 5 MeV with an accelerating gradient of 1.5 MeV/m. Fabrication of the structure started October 4, 1982, and was completed February 28, 1983, when it was tested with a cw power level of 82 kW. Subsequently, the power level was raised to 131 kW, which corresponds to an accelerating gradient of 2 MeV/m. The preaccelerator is shown mounted on the test stand in Fig. 2. No change in field distribution was detected at any power level. The operating frequency is 2380 MHz.

The unloaded Q (Q_u) measurement for the almost completely brazed structure (only the drive cell was not brazed) yielded a 15 300 Q compared to the 18 340 SUPERFISH value. The loaded Q (Q_l) was measured after the iris was cut with a match of $\beta = 1.04$; Q_l is related to Q_u by the relation

$$Q_l = \frac{Q_u}{1 + \beta} \quad .$$

The Q measurements, made before and after the iris slot was cut, agreed within 1% using this relation. The measured values of Q and ZT^2/Q yield 82.5 M Ω /m for the shunt impedance, ZT^2 .

Using a least-squares fit of the measured mode spectrum to the predicted mode spectrum, the derived parameters of the SCS, given in Table I, were calculated using the coupled-circuit model. The measured mode spectrum was

Fig. 2. RTM side-coupled preaccelerator.

TABLE I

PARAMETERS OF THE SIDE-COUPLED STRUCTURE

Measured Parameters

Operating frequency	2380 MHz
Standard deviation of accelerating-cell frequencies excluding the two end cells that are tuned ~ 2.1 MHz lower ^a	200 kHz
Standard deviation of coupling-cell frequencies ^a	28 kHz
Q_A , accelerating-cell Q	15 300
Q_C , coupling-cell Q	7 500
ZT^2 , effective shunt impedance	82.5 M Ω /m

Derived Parameters

Accelerating-cell frequency	2387.0 MHz
Coupling-cell frequency	2378.4 MHz
Nearest neighbor coupling constant K	0.0476
Direct coupling between accelerating cells K_A	-0.006
Direct coupling between coupling cells K_C	0.0015
Stop band ^b	0.296 MHz

^a The standard deviation of cell frequencies are from measurements made of cell frequencies during tuning.

^b The stop band given in the table is derived from the fit to all the modes; whereas, the stop-band values given in the text are determined from only three modes: the accelerating mode and the two nearest modes that couple to the structure drive. The two modes next to the accelerating mode do not couple to the structure drive and, therefore, cannot be used to determine the stop band when the structure is under power.

obtained from the 2.7-m section consisting of 43 accelerating cells and 42 coupling cells.

Estimates of power-flow droop, power-flow phase shift, and tilt sensitivity can be made using the coupled-circuit model. For the rf drive in the center of the 2.7-m SCS with the parameters given in Table I, the estimated power-flow droop from the center to each end is 0.3%. The power-flow phase shift is 0.5° for a 400-kHz stop band. Under full power when the stop band is 770 kHz, the power-flow phase shift increases to 1.0° . The tilt sensitivity (tilt produced by deliberately detuning the end cells equally and oppositely) is 1%/MHz of end-cell detuning for the 400-kHz stop band and 2%/MHz for the full-power 770-kHz stop band.

Using SCRAM (a program that solves the general coupled-circuit model), we have determined semiempirically that the rms amplitude fluctuation is $\sigma = 11 N/K^2 (\Delta\omega/\omega_{\pi/2})_{\text{rms}} \cdot (\Delta\omega_s/\omega_{\pi/2})$, where N is the number of accelerating cells, K is the nearest neighbor coupling constant, $(\Delta\omega/\omega_{\pi/2})_{\text{rms}}$ is the relative rms deviation of cell frequencies, and $(\Delta\omega_s/\omega_{\pi/2})$ is the relative stop-band width. For the parameters in Table I, $\sigma = 0.2\%$. This effect is much smaller than the effect of coupling-constant errors. The effect of errors in coupling constant on the field distribution of resonantly coupled accelerator structures also can be predicted using the coupling-circuit model. If the two coupling constants from a coupling cell to the accelerating cells on each side of it are not matched, the amplitude ratio of the two accelerating fields will be the inverse of the corresponding coupling-constant ratio. Because this effect is cumulative, a small systematic error in the coupling-constant ratio can result in significant tilt if it continues over many cells. For example, if the coupling constants are consistently unbalanced by 0.5%, the field tilt will be 16% over 32 cells. Random fluctuations of 0.5% are not significant. The solution to this potential problem is to assemble the structure before brazing and measure its field distribution by the bead-pull technique. Any tendency for coupling-constant errors to accumulate can be counteracted by reversing some of the cells so that the coupling errors tend to cancel each other.

The structure was assembled before brazing, and the field distribution was measured by the bead-pull technique. The ordering of the cells then was changed to counteract the field tilts caused by the coupling-constant errors. The field fluctuations that remained after this process essentially were

unchanged by the subsequent brazing and tuning operations. When first clamped together, the structure had a 5% maximum rms amplitude fluctuation, and the first half of the structure had an average amplitude ~8% greater than the second half; whereas, after reordering, brazing, tuning, and final assembly, the difference was only 0.4% between the first and second half with only 2.1% rms amplitude fluctuation. This improvement in the field distribution (see Fig. 3) illustrates the power of the reordering technique.

A short brazed section was used to determine the approximate size of the coupling iris required for a full-length accelerator section. The coupling factor β_2 , obtained when a structure has N_2 accelerating cells of $Q = Q_2$ and when the coupling factor is β_1 for a geometrically identical structure with N_1 accelerating cells of $Q = Q_1$, is

$$\beta_2 = \frac{Q_2}{Q_1} \frac{N_1}{N_2} \beta_1 \quad ,$$

assuming the fields are uniformly distributed in each case.

Fig. 3.
Relative field amplitude in accelerating cells after brazing.

The product $\beta_2 \cdot N_2$ for $Q_2 = 15\,000$ is plotted in Fig. 4. The solid line represents the data (dots) from the six-cell test cavity. The + symbols represent the data obtained from cutting the iris on the preaccelerator. The iris was 13 mm wide on the six-cell test cavity, and the edges were left square; whereas, on the preaccelerator, the iris was 9.5 mm wide with all edges rounded off. The length of the slot has the predominant effect on the coupling. The slot width virtually has no effect. The fact that the edges were rounded on the preaccelerator coupling iris probably accounts for the slightly greater coupling than that observed with the test cavity.

A tapered- β SCS capture section designed to accelerate a 100-keV electron beam to 1.3 MeV has been built as part of the 5-MeV injector for the RTM. A 100-keV electron beam has a β of 0.55; the length of each cell in this structure must, therefore, be nearly equal to the distance the electron moves in that cell during half an rf period. The cavity fields must be known throughout the whole structure to determine these cell lengths. SUPERFISH was used to

Fig. 4.
Data showing the product of number of cells times coupling β versus slot length for the six-cell test cavity with $Q = 15,000$ are shown as dots and are closely represented by the smooth curve. The final results for the preaccelerator are shown by the + symbols.

calculate the fields in each length cell from $\beta = 0.55$ to 1 in steps of 0.05. The average field was assumed to remain constant throughout the structure. This assumption later was determined to be correct based on bead-pull data of the clamped-together structure. These cavity-field results then were used by the program PARMELA to calculate the beam dynamics for this structure. The cell lengths were varied to optimize the beam-transmission characteristics.

The basic $\beta = 1$ cell geometry was used throughout the structure with the cell lengths adjusted by cutting the accelerating half-cells shorter on the center line. No change was made to the coupling cavity or coupling slots. The accelerating cavities were tuned to 2380 MHz by machining the noses shorter.

The completed tapered- β section had an unloaded Q of 14 830, which is 88% of the Q value predicted by SUPERFISH. The value of ZT^2/Q for this structure from SUPERFISH is 5514, which gives a ZT^2 of 81.8 M Ω /m. The ZT^2/Q measured with the bead-pull technique was consistent with the SUPERFISH value. The waveguide is slightly overcoupled to the structure, having a coupling coefficient of 1.10 with a slot length of 3.38 cm, corresponding to a value of 16.3 for the product $\beta_2 \cdot N_2$ plotted in Fig. 4. This value is just slightly above the line and is consistent with the data from the preaccelerator.

CHOPPER/BUNCHER rf SYSTEM

The complete chopper/buncher rf system has been assembled and tested and is now ready for shipment to the National Bureau of Standards (NBS). This system consists of three rf cavities, together with the associated rf power supplies, rf phase-and-amplitude controls, and a local computer-control secondary station. This system was run 24 h a day for 3 wks during this test with only a few minor problems. The secondary station was used during this test for control and monitoring of all the relevant parameters on this system.

THE rf SYSTEM

Since its installation, the 65-kV, 16.5-A power supply has suffered an ~10% ripple at full power. The problem was diagnosed to be an imbalance of the three-phase line caused by the variable transformer. The vendor has built a set of compensation coils, and a new variable transformer was shipped to Los Alamos in early spring. The old variable transformer has been returned to the vendor and has been modified for shipment to NBS. The Los Alamos power supply now meets its 1% ripple specification and the reworked transformer is expected

to solve the ripple problem at NBS as well. The Los Alamos power supply now meets all of its specifications and performs very well.

The rf system has been completely tested in the manual-control mode and has been used to drive both the DAW and the side-coupled preaccelerator sections well beyond their full design power. A prototype resonance controller has been tested with the preaccelerator cavity.

The electronic and manual phase-and-amplitude control systems have all been built and tested. The overall system is complicated because five chopper/buncher fields and four acceleration cavity fields must be monitored and controlled. The entire chopper/buncher system and one of the four high-power cavity systems have now been tested under full power.

A new, space-saving spark-gap crowbar has been designed and tested.¹ Besides saving valuable floor space at NBS, the new crowbar should be more reliable and require less maintenance. Because of the decision to use two side-coupled main acceleration tanks rather than one long tank, part of the high-power rf system has been redesigned. Detailed layouts of the waveguide system have been made, and all waveguide components are either on hand or on order. A total of three-and-one-half racks of electronic equipment and a compact crowbar enclosure have been designed, built, and tested.

RTM CONTROL SYSTEM

During the period January 1 to September 30, 1983, the computer control system for the RTM was considerably enlarged as the original distributed-intelligence concept was fleshed out and actual system elements were controlled under operating conditions. Based on experience with the rf power-test system, the database was expanded by adding general-purpose interface-bus (GPIB) devices and binary-fault chain elements. The secondary interpreter, having proved exceedingly useful in temperature-control tests, was augmented by adding multiply and divide operators, and adding mixed-mode arithmetic to permit intermixing binary coded decimal (BCD) devices with normal binary devices in arithmetic calculations.

Tertiary software was completed and fully tested, both on the magnet power supplies and the injector tertiary station. The magnet power supplies for the smaller steering magnets, dipoles, and quadrupoles were built, the racks configured, and the control elements calibrated and tested.

Basic primary-stations software was completed and tested with one of the two joysticks on the control system and was found to be responsive and relatively easy to master. The software for the link traffic handling was written and tested with two secondary stations and one tertiary station and was error free. Collisions on the link bus were avoided by priority tasking at the primary-station software handler.

The rf secondary-station database was established and programmed, and the chopper/buncher section was successfully tested and controlled.

FORTTRAN applications software on an auxiliary station was written and tested with the rf secondary station, using the regular primary- and secondary-link software and was found to be useful in increasing the diagnostic capabilities of the secondary station.

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CERN EXPERIMENT NA-12

Development of the fast-trigger electronics for the joint Los Alamos/CERN experiment NA-12 progressed significantly.

Testing of the 575 photomultiplier adders, which included an additional 35 for the hadron calorimeter and spares, was completed and they were shipped to CERN.

A crate for 16 photomultiplier adder fan-outs was fabricated, and the boards were installed and tested. Only a dc power receptacle was installed to allow installation of a European-standard power supply at CERN.

Seventy boards for summing the weighted signals of two groups of eight outputs from the photomultiplier adder fan-outs (called the photomultiplier adder squared) were designed, fabricated, tested, and shipped to CERN. Two crates were assembled as above.

Twenty boards capable of inverting the signals for negative-weight channels (called inverting/noninverting amplifier) were designed and partially fabricated, and prototypes were shipped. Half the boards await shipping of a single connector for completion. These boards can be accommodated in the aforementioned crates.

A CAMAC crate with European-standard power input and a crate controller were procured, tested, and shipped.

Installation of photomultiplier adders on a portion of the array was accomplished during a visit to CERN. The installed portion of the system was tested from the array back to the electronics area. The noise performance was found to be excellent.

Remaining activities include (1) final installation of all components, (2) selection and installation of weighting networks, (3) signal patching, (4) design and production of the CAMAC interface, (5) final system check-out, and (6) production of an IBM 168/E emulator.

LAMPF II

The LAMPF II project aims at a conceptual design for a kaon factory at LAMPF. Central to the design will be a rapid-cycling synchrotron complex delivering 100 μ A of protons at an energy at or above 10 GeV (the final energy has yet to be decided). Magnet-design and cost-estimate effort has shown that a two-stage booster-accelerator scenario is not more expensive in magnets than a single-stage 30-GeV ring. A general-purpose magnet-design program has been written for exploration of possible scenarios. Studies of the properties of ferrites at 50 MHz and high power have been undertaken to develop a tunable resonator for the LAMPF II project.

At the LAMPF II Summer Study, it was speculated that muons from LAMPF II could be cooled and injected into a multi-TeV rapid-cycling synchrotron to obtain high-energy, high-luminosity collisions.

Program development of ARCHSIM into a general-purpose accelerator-design tool continues; this program is also used in PSR calculations and was presented at the International Accelerator Conference (Fermilab, August 1983) and the Computing in Accelerator Design and Operation Europhysics Conference, September 20-23, 1983.

We are continuing to explore possible instability limitations for LAMPF II scenarios (longitudinal, transverse impedances, synchrotron resonances).

PROTON STORAGE RING

STATUS

Construction of the Proton Storage Ring (PSR) is proceeding on schedule. The contractor has completed the ring tunnel, and installation of equipment has started. The equipment building above the ring is also nearly finished. Procurement of standard equipment for the PSR is proceeding rapidly; about three-fourths of the equipment has been received or is on order. Meanwhile, staff of Accelerator Technology, Medium Energy Physics (MP), and Physics Divisions are developing special state-of-the-art systems required for PSR.

Below we discuss major progress made during this period in defining and implementing the computer control system and also discuss theoretical effort on the PSR.

PSR CONTROL SYSTEM

The existing controls for the beamline, Line D, and the Weapons Neutron Research (WNR) consist of a single computer with ~950 channels connected to it. The new PSR control system¹⁻⁵ will take over these channels and will add ~1500 new channels. However, the controls problem does not scale with channels. The PSR (see Fig. 5) adds a new dimension of complexity to the facility, and the machine physicists and the operators need much more help than the existing controls system on WNR can give.

Requirements

The PSR control system's overall requirements are listed below.

- The system must provide the operator with full and responsive facilities for bringing on-line all the equipment that makes up the PSR
- The system must automatically monitor equipment for normal operation and report exceptions to the operator
- The system must present information to the operator about the current state of the PSR, or any selected section, in an easily understood form
- The system must maintain a log of significant events
- The system must be flexible enough to add new equipments and channels easily, as well as to add new programs for operator interaction

PROTON STORAGE RING

Fig. 5.
Proton storage-ring schematic.

These requirements specify two kinds of processing required of the computers in the system. The first kind is single-word input/output (I/O) processing associated with reading values from and writing them to the interfaces connecting the PSR's equipment to the control computers. This task also will include simple routine conversions and range checks, and the magnitude of the task scales with the amount of equipment and number of channels. The second kind of processing relates to the provision for operator interaction, and the magnitude of this task scales with the number of operators and their activity.

The choice of microprocessors for the first task and a computer system for the second task is a natural one. To simplify the software development, the microprocessors and the computer were chosen from a compatible range and are Digital Equipment Corporation (DEC) LSI-11/23's and LSI-11/73's running RSX-11S and a VAX 11/750 running VAX/VMS. Thus the LSI-11's are memory-only systems that are down-line loaded from the VAX 11/750.

The third requirement calls for not only a connection to all the power supplies, etc., but also suitable, well-placed diagnostics devices in the beam-lines and the storage ring that are connected into the control system. These devices present extra challenges to the software designers because invariably they are more complex than power supplies, vacuum systems, etc.

For many reasons, CAMAC was chosen as the interface system between the computers and microprocessors of the control system and the equipment of the PSR. This is also an excellent choice for the diagnostics because of the wide range of suitable CAMAC plug-ins available on the market. Nothing in the design of the software or hardware of the system precludes the use of other interfacing systems, for example, IEEE 488, where appropriate. A recent analysis of the software overhead, hardware costs, and performance showed that, given the communications needs of the system, a serial CAMAC system was the best choice for the communications between the VAX 11/750 and the LSI-11's.

Detailed Hardware Description

Figure 6 shows schematically the hardware of the system, which is located in several buildings. The computer-related items on the two operator consoles are six color-graphics displays with touch screens, twelve computer-assignable knobs, and a conventional computer terminal. The remainder of the console contains oscilloscopes, TV monitors, and other dedicated instrumentation. Although the touch screens and color-graphics systems are commercial products interfaced to the VAX 11/750 Unibus, the programmable knob units are being constructed in-house and are interfaced through CAMAC modules. These devices make up the main hardware of the operator interface with the control system. The console consists of ten bays arranged to form two operator consoles and one single-bay alarm console.

The CAMAC driver on the VAX is a powerful interface with extensive direct-memory access (DMA) facilities, and it has a software driver under VMS, the VAX operating system. As can be seen in Fig. 6, the serial highway from the VAX 11/750 controls the CAMAC crates in which are mounted the LSI-11 microprocessors. One component of the LSI-11 system is a module that gives CAMAC access to the Q-bus of the LSI-11. It is this module and the DMA facilities of the CAMAC driver that allow the VAX 11/750 to keep databases up to date with minimum VAX software overhead and almost no LSI-11 software overhead. Both processors also are able to interrupt the other by CAMAC Look-at-Me (LAM) interrupts.

There are six such LSI-11's planned, including one for development, and each will have a serial highway of its own to connect its CAMAC crates. These crates hold the CAMAC plug-ins that connect to the equipment of the designated area for the LSI-11. A watchdog system in each LSI-11 crate will ensure that

Fig. 6.
PSR control system hardware.

if a fault occurs in the LSI-11, the run permit for the PSR will be dropped within 1 s. The LSI-11 and its associated CAMAC system is termed an Instrumentation Sub-system (ISS); the "PSR Passive" ISS is the shaded area in Fig. 6.

At this time, there is one LSI-11 allocated to act as the "diagnostics" ISS. However, some diagnostic devices are better placed on the CAMAC serial highway of the VAX and controlled directly by the VAX. Another diagnostic is in fact controlled by an 8085 microprocessor, and this communicates directly with the VAX like any ISS.

Data in the System

In the control system, data exist in one of four forms. Binary data represent two-valued inputs and outputs, such as on or off. Analogue integer data represent I/O values that are covered by an integer in the range -32 000 to +32 000. Analogue real data are used for all other single-valued channels.

Finally, analogue vector channels are used where an array of integers is required, for example, to specify a waveform. Each of these forms can be in a number of different types:

- Interface units—the value in primary SI units at the front panel of the CAMAC or IEEE 488 unit
- Hardware units—the bit pattern read or written across the I/O bus
- I/O units—hardware units modified to a legal PDP-11 and VAX-11 data type (the form in which data are stored in the run-time database)
- Engineering units—value in meaningful units to an operator; for example, pounds per square inch, amperes, degrees Celsius
- Physics units—value converted to a higher level unit that in some cases is a more meaningful indication of the physics of the process; for example, tesla
- Process units—high-level units that cannot directly translate to a single I/O channel, for example, tune

Not shown on the diagram of the software, Fig. 7, is that the conversion between I/O units and engineering or physics units is carried out by a conversion module. This module has coded into it the various required algorithms and has access to the run-time database to obtain the parameters needed for each conversion.

Detailed Software Description

The overall software has been broken down into a number of modules, each having a well-defined function and a clear interface to the rest of the system. In fact, the modularity of the software reflects that of the hardware, allowing ease and flexibility in making changes. The modules are defined so that

- one or more modules make up a program or task;
- ideally, each module should be less than one month's work to code and test; and
- the intermodule interface is chosen to isolate future changes.

The first step was to isolate in a single database all information that relates to the individual equipment and its associated channels. The information in this database is held in an ASCII file established and maintained using a DEC product, DATATRIEVE. DATATRIEVE allows easy maintenance of a database and easy-to-use sorting of the data and report writing.

Fig. 7.
PSR control system software.

From this database is generated a machine efficient, run-time Control (COOL) database. It is this database that exists in main memory of the VAX 11/750 and the LSI-11's, and that which the programs reference. As an example, the address of a CAMAC plug-in will take several ASCII characters in separate fields in the ASCII database from which the run-time database-generation program will produce packed binary addresses. The format of the packed address will be defined by the CAMAC coupler, so that it can be used directly at

run-time. The run-time database generation also will produce any data tables required by individual programs or tasks. Thus the generation of a new database will at least mean relinking much of the system.

Figure 7 shows schematically the system's software layers. Generally, the LSI-11's act as intelligent I/O controllers to the VAX 11/750, enabling the VAX 11/750 to carry out operator-requested functions.

At the center of the VAX 11/750 software is the COOL database that is referenced through access routines to isolate the detailed structure of the database. On top of the access routines come all the other modules of the system.

The command module is responsible for the interaction with the operator to assign knobs or start specific operator-interaction programs. It is also responsible for keeping track of console resources. This is the module that comes up first at the console when the system is started.

The knob module is responsible for accepting knob assignments, taking knob input, and making the corresponding changes in the COOL database. It also maintains the one-line display on the knob unit.

The alarm module is responsible for maintaining the alarm screen and the log of significant events. Each channel, soft or hard, will have three sets of limits associated with it. Warning and alarm limits are self-explanatory, but the log-by-exception limits are less clear. These define a delta so that when an input channel is more than this delta from its last logged value, the new value is logged with the time and date. For control channels, these data are maximum range, normal range, and maximum rate of change.

The data migrator ensures that the varying data and the flags that indicate changes are kept current between the VAX 11/750 and the individual LSI-11's. For this the CAMAC system is used as described above.

Although all the above are single modules, the process modules are many and varied. It is here that the expansion takes place, and the system is tailored to the particular needs of the PSR. Selected process modules are started by the command module on the request of the operator. The running process modules have full access to the graphics devices on the console and the COOL database, which includes the last inputs from the touch screens. Thus, they have full information on the state of the PSR and full control of the PSR equipment. It is in the process modules that the flexibility of the system exists.

The next layer of the software is the operating system, VAX/VMS, through which goes all communication with the real world. For this purpose, VAX/VMS includes the I/O drivers added for CAMAC and the Lexidata color-graphics system.

Finally comes the operator interaction and CAMAC communications layer, which represents the main functions of the VAX 11/750.

There are two fundamental differences between the VAX 11/750 software layout and the LSI-11 software layout. The first is that the RSX-11S operating system is used only for task management and not for I/O management. This gives rise to the double-centered representation of the software. The second difference is that, as shown, the VAX 11/750 has direct access to the LSI-11 COOL database. This is a simplification in some respects, because the VAX 11/750 data migrator has control access to the data migrator in the LSI-11 to ensure that the LSI-11 takes action on the changed data.

Input channels are handled differently from output channels by the ISS. Two software modules, the LAM module and the hardware reader, are responsible for ensuring that the COOL database input-channel data in the ISS are up to date. The LAM module does this for I/O plug-ins that are interrupt or LAM based, whereas the hardware reader does the updates on a timed basis. All the other software modules access input data from the COOL database.

The surveillance module is responsible for checking input data against specified limits and reporting exceptions to the alarm module in the VAX 11/750 through the COOL database.

All changes to be made to equipment parameters must be made through an equipment module, which is a separate program for each set of equipment. This module can check input channels in the COOL database and apply the change in a manner specific to that equipment. This allows checks to be programmed into the system to ensure safe and correct operation. The equipment module also implements soft channels. These channels do not relate directly to a single hardware channel, but to two or more channels in a specific way. A simple example might be the on-off control of an equipment where a single, soft on-off channel might be translated by the equipment module into a pulse output on one of two binary output channels.

All access to the I/O plug-ins by the LSI-11's is through the Hardware modules and the Interface Modules. These modules are designed to hide the differences between I/O plug-ins of similar function but different detailed

design. Thus the code in an equipment module need only reflect the type of I/O, not the details of the actual I/O plug-in used. The hardware module also has no need to know the details of how the I/O bus is connected to the computer, but rather it issues calls in terms of the I/O bus (CAMAC, IEEE 488 etc.) to the interface module that localizes the code reflecting the actual connection of these buses. To illustrate: if a pair of wires bringing a 0- to 10-V signal to a CAMAC plug-in were to be moved to a similar IEEE 488 unit, all that would need changing would be the run-time database.

DIAGNOSTICS INTERFACING FOR THE PSR

Beam-Position-Monitor System

This system has already been described in some detail elsewhere.⁶ It consists of a large number of detection units with an rf multiplexer system to select the unit of interest. The output of the multiplexer is then processed by rf signal-processing electronics that provides an X- and Y-position signal to two fast analogue-to-digital converters as well as a beam-present signal. Some further linearization of the signal is then required before the two X- and Y-positions of the centroid of the beam are obtained.

The detectors used consist of four pickup plates equispaced around and just inside the beam pipe. As such, they do not intercept the beam and so give a nondestructive read-out of the beam position.

To control the timing and sequencing of data acquisition and take account of the operating modes of the PSR, a microprocessor system has been implemented based on an Intel 8085. This system has two control ports. One is an RS 232 port that allows an exerciser to operate the system locally for initial setup and trouble-shooting. The second port is a 16-bit parallel port connected to the VAX 11/750 computer. This second port is implemented with commercial 16-bit FIFO I/O CAMAC units. In addition, there are separate signals to allow the 8085 to interrupt the VAX to indicate that there is a message in the input FIFO and to allow the VAX to initialize the 8085. Thus, rather like the LSI-11's, the communications are CAMAC based although they are message oriented. The 8085, therefore, can be looked on as a single-purpose ISS as far as the hardware is concerned.

In the software, the process module that is called by the operator to handle the beam-position-monitor system communicates directly with the system

through the CAMAC driver in the VAX. Messages have been defined that cause the 8085 to set the various delays and multiplexers and collect position data. When all the requested data are collected, the 8085 places a message in the input FIFO and sets a CAMAC LAM so that the process module in the VAX will be started, will read the data, and will present it to the operator.

The high speed of the analogue-to-digital converter (ADC) allows the collection of a large amount of data from a single detector during one cycle of the PSR. However, the delays involved in resetting the multiplexers and the associated delay settings preclude taking data from more than one detector in a single cycle. Thus some of the commands to the system can take from a considerable fraction of a second to several seconds to complete, depending on the repetition rate of the PSR as well as on the actual command. The final details of the timing and the VAX interface are being completed.

Beam-Profile Monitors—Harps

The harp units consist of an X-Y grid of wires that is placed in the beam-transport lines. The current on each wire is proportional to the integrated intensity of the beam along the wire. Thus, measuring the charge collected in one cycle of the PSR on all the wires gives an X- and Y-profile of the beam. The resolution of this profile depends on the spacing of the wires, and the sensitivity depends on the thickness of the wires and the noise in the electronics.

The harps will perturb the beam, especially in the injection line where they will cause the beam to be partially stripped from H^- to protons. For this reason, the harps are introduced into the beam only when a measurement is needed. In the storage ring itself, the high circulating charge precludes the use of harps.

The read-out of harp wires will be by specially constructed multiplexers. The input stage of the multiplexers has a sufficiently high impedance that over a cycle of the PSR it will integrate the accumulated charge. After a cycle of the PSR, the multiplexers will cycle through the 32-X and 32-Y wires and provide an output voltage and trigger pulse for an ADC to digitize the beam profile. This ADC will be operated by the diagnostics ISS and the results will be migrated to the VAX in the normal way. In this case, commands to insert a harp, make a measurement, adjust the gains of the ADC, etc., will be normal-output or control channels to the ISS.

Loss Monitors

These monitors are designed to study the beam spill at various positions along the transport lines and storage ring. The actual monitors are mounted on the walls of the tunnel and consist of 1-pint cans filled with Nuclear Enterprises scintillator 235A viewed by an RCA 4552 phototube. The amplifier electronics has two outputs. The first allows the loss to be seen on an oscilloscope as a function of time and the second is connected to a gated ADC so that the loss as a function of time can be recorded by the control system. This recording will be done by the diagnostics ISS and the result then is migrated to the VAX in the normal way.

Activation Protection Monitors

These monitors are the same as the loss monitors but the electronics differs. The amplifiers have a longer time constant than the loss monitors and the output is compared with a preset trip level. If the level is exceeded, the output will activate a fast-protect system so as to either stop injection or rapidly dump the stored beam, depending on the time and location of the trip. The fast-protect system is quite separate from the control system, although the control system is able to read out the inputs that caused a fast-protect trip. Each new cycle of LAMPF and the PSR will attempt to reset fast protect. The activation protection electronics provides a dc output that is proportional to the average loss expressed as a percentage of the trip level. The activation protection monitors are used to regulate the spill budget of the facility. As such, each monitor will be set to a trip-level appropriate to its location.

Phosphor Screen

One insertable phosphor screen will be installed in the region downstream of the injection-line stripper magnet before the injection point. At this point, the beam is a neutral hydrogen atom beam. Read-out of the phosphor screen is by a television camera, and thus no read-out to the control system is planned. The screen will be inserted by command from the control system, however.

Energy Measurement

The energy acceptance range of the PSR $\Delta p/p$ is less than about 0.1%, requiring stabilization of the energy of the beam from LAMPF. At 800 MeV, the

protons and H^- ions are not fully relativistic, traveling at about 0.8 c; thus, a time-of-flight measurement can be used to determine the energy. This requires two pickups with a time measurement made as a bunch traverses between them. A flight path between the pickups of about 100 m is needed, assuming a 100-ps time resolution. Quite standard commercial CAMAC units are able to achieve this; therefore, the energy measurement in this case would be a simple input channel on the diagnostics ISS.

The present beam from LAMPF has no stringent requirement on absolute energy. On the short term, it has been observed to vary by 0.5 MeV from its nominal 800 MeV. This variation is within the acceptance of the PSR, but closer control is desirable. Long-term variations of up to 10 MeV have been seen, and these are outside the acceptable limits. One solution for reducing the fluctuations is to control the phase of the last rf tank of LAMPF. This would be a feedback loop from the energy measurement through the diagnostics ISS and is currently being implemented.

Quadrupole Moment Detector

The quadrupole moment detector uses the same design of pickup as the beam-position-monitor system, but processes the signal in a different way to generate the X- and Y-widths of the beam, which then give the quadrupole moment. The pickup will be placed in a straight section of the ring rather than inside the quadrupoles as are the position-monitor pickups in the ring. The output voltage of the pickups will be read by a gated ADC attached to the CAMAC system of the diagnostics ISS. The result is a single-valued channel migrated to the VAX in the normal way.

Frequency Monitor

The frequency monitor in the ring consists of a simple pickup inside the pipe with a fast spectrum analyzer to analyze the signal detected. As the spectrum changes with time, a real-time spectrum analyzer is required. The signal can be observed simply with the CRT of the analyzer, but the system is much more versatile if the frequency spectrum is read into the control system. This versatility will allow reading the spectrum as a function of time as well as further processing of the information. As with the beam-position-monitor system, such an instrument will be connected directly to the VAX.

Satellite Detector

The chopper's function is to prepare the time structure of the H^- beam to be accelerated by the linac so that it suits the particular operating mode of the WNR/PSR facility. Satellites are defined as bunches or parts of bunches appearing before or after the desired bunch. They could arise if the chopper does not deflect the beam sufficiently or if it is incorrectly phased. Thus, a satellite detection system is essential to adjust the chopper. The satellite detector consists of a foil that can be inserted into the beam in the transport line between the end of LAMPF and the storage ring. The flash of γ -rays is recorded with a fast detector as a function of time to obtain the time structure of the injected beam with respect to the chopper frequency. A time-to-digital converter in the ISS CAMAC will be used to store the information in the control system.

Current Monitors

These will be ferrite toroids with the beam acting as the primary winding. The secondary winding will have about 100 turns, the output of which is then amplified and passed through a voltage-to-frequency converter. A gated scaler as part of the diagnostics ISS will then measure the beam charge for the gate period. The injection line current monitors will be an existing LAMPF design. The ring monitor cannot be highly inductive, and so a wall current monitor will need to be developed. For the extraction line, the behavior of the LAMPF monitor needs to be investigated for peak currents of up to 46 A.

THEORETICAL EFFORT

Theoretical work on the PSR included

- beam injection and rf power in the PSR,
- coherent transverse motion of short bunches in the PSR, and
- influence of localized rf cavity impedance on the longitudinal stability of a long proton bunch in a storage ring.

Beam Injection and rf Power in the PSR

Beam injection with constant bunching voltage has been considered for PSR operation until recently. To maintain a low longitudinal emittance, a linearly ramped bunching voltage is being considered. In this case, we found that if

the magnitude and the phase of the rf voltage were kept constant, then the cavity tuning speed would be substantially higher than that for the constant bunching voltage case. Thought then was directed toward the tuning of the phase and the magnitude of the external rf power, together with the resonant frequency of the cavities. Analysis for the power requirement and the combined tuning of rf source and cavities have been carried out. The results show that varying the phase and the magnitude of the rf voltage can indeed ease the cavity tuning speed required; the klystron power originally specified is sufficient to handle the mismatched situation caused by this kind of tuning.

Coherent Transverse Motion of Short Bunches in the PSR

Owing to the short axial length (1 ns) and the high proton intensity in the short bunches in the PSR, appreciable transverse tune variation from the ends to the center of the bunch is anticipated. This variation raises some practical questions concerning coherent transverse motion of bunches, particularly in the coherence time of transverse oscillations related to the feedback damper design. These problems currently are under investigation. Theoretical analysis results to date show that for the hypothetical situation of no external boundary, the chromaticity effect is weak and the tune depression from space charge will not affect the coherent transverse motion of a bunch. The influences of a surrounding wall are now under study.

Influence of Localized rf Cavity Impedance on Longitudinal Stability of a Long Proton Bunch in a Storage Ring

In most longitudinal stability analyses, the impedance of rf cavities is usually counted as a part of the total impedance of a storage ring; but the fact that the cavities only occupy a small portion of the circumference of a storage ring is neglected. A more accurate analysis should consider the effect of localized rf cavity impedance. A dispersion relation has been obtained from a one-dimensional electrostatic analysis on the cold fluid model, and the numerical computation of the dispersion relation has begun.

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PORTABLE RADIOGRAPHIC LINAC

During the past year, a portable radiographic machine has been assembled. We wanted to develop a machine that could be taken, perhaps in a specially equipped van or aircraft, to a work site where its capabilities were needed. (At the present time the work is usually brought to a permanent radiography facility.)

An 8-MeV linear electron accelerator (linac) is ready to be tested. The machine is rugged, two-man transportable, and designed to be capable of withstanding extreme environmental conditions: sunlight at 120°F, snow at -30°F, and blowing sand. This linac will serve as a source of high-intensity x rays for radiography and photoneutron production. The machine comprises seven reinforced aluminum enclosures weighing around 200 lbs each, including all the accelerator components. Now that assembly of the machine has been completed, it must be installed and tested in an area that will provide natural or locally installed shielding because of the high x-ray radiation.

Potential scientific applications for this linac include nondestructive testing, radioactive waste-management programs, and safeguards. The linac would provide neutron and gamma sources only when operating, thus avoiding some of the problems of constantly emitting radioactive sources. Additional information might be obtained from time-history measurements following pulsed-neutron interrogation. Also, such a portable linac could serve industrial radiographers. As a high-intensity source of penetrating x rays, the linac will provide increased depth of penetration, shortened exposure times, and improved resolution inherent in the reduced focal spot size—all in a convenient portable electronic radiation source. The high intensity and pulsed nature of the x-ray beam also will make possible x-ray cinematography.

The electron beam produces an x-ray beam by hitting a metal target; the x-ray beam travels through the air to the object to be radiographed or to a material that produces neutrons when struck by the x ray. The radiograph is made when the x-ray or neutron beam passes through the object and exposes a photographic film plate. For this machine, the central axis x-ray intensity at 1 m from the metal target is at least 400 rads/min at 8 MeV. Such a machine is capable of enhanced field radiography that would include spatial resolution previously unattainable outside fixed laboratory facilities.

Technology transfer from our Los Alamos development program back to industry for application in the commercial market is a specific goal. There is considerable interest outside the Laboratory in portable radiographic sources of this type. For many years, Varian Associates of Palo Alto, California, has been the leading supplier of linacs for radiography, not only in the US but in the rest of the industrialized countries of the world as well. The workhorse of this product line has been the Linatron 2000, which weighs approximately 3600 lb. The AT-Division portable radiographic linac uses Linatron 2000 subsystems as principal components. The redesigned version of the Linatron 2000 not only is portable, but also includes additional features that add versatility to the machine's capabilities such as a very low dose per pulse mode. The main reasons for using the Linatron 2000 as the basic building block for our system are that spare parts are readily available and crucial system components already have been extensively field-tested.

KLYSTRON CODE DEVELOPMENT

STATUS

Substantial progress has been made on a new klystron simulation code in which usefulness in the klystron design process has been emphasized. We have done a successful initial bench-mark test against an actual operating tube. As a result of this success, we are now engaged in additional bench marks and in a project to redesign the klystron that Oak Ridge uses in their linear accelerator to achieve higher output power at greater efficiency.

INTRODUCTION

Inefficient klystrons cost money in the form of wasted electrical power. Therefore, it has been the goal of this project to develop a computer code that contains the necessary physics to completely describe a klystron, but one fast and inexpensive enough to run that it can be used as an effective design tool for advanced tubes with efficiencies greater than 60%.

Current computer codes used for analysis of klystrons use two approaches to describe space-charge, the mutual repulsive forces between electrons in the device: the disk-model and the particle-in-cell method. In the disk model, the electron population is approximated by disks, and the interaction is calculated between disks—this is an oversimplification that cannot accurately simulate high-efficiency klystron behavior at and beyond saturation. In addition, these codes do not, in general, calculate self-consistent results. Hence, their use for the design of high-efficiency klystrons is not possible, although the disk model is sufficiently accurate at the 50% efficiency level. The particle-in-cell codes are too complicated, and contain more physics than is necessary to describe the problem. These, though accurate, are prohibitively expensive to use.

The project's goal is to derive a better model that contains the necessary physics to completely and self-consistently describe a klystron but that also uses its inherent symmetries to keep the code relatively inexpensive to operate. This program then would be used as a design tool for high-efficiency klystrons with the first application being to improve the efficiency of the LAMPF klystrons. The code so developed includes large signal effects, relativity, fundamental and harmonic cavities, and self-consistent calculations of the induced currents and gap voltages. Realistic cavity-field distributions

and initial conditions for the electrons are calculated from the SUPERFISH rf-cavity design code and electron-gun codes. The codes' calculations are for the steady-state klystron behavior.

MATHEMATICAL MODEL

The klystron is modeled as an axisymmetric, linear electron-beam device with periodicity in time. The electrons in one cycle of this fundamental frequency will be used. The beam is broken into rings, each ring a "super-electron" in both the radial and axial dimensions. Each ring has thickness and width, and together they completely fill the original beam. Time is used as the independent parameter (as opposed to axial position z) and as time increases, these superelectrons experience electric and magnetic fields, and their motions obey the Lorentz force law.

Green's functions are used to calculate the particles' relative space-charge forces. At a point (r, z) that is due to a unit-charged, infinitely thin and narrow ring of radius r' and location z' in a perfectly conducting cylinder of radius a , the space-charge fields are¹

$$E_{rsc}(r, z; r', z') = \frac{\gamma_0}{2\pi\epsilon_0 a^2} \sum_{\ell=1}^{\infty} \frac{J_1(v_\ell r) J_0(v_\ell r') \exp(-v_\ell \gamma_0 |z-z'|)}{J_1^2(v_\ell a)} ,$$

$$E_{zsc}(r, z; r', z') = \frac{\text{sgn}(z-z')}{2\pi\epsilon_0 a^2} \sum_{\ell=1}^{\infty} \frac{J_0(v_\ell r) J_0(v_\ell r') \exp(-v_\ell \gamma_0 |z-z'|)}{J_1^2(v_\ell a)} ,$$

and

$$B_{\phi sc}(r, z; r', z') = u_0 E_{rsc}(r, z; r', z')/c^2 ,$$

where u_0 is the ring's axial velocity and v_ℓ is the ℓ th solution of $J_0(v_\ell a) = 0$.

For the fields caused by a superelectron, these expressions are integrated over the source particle's length (an integral over z') and width (an integral over r'). This technique results in correct particle motion for a variety of test cases, as will be seen later.

The cavity-gap fields are used in superposition with the space-charge fields. The SUPERFISH code² is used to map the fields' relative magnitudes on a grid superimposed around the gap. Knowledge of the gap voltage gives the absolute magnitude of the fields. Both the induced current of the cavity, and the gap voltage, must obey the energy balance integral:

$$I_{\text{ind}}(t) V_{\text{gap}}(t) = \int J(t) \cdot E_{\text{gap}}(t) d x^3 , \quad (1)$$

and the cavity impedance, gap voltage, and fundamental Fourier component of induced current must obey Ohm's law:

$$Z_{\text{cav}} I_{\text{ind}_1} = V_{\text{gap}} . \quad (2)$$

The impedance is a known function of the cavity shunt impedance, resonant frequency, and cavity quality factor. Initially, an estimate based on linear theory is made for the voltage and phase at a gap; then, the particles are followed through the gap and the induced current is calculated using Eq. (1). The fundamental component is calculated, and with Eq. (2) the new voltage and phase at the gap are calculated. The process is repeated until successive values of the voltage and phase are within a prescribed error tolerance of the past values. In actual practice, four to eight iterations are usually required through each gap. Both fundamental and higher harmonic cavities can be dealt with in this manner, and superposition of any number of distinct cavity fields can be included. The superelectrons obey the Lorentz force equation as

$$\ddot{\vec{m}}\vec{x} = q (\vec{E} + \vec{v} \times \vec{B}) ,$$

infinitely small-point particles at the superelectron's radial and axial positions. As the rings' radial positions change, the radial width varies in a laminar manner. The code calculates the forces and motions in Cartesian coordinates to remove the $1/r$ singularity these equations have in cylindrical coordinates. Busch's theorem³

$$r^2 \ddot{\theta} = \frac{e}{2m} (B_z r^2 - B_{\text{cathode}} r_{\text{cathode}}^2)$$

can be alternately used to find the $d\theta/dt$ motion of the rings. These equations are, of course, all fully relativistic.

The time periodicity provides simplification of the model. Only one wavelength of beam is needed to represent the entire beam. However, the wavelength followed is dynamic, with particles passing in and out of it, and careful book-keeping is needed to ensure the periodicity. Once a periodic solution is obtained, that forces self-consistent particle motion. Particles that have turned around and are heading toward the cathode are treated completely satisfactorily (if not perhaps totally naturally) with no loss of the periodicity. An example of this is shown later.

Further simplification of the model, with no loss of generality, occurs with the use of the fundamental Fourier components to describe the induced current and gap voltages. In addition, any external coupling can be included by simple circuit analysis. For example, a cavity driven by both the beam and an external current generator operating at the fundamental or some harmonic frequency can be represented by the circuit of Fig. 8. This also must be calculated self-consistently because the effective current generator i_g' depends on both the cavity-induced current i_b and the actual generator current i_g ; and i_b , as before, depends on the total cavity voltage $V_{\text{gap}} = -(i_b + i_g') Z_{\text{cav}}$ (in this case).

It should be emphasized that this analysis is for the steady-state solution only; no transient behavior will be detected.

Interpretation of the klystron behavior is made both with the particles' lost energy and with the Fourier circuit analysis above. All Fourier components are solved with integration in time (as opposed to axial distance z).

Fig. 8.
Equivalent circuit for the coupling of a beam-driven cavity and a current generator-driven cavity.

TEST RESULTS

Some dc test runs have been made for the LAMPF klystron (with 50% efficiency) with $I_0 = 24$ A and $V_0 = 86$ kV. The beam tunnel radius is 25.4 mm and the beam radius is 0.7 times the tunnel radius. The maximum error between the calculated space-charge radial field and Gauss' law in a balanced flow situation is 0.5% with four rings. This error occurs at the inside ring and is independent of n_z , the number of axial subdivisions of the wavelength. Figure 9 is a dc test case for a Brillouin beam that enters a zero-field region at $Z = 0$, where $Z = zw/u_0$, ω is the fundamental radian frequency, and u_0 is the electron velocity at the beginning of the problem on the axis.

The rings should follow the universal beam-spread curve³, and the agreement is within 10% at $Z = 5$. Most of the error is due to the first and last electrons in the wavelength. The space-charge forces are assumed periodic in Z , but in reality they are not, especially with such an expanding beam as shown in Fig. 9. If the first and last electrons were omitted, the agreement would be within 2%. With the minor modification of removing the periodic statement in the space-charge subroutine, the code could be adapted for analyzing the motion of isolated bunches of charge for steady-state conditions.

Fig. 9.
R- versus Z-trajectories for
an unmodulated beam entering
a zero-field region at $Z = 0$.

Figure 10 shows the axial bunching for an ideal beam of four rings and eight axial subdivisions that hits a thin gap at $Z = 0$. The axial field is twice the Brillouin value. The plasma frequency reduction theory⁴ predicts a

Fig. 10.
Axial bunching diagram with
 $B/B_{BR} = 2.0$, for a single
thin gap at $Z = 0$ and
 $V_g/V_0 = 0.12$.

maximum of i_1/I_0 at $Z = 25.9$; however, the output shows a maximum at $Z = 26.3$, an error of 1.5%. Tests with more than one radial subdivision show the effect of different plasma reduction factors for different radii inside the beam, whereas the model used in the plasma-frequency reduction theory assumes a uniform reduction factor.

Tests with only one radial subdivision show better agreement with the theory. Tests with no space charge show agreement to within 1% for the location of the harmonic current's maximum. Runs between the ballistic limit and the space-charge limit agree fairly well with previous results.⁵

Particles that have turned around do not exhibit any pathological behavior, and the code arrives at a periodic and self-consistent result with them too, Fig. 11. This is a unique feature of this code, and important for correct modeling of high-gain, high-efficiency klystrons.

In a second bench-mark test against the standard LAMPF klystron, a series of runs has been made to derive a typical power-transfer curve as shown in Fig. 12. This curve agrees fairly well with the general class of power-transfer curves measured experimentally for these tubes. This test is

Fig. 11.
R- versus Z-trajectories
for a beam with two particles
that have turned
around, one at $Z = 21$,
and the other at $Z = 25$.

Fig. 12.
Calculated power-transfer
curve for LAMPF klystron.

considered significant because there is agreement up to and through saturation—previous codes could not handle this wide dynamic range. Therefore, this test gave us great encouragement and convinced us to test the code against other tubes, especially the very high voltage tubes where other effects, such as relativity came into play.

A few runs have been made for the standard Stanford Linear Accelerator Center klystron at a beam voltage of 270 kV. So far, no obvious errors have been apparent, providing a check on the correct relativistic dependence in the equations of motion. In addition, a study of the Oak Ridge klystrons has just begun.

Comparison of further runs with the experimental data on these tubes will provide a measure of the code's accuracy; if the comparisons are favorable, they will show that the model used in the code is sufficiently accurate to be used for the design of future high-efficiency tubes.

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PERMANENT-MAGNET DEVELOPMENT

STATUS

The objectives of the permanent-magnet (PM) development (to complete the design code, use it to design a solenoid-like magnet, and to build and test the magnet) were scheduled to be completed by October 1, 1983. Unfortunately, the parts made of PM material, received from a vendor at the end of August, were of poor workmanship and had to be rejected because they did not meet our tolerance specifications. Thus, tests could not be completed.

INTRODUCTION

In 1965, J. P. Blewett¹ suggested the use of PM material in the construction of a quadrupole. He also derived an expression for the pole-tip strength of such a quadrupole that was directly proportional to H_c , the H-coercive force of the material.

Since this work was done, rare-earth cobalt (REC) magnet material has become available. Specifically, samarium cobalt is now available and has the capability of being magnetized to field levels much stronger than previous PM materials. This capability has made it possible to realize, in a practical sense, Blewett's suggestion of 1965.

A substantial amount of theoretical work has been done by Klaus Halbach at Berkeley to develop the design criteria for beam-transport magnets using REC material.² The first actual use of this type of magnet was in a design by Ron Holsinger and Halbach for the New England Nuclear (NEN) linac.³ This system uses 109 PM quadrupoles in the 45-MeV linac at NEN.

It was noted in an informal report in March 1983 that this project covered two activities. The first and most important task was to design, build, and test a PM solenoid. The second task was to conduct radiation-damage experiments on REC material. Because the funding received was less than requested, the radiation-damage task was not pursued. All efforts were directed towards design, fabrication, and test of a PM solenoid.

DESIGN CODE

With the assistance of Halbach and Holsinger, the equations describing a solenoidal-type magnet using REC have been completed. These equations have been incorporated into the PANDIRA code, which is used for magnet design in AT

Division. Primarily, this incorporation consisted of modifying the code to handle cylindrical coordinates.

MAGNET DESIGN AND FABRICATION

A magnet has been designed using the modified PANDIRA code and is shown in Figure 13. The magnet was designed using readily available REC blocks that are 2 by 2 by 1/2 in. The arrows in the REC material show the direction of the easy axis. The resulting magnet is the approximate size to be used in the injector for the accelerator test stand.

The PANDIRA code is two-dimensional and calculates magnetic fields along a cross-sectional cut passing through the axis of a cylindrically symmetrical magnet. Figure 14 shows magnetic field lines across one of the gaps in the magnet we have designed. The magnet and field lines have axial symmetry about the left-hand side of the figure and are antisymmetric about the lower boundary; that is, in the other gap (now shown); the field lines occupy identical positions but run in the opposite direction.

Figure 15 shows the calculated field strength on-axis plotted against position on the axis. The antisymmetry of the magnet is obvious. Note that this calculation may be slightly inaccurate because the solenoid is not truly axisymmetric. The gaps between the magnets in the outer layer, as shown in

Fig. 13.
Cross section of PM solenoid. (Dimensions in inches).

Fig. 14.
Magnetic field lines in half
a magnet.

Fig. 15.
On-axis magnetic field.

Fig. 13, are not amenable to modeling with PANDIRA. In any event, the influence of these components is small, most of the field across the gap resulting from the inner layers.

The metal pieces of the magnet have been designed and fabricated. Parts drawings exist for all fabricated parts. Assembly jigs have been fabricated also.

Initially, it was planned to glue the magnets to the pole pieces. The magnet blocks are a sintered material, and it was discovered that the binding in the material itself was insufficient to hold the blocks in place reliably. As an alternative, a plastic wedge has been designed for this purpose.

TESTING

As previously mentioned, all the magnetic blocks were rejected because they did not meet the dimensional tolerances. The edges of nearly every block were chipped and were not flat. (The dimensional tolerances to which the blocks were bought were 2 in. ± 0.005 in.) This failure to meet dimensional tolerances made it impossible to achieve good contact with the pole pieces. Because this is an experimental magnet, we felt that initial tests should not be made with clearly inferior material. Thus, the material was rejected. As a consequence, test results are not available.

APPLICATIONS

The main application for this device is as a beam-transport element in the injection system for particle-beam accelerators. We also have discovered a potential use in electron microscopy: the focusing of high-energy electron beams to improve resolution.

REFERENCES

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3. R. F. Holsinger, "The Drift Tube and Beam Line Quadrupole Permanent Magnets for the NEN Proton Linac," Proc. 1979 Linear Accelerator Conf., September 10-14, 1979, Montauk, New York, Brookhaven National Laboratory report BNL 51134, p. 373 (1979).

ACCELERATOR THEORY AND SIMULATION

GENERAL CODE SUPPORT

The POISSON Group of programs is maintained and distributed, in collaboration with R. Holsinger (Field Effects, Inc.) and K. Halbach (Lawrence Berkeley Laboratory). Some modifications and corrections to these codes are detailed below.

PANDIRA

During Ron Holsinger's visit, February 19-22, 1983, we made major changes to correct field calculation errors in cylindrical geometry problems. The new PANDIRA was checked out with results obtained from a POISSON run and agreement was within 0.2%. Either program, PANDIRA or POISSON, may be used to compute magnetic field calculations but only PANDIRA does permanent-magnet calculations. This updated PANDIRA, which has been implemented on both the MP-VAX and on LTSS machines, now accurately calculates the fields of permanent magnets for both cylindrical and rectangular coordinates.

POISSON

Additions were made to POISSON to calculate the charge associated with fixed potential points in electrostatic problems. Before, POISSON computed the current for the fixed potential points only in magnetostatic problems. Using the same options (XJFACT=0 — electrostatic; IBOUND=-1 — fixed potential points) as described in the User's Guide, POISSON now computes the charge on the fixed points and the total charge for both cylindrical and rectangular geometry. The charge at each point is calculated by

$$Q_{x,y} = \epsilon_0 E_t \ell \quad \text{for rectangular coordinates, and}$$

$$Q_{r,z} = 2\pi r \epsilon_0 E_t \ell \quad \text{for cylindrical coordinates}$$

where

$$\epsilon_0 = 8.854 \cdot 10^{-8} \quad \text{Farad/m,}$$

E_t = normal component of electric field (in V/m) at point (x,y)/(r,z), and

ℓ = average length computed from the preceding and succeeding fixed points.

SUPERFISH

On LTSS, SUPERFISH has trouble finding the cavity length if the maximum dimension of the cavity is not on-axis. We have added the option [prbcon(70)] to input the cavity length in those cases. In addition, we have changed the print formats and added labeling of axes to make the output more informative.

URMEL AND TBCI

T. Weiland's codes URMEL (modal analysis of rf cavities) and TBCI (time-domain analysis of beam-cavity interaction) are available for use on LTSS and CTSS. We expect to receive a new, improved, and much faster version of URMEL by the end of calendar year 1983. This new version incorporates a new eigenvalue-finding routine devised by J. Tückmantel of CERN.

The TBCI version of August 18, 1983, has major revisions and is considerably faster. Initially, it was translated to run on CRAY with PLOT10 graphics output. To expedite future translations of new versions of TBCI or URMEL, the plot routines (which require most of the translating effort) were put into two separate libraries—one for PLOT10 routines and the other for DISPLAY routines. The running codes RBCID and RBCIP have DISPLAY and PLOT10, respectively, for graphics output.

FREE ELECTRON LASER TECHNOLOGY

SUMMARY

The FEL program includes contributions from AT Division, the Tunable Sources and Applications Group of the Chemistry Division, the Optical Science and Engineering Group and the Neutron Measurements Group of P Division, and the Inertial Fusion and Plasma Theory Group of the Applied Theoretical Physics Division.

The present FEL program consists of several proof-of-principle experiments and conceptual designing of high-power units. An oscillator experiment will demonstrate the properties of an efficient, modest-power FEL. The design of the follow-on experiment to improve the energy efficiency of this FEL is nearly complete, and some fabrication has started. Another accelerator-related experiment, now in the initial design stage, will demonstrate an electron linac injector operating at high average currents with improved emittance.

OSCILLATOR EXPERIMENT

During this period the installation of the oscillator experiment was completed and initial operational tests were started. The layout of the apparatus is shown in Fig. 16. It consists primarily of an electron accelerator, a

1. 80-KeV ELECTRON GUN	6. SLOW VERTICAL DEFLECTOR
2. 108- AND 1300-MHZ BUNCHERS	7. 1300-MHZ VERTICAL DEFLECTOR
3. 10-MeV LINAC TANK	8. ELECTRON SPECTROMETER
4. 11-MeV LINAC TANK	9. OPTICAL RESONATOR MIRRORS
5. WIGGLER	10. OPTICAL DIAGNOSTICS

Fig. 16.
Los Alamos FEL oscillator experiment

wiggler located within an optical resonator, and the associated beamline and diagnostics. The accelerator produces a 100- μ s macropulse containing 2000 high-current micropulses arriving at the wiggler with a spacing of 46 ns—the round-trip interval of the optical resonator. If the optical gain exceeds the losses, the optical power in the resonator will build up to a saturation level determined by the efficiency of the system. If the net gain is approximately a few per cent, the saturation limit should be reached within the 100- μ s macropulse. The 2.7-cm wiggler period and an electron energy of 21 MeV should produce an optical wavelength near 10 μ m.

Calculations were made for the oscillator experiment that indicated beam-breakup effects might be observable in the linac operation, but that they would not be detrimental to the experiment. The design parameters are listed in Table II. Additional theoretical effort for the oscillator experiment project included rf cavity calculations of the subharmonic buncher cavity using SUPERFISH, URMEL, and TBCI, and analysis of the deflector cavity both analytically and using URMEL. A visit by Thomas Weiland from DESY (Hamburg, West Germany) gave us a good start on the development of a three-dimensional rf cavity analysis code. Weiland is the author of the widely used codes TBCI and URMEL, the latter originally written while at Los Alamos.

ACCELERATOR

The first of three Litton 20-keV triode guns was assembled with a post-acceleration stage so that the electron energy would match the linac design input energy of 80 keV. Initial problems of arcing and overheating were eliminated by replacing some stainless steel components with copper ones and by placing the gun assembly in an oil bath rather than a potting compound.

Successful performance of the grid pulser fabricated in-house was demonstrated by observing the response from a wall-current monitor 40 cm from the postacceleration anode. Individual current pulses in the 100- μ s train of 2000 pulses were found to have a near-Gaussian shape with FWHM of 2.8 ns and a peak amplitude of 6 A.

The transverse emittance of the beam from the gun was measured by the "pepper pot" method 50 cm from the anode. Beamlets formed by 13 μ m-diam holes in a 15- μ m-thick tantalum plate were observed downstream from the plate on a P11 phosphor deposited on a 15-cm-diam viewing port. The measured normalized emittance with a peak current of 6A was 2π cm $\cdot$ mrad, 80% of the value predicted

TABLE II
OSCILLATOR EXPERIMENT DESIGN PARAMETERS

Optical

Wavelength	10.6 $\mu\text{m} \pm 10\%$
Optical power in cavity	~ 1 GW
Pulse length	30 ps
Rayleigh length	0.4 to 0.6 m
Mirror reflectivities	
Input mirror	99.5%
Output mirror	99.5-90.0%
Mirror separation	6.923 m
Precision of control of mirror separation	$\pm 1 \mu\text{m}$

Electron Beam

Energy	21 Mev $\pm 5\%$
Energy spread	$\pm 0.5\%$
Emittance	2π mm•mrad
Peak current	100 A
Micropulse length	30 ps
Micropulse separation	46.15 ns
Micropulse/macropulse	2000

Wiggler Performance at 40-A Current and No Energy Spread

Standard 12% taper	
Small signal gain	15%
Saturated power	~ 1 GW
Time to saturation	70 μs
No taper	
Small signal gain	100%
Saturated power	~ 0.25 GW
Time to saturation	25 μs

by Litton. With the current reduced to 0.8 A by passing the central core of the beam through a 4-mm-diam aperture upstream from the pepper-pot plate, the normalized emittance was reduced to 0.5π cm•mrad.

The seven large-bore solenoid magnets were installed on the beamline. The magnetic center of each solenoid was located by finding the axial locus of zero transverse magnetic field using a Hall probe mounted in a jig. With optical targets replacing the Hall probe in the jig, the solenoid axis was then located on the optic axis of the beamline. With the bunchers and their associated hardware installed inside the solenoids, the injector assembly was complete.

Initial tests were carried out with and without rf power supplied from the power amplifiers. For the design operating conditions of the subharmonic bunchers, the equilibrium level of the beam-induced field is comparable to the desired bunching field and shifted 90° in phase. Consequently, the closed-loop control circuits for buncher amplitude and phase must cover a range of nearly a factor of 2 and over 45° , respectively. The control loops may require substantial feedforward to operate within specifications.

Multipactoring is a persistent problem, especially in the subharmonic bunchers. Multipactor breakdown occurs over a wide range of cavity power, with and without the solenoidal guide field. It seems likely that the geometry of the re-entrant coaxial resonator used in the bunchers is prone to matching the resonance requirement for multipactoring over a wide range of cavity powers. Preparations are under way to coat the interior copper surfaces with a titanium film of at least 10-nm thickness to reduce the secondary electron emission coefficient to less than one.

The beam bunching was monitored with a wall-current monitor placed in the location of the first accelerator cell. The performance of the bunchers was approximately as predicted. The subharmonic buncher amplitudes could be varied by 50% without serious effect, but the relative phases had to be correct within 10° . The 4-GHz bandwidth of the wall-current monitor prevented a precise measurement of the bunch width at this point in the beamline.

The linac tanks conditioned quickly to their operating gradient of 7 MeV/m. Because of the multipactoring in the bunchers, most of the operation during this period utilized only the fundamental buncher and the two linac tanks. Micropulse peak currents of 40 A were achieved through the wiggler. These have a 1% FWHM energy spread and a measured transverse emittance of approximately 2π mm·mrad. The beam was not scraped to further reduce the energy spread and emittance. The diagnostic screens in the achromatic bend, the wiggler, and the spectrometer made the accelerator tune-up quite simple. The phosphor screens in the wiggler have been damaged by the intense beam and will be replaced by fused silica screens.

PRELIMINARY OPERATION

Under the above conditions, the optical radiation out of the wiggler on a single pass was measured. By filtering, this spontaneous emission (synchrotron

radiation) was determined to be near $10.6\text{ }\mu\text{m}$, confirming the electron-beam energy.

The optical resonator mirrors have now been installed, and the length of the resonator has been adjusted to within 1 mm in preparation for oscillator build-up measurements. The bremsstrahlung from the electron beam causes a noise spike in the optical detector. However, it is small and out of time from the spontaneous light pulse, so there is no difficulty distinguishing the latter. Because the subharmonic bunchers were not being used, the micropulse structure of seven bunches could be seen on the spontaneous-emission pulses.

Preliminary oscillator operation will be attempted soon with an untapered wiggler. If the bunchers are still unreliable, operation will be under the above conditions. There should still be adequate gain to achieve saturation within the 100- μs macropulse. Once the performance of the laser has been stabilized and characterized, the performance with a tapered wiggler will be studied.

ENERGY-RECOVERY EXPERIMENT

The oscillator experiment will demonstrate a high-efficiency FEL starting up from spontaneous emission and reaching high-power saturation in a long-pulse mode. The energy-recovery experiment (ERX) is an add-on to the oscillator experiment to demonstrate a technique to substantially improve its overall efficiency. After passing through the FEL, the electron beam will have more than 90% of its original power and still will have its microbunch structure. The mix of particles that were and were not captured by the photons' decelerating bucket introduces a 5% full-width energy spread. This spread makes the beam unsuitable for recirculation through the wiggler. However, the FEL's overall efficiency can be greatly enhanced through recovery of most of the power in the residual electron beam. It appears that the most efficient method of recovering the kinetic energy of the beam is through deceleration in rf-excited linear accelerator structures. The kinetic energy is converted into rf power, which is used to accelerate new beam. Excellent conversion efficiencies are expected if beam breakup caused by excited deflecting modes can be avoided.

Calculations made for the ERX, in which the electron beam is decelerated after passing through the wiggler to recover the rf energy of acceleration, indicated that fabrication tolerances would have to be tightened to avoid beam being lost in the decelerator because of the beam-breakup interaction. These

calculations are summarized in the various preprints listed in the publications section.

The first energy-recovery experiment will use decelerator structures that are separate from the accelerator to provide maximum experimental flexibility. The decelerator tanks will be essentially identical to the second ($B = 1$) tank in the accelerator. Variable rf bridge couplers will facilitate the rf power transfer over a wide range of deceleration values. A scheme for a variable bridge coupler joining the two tanks of the FEL energy-recovery experiment was tried using cold models. The bridge couplers must provide resonant coupling between the accelerators and decelerators and accommodate the variable power-feed ratio. The effective coupling constants to the bridge coupler were changed by adjusting the symmetry of the capacitive loading of the central bridge-coupler cell. Initial measurements indicate that the variation in coupling was more than adequate, but the field at the waveguide coupling slot also varied, creating an unacceptable change in voltage standing wave ratio (VSWR) as the field was tilted.

The energy-recovery experiment parameters are listed in Table III and its layout is shown schematically in Fig. 17. The major new systems added to the oscillator experiment are an isochronous return beamline, two side-coupled decelerator tanks, and two variable bridge couplers. Each accelerator/decelerator pair is excited by a common klystron with the gradient ratio in the two structures determined by the bridge coupler. As the beam loading is increased, the efficiency improves because the structure losses make a smaller fractional contribution. The beam loading will be increased by a factor of 2 over the oscillator experiment to achieve a 50% improvement in efficiency. In higher energy high-power FELs, much greater improvements can be expected.

The TRANSPORT calculations on the ERX beamline and basic physics designs on the magnets were completed, permitting the physical layout of the beamline to be made, and detailed design of all beamline components and supporting structures to begin. The preliminary design was released to drafting in late May. Estimated costs and schedules were prepared and a laboratory was set up in which the preassembly of the ERX will take place. All commercial hardware to be purchased is under procurement. Prototypes have been built of selected quadrupoles, sextupoles, triplet quadrupoles, and dipoles, and fabrication of 28 magnets of 10 different types is proceeding.

TABLE III

FEL ENERGY-RECOVERY PARAMETERS

	<u>Oscillator Experiment</u>	<u>ERX</u>
Macropulse duration (μ s)	100	100
Micropulse duration (ps)	30	30
Micropulse repetition rate (MHz)	21.7	108.3
Peak current (A)	50	90
Average current (A)	0.033	0.29
Full energy spread ($\Delta W/W$)	0.008	0.015
Beam loss on ΔW slit (%)	50	10
Accelerator beam loading ($P_b/(P_b + P_c)$)	0.36	0.74
Deceleration (MeV)	0	18
Total excitation power (MW)	2.7	4.5
Beam power (MW)	1.5	7.6
Recovered power (MW)	0	5.2
η (P with ER)/(P without ER)	1	0.67

(1) OSX ACCELERATOR AND FEL
OPERATING AT FIVE-FOLD INCREASE
IN AVERAGE CURRENT

(2) ISOCRONOUS 180° BEND
ON TRANSLATION TABLE

(3) ISOCRONOUS 60° BEND

(4) TWO 1.8-m DECELERATOR
(ENERGY-RECOVERY) SECTIONS

(5) TWO VARIABLE rf BRIDGE COUPLERS

(6) BEAM DUMP FOR 2- TO 3-MeV BEAM

Fig. 17.
FEL energy recovery experiment

The adjustable-table design was completed and put into production. This table adjusts the phase of the spent micropulses relative to the accelerated beam. The table is accurately positioned on frictionless bearings by a motordrive. Positioning reproducibility is ± 0.0005 in. A nonvolatile memory-position read-out is used to deliver the position indication to the control room.

An in-depth analysis of the beam-breakup instability in rf linacs was produced, including the effects of rf structure, of the beam, and of focusing. An exact analytical solution was found for a coasting beam, and analytic approximations that agree well with numerical simulations were derived.

It is expected that the installation of the energy-recovery experiment will begin during the fall of 1984, after the completion of the oscillator experiment.

INJECTOR DEVELOPMENT

The principal objectives of the FEL Injector Development are (1) the production of electron bunches of at least 5 nC each, (2) an average current of i A, (3) normalized transverse emittance not more than 2π cm·mrad, (4) energy spread not more than 1%, and (5) a bunch width of 30 ps.

Conventional bunching systems, comprising one or more bunchers with interspersed drift spaces, evidently cause an increase in emittance that may be a factor of 10 or more. Attempts are being made to improve on this.

The first approach was to use a large number of rf cavities that bunch and gradually accelerate the beam. In this respect it would resemble the longitudinal features of the RFQ, but the transverse focusing would be provided by separated-function magnets. However, the results of calculations carried out on this "adiabatic-buncher" scheme were not encouraging. It was difficult to get an adequate accelerating field without radially overfocusing the electrons, and the large space-charge forces in the 5-nC bunches caused an intolerable growth in transverse emittance. The principal conclusion drawn from this work was that the beam should be accelerated as rapidly as possible.

The second conceptual design combined a crudely bunched beam, formed by a thermionic cathode in an rf cavity, with rapid acceleration to about 1 MeV followed by a magnetic bunching device or phase compressor. All of the components in this scheme have been demonstrated separately, so the feasibility of the approach seems reasonably assured.

The third, and most promising, design is based on rapid acceleration of an optically pulsed beam of electrons from a bright photocathode illuminated by a laser that is phase locked to a master oscillator. The required current density of about 200 A/cm^2 has been demonstrated at Standard Linear Accelerator Collider (SLAC) in injector development for the SLAC Linear Collider. A program has been started to develop semiconductor photocathodes that could be used in an advanced injector for FELs.

REFERENCE

1. K. R. Crandall, R. S. Mills, and T. P. Wangler, "Beam Dynamics Problems in FEL Electron Buncher Design," Los Alamos National Laboratory memorandum AT-1:83-132 (May 5, 1983).

ACCELERATOR TEST STAND

STATUS

A 100-keV to 2-MeV RFQ was designed, constructed, installed on an ATS, and tested. Although the output of the RFQ consisted of 2-MeV negative hydrogen ions, the performance was degraded for two reasons:

(1) The ATS low-energy beam transport, which was used to test the RFQ, was originally designed for a 250-keV, 20-mA beam, but the RFQ requires a 100-keV, 35-mA beam. This resulted in large emittance growth, and the magnet apertures proved inadequate to transport the full beam.

(2) The RFQ proved to be extremely sensitive to errors in the vane positions, giving large field errors both transversely and longitudinally, and resulted in transmission lower than the design value. However, when the measured fields were inserted into the simulation code, PARMTEQ, the agreement with experiment was excellent.

Under these circumstances, the RFQ performance resulted in transmission of a 19-mA beam with an energy distribution to 2-MeV with injection of 35-mA negative hydrogen ions at 100-keV. Recently, the RFQ was modified for more uniform fields, and improvements were made to the low-energy beam transport. These improvements are now under evaluation and testing.

At the present time, the ATS consists of

(1) a negative hydrogen ion source, capable of producing a high-brightness, 180-mA beam—the small-angle ion source yielded normalized rms emittance of $0.027 \pm 0.007\pi$ cm·mrad at 140 mA;

(2) a low-energy beam transport with quadrupoles for matching the beam into the RFQ; and

(3) a 2-MeV RFQ.

Planned additions are an RFQ-DTL matching system and a DTL accelerator to reach a final energy of 5-MeV.

TDA LINAC CONCEPTUAL DESIGNS

Preliminary H^- and D^- linacs were designed for the technology demonstration accelerator (TDA) application.¹ Both accelerators consist of an RFQ and three DTL tanks. Initial attempts were begun to investigate frequency doubling in the DTL. The beam-dynamics requirements for both H^- and D^-

were within the specifications, as demonstrated by simulation using PARMILA, even though the designs were unoptimized.

THEORETICAL EFFORT

The bulk of the theoretical effort on the ATS project centered on low-energy beam-transport instabilities (summarized in Accelerator Theory Notes) and RFQ beam-dynamics studies summarized below.

We have upgraded RFQTEP, a fast RFQ particle-tracing simulation code, to do the space-charge expansion about an r - z parabolic density-profile ellipsoid and to include the effects of adjacent bunches. The entire RFQ, including the bunching region, can be simulated on the CRAY computer in only 1.7 s of CPU time. This speed indicates that RFQ design using a nonlinear optimizer to vary parameters could be practical. Structured programming was used in developing this code, and graphical documentation was prepared (using the CD2000 CAD/CAM system) that shows the high-level control flow, module hierarchy, and data flow on one chart. We find the major advantage of this approach is that modifications to the code are very easy to make. We used RFQTEP to study field errors in the ATS RFQ by parametrizing the voltage distribution along the vanes in terms of an error amplitude and phase.

To test further the idea of designing RFQs by optimizing in a simulation code, we wrote the BUNCHOR code. This code consists of a nonlinear optimizer running an RFQTEP-like simulation for the early part of an RFQ (where bunching occurs). Conventional design techniques are complicated for this region because the motion is not adiabatic there. We represented the modulation factor by a polynomial in the distance along the vanes. The nonlinear optimizer varied the polynomial coefficients, minimizing the transverse and longitudinal emittances and the bunch length. BUNCHOR usually finds a solution in about 13 s of CPU time. About 70 calls are made to the simulator running 360 particles through 50 rf periods. To design an actual RFQ this way, we must also parametrize the synchronous phase as a polynomial.

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