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**The PIGMI Program at the
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LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

THE PIGMI PROGRAM AT THE LOS ALAMOS SCIENTIFIC LABORATORY

by

James E. Stovall

ABSTRACT

The PIGMI Program at the Los Alamos Scientific Laboratory, supported by the National Cancer Institute, Division of Research Resources and Centers, Department of Health, Education, and Welfare, has completed 3-1/2 yr of a project to develop the technology for the optimal pion generator for medical irradiations (PIGMI). The program is progressing well and is designed to converge during the next year into a rather detailed description of the technologies required to build a PIGMI.

Some of the activities reported here were partially supported by other budgets in recognition of the applicability of these activities to those programs as well as to the PIGMI Program.

The major accomplishments under the program include

- completion of the injector beam measurements,
- completion of the 440-MHz radio-frequency (rf) power source,
- assembly and test of the alternating phase focusing accelerator section,
- development of the rf-quadrupole (RFQ) beam-dynamics program, PARMTEQ,
- design, fabrication, assembly, and test of the RFQ accelerator,
- final decision on low-energy configuration for PIGMI,
- assembly of the drift-tube linac section of the PIGMI Prototype,
- completion of sample set of permanent magnet quadrupoles,
- optimization of the disk-and-washer (DAW) cavity geometry,
- fabrication of model cavities of the DAW,
- final decision on DAW support geometry,
- acquisition of additional laboratory space for the DAW power test,
- partial assembly of the 1320-MHz rf power source for the DAW test, and
- pion channel design studies.

I. INTRODUCTION

The PIGMI Program at Los Alamos, supported by the National Cancer Institute, Division of Research Resources and Centers, Department of Health, Education, and Welfare, has completed three and a half years of a project to develop the technology for the optimal pion generator for medical irradiations (PIGMI). The program is progressing well and is designed to converge during the next year into a rather detailed description of the technologies required to build a PIGMI.

Some of the activities reported here were partially supported by other budgets in recognition of the applicability of these activities to those programs as well as the PIGMI program.

The major accomplishments under the PIGMI program during the report period include

- completion of the injector beam measurements,
- completion of the 440-MHz rf power source,
- completion of the instrumentation-and-control system,
- assembly and test of APF accelerator section,
- installation of low- and high-energy beam transport systems,
- development of RFQ beam-dynamics program, PARMTEQ,
- design, fabrication, assembly, and test of the RFQ accelerator,
- final decision on low-energy configuration for PIGMI,
- assembly of the DTL section of PIGMI Prototype,
- completion of sample set of PM quadrupoles,
- optimization of the DAW cavity geometry,
- fabrication of model cavities of DAW,
- final decision on DAW support geometry,
- acquisition of additional laboratory space for DAW power test,
- partial assembly of 1320-MHz rf power source for DAW test, and
- pion channel design studies.

II. INJECTOR

The injection system continued to work well throughout the year, but powerline transients and electromagnetic radiation generated during the spark-downs continued to interrupt the control system and interfere with beam measurements. Special care was taken to isolate the high-voltage system and to

provide a single-point ground. In addition, the entire injector was enclosed in a Faraday cage. These measures helped significantly; however, one additional modification has essentially eliminated sparkdowns and their associated problems. All of the utility and instrumentation cables connecting the ion source to the high-voltage dome were wrapped around an insulated cylinder, adding inductance to the path over which arcdownd currents must flow. This limits to a sufficient degree the instantaneous energy dissipated during an arcdownd, thereby greatly reducing the amount of radiated noise. This modification has reduced by about 90% the frequency of arcdownd by apparently quenching sparks in their early stages of formation.

Two new pieces of equipment, designed and implemented in the injector, have significantly improved the ion source operation. The new master timer provides a locked sequence of instrumentation signals to synchronize the operation of the ion source, the rf, and any diagnostic measurements. All of the necessary variables, including pulse widths, delays, and frequencies are adjustable. The arc-pulse signal is transmitted to the high-voltage dome through a fiber-optic link. This signal triggers a new arc-pulse power supply that generates a very sharp flat arc pulse. This new supply eliminates the need for an arc starter and delivers a pulse whose shape is independent of length and repetition rate.

The brightness of the beam was improved with the installation of a boron nitride collar in the plasma expansion cup. To reduce the erosion observed in the anode aperture, which is caused by backstreaming electrons, a small, permanent-magnet electron trap was installed just downstream of the ground electrode. Because of the instrumentation problems associated with sparkdowns, the plan to provide remote control of the ion source, with a microprocessor at high voltage, was abandoned. The few necessary adjustments are easily made with a lucite rod from outside the Faraday cage.

Following a program of measurements to characterize the operation of the alternating phase focusing (APF) accelerator, the accelerating column was modified to a two-gap configuration to deliver about 40 mA at 100 keV for injection into the radio-frequency quadrupole (RFQ) test accelerator. Likewise, the low-energy transport system was modified to deliver a matched beam to the RFQ. During each of these phases the operation of the injector and low-energy transport systems were fully studied. Emittance measurements

of the beams emerging from the dc column were very close to those expected from numerical calculations and indicate an exceptionally high brightness. Beam-profile measurements made downstream of the solenoid indicated a slight misalignment between the source and the solenoid. Because each device was aligned to within a reasonable tolerance, steering magnets were designed, fabricated, and installed on the beam line; this has solved the problem. A second emittance measurement made downstream of the solenoid showed that for the 100-keV beam, spherical aberrations were causing distinct degradation in the transverse properties of the beam. This would only be correctible with a new larger aperture solenoid.

For both accelerator tests the transport design was confirmed by on-line emittance and profile measurements. Numerical fits to the experimental data were used in the TRACE code to represent beam sizes and emittance orientation. By allowing for space-charge neutralization, agreement between measurements and calculation was easily demonstrated.

III. RF POWER SOURCE

The rf power system, including a 440-MHz klystron, modulator, and associated amplifiers and controls, worked well throughout the tests of both the APF and RFQ structures. The APF cavity required about 850 kW of pulsed power, whereas the RFQ required about 300 kW. Each test was carried out over a period of several months and the power stand performed admirably. A closed-loop frequency-control unit was installed for the RFQ tests, which caused the klystron to track in frequency for variations in cavity temperature. This has all but eliminated the necessity for adjusting the rf during accelerator runs.

IV. INSTRUMENTATION AND CONTROL SYSTEM

In support of accelerator studies, a complete complement of computer-based beam-diagnostic measurements was implemented. The beam line equipment provided the following measurements and control.

1. Emittance measurements,
2. harp-and-wire scan profile measurements,
3. faraday-cup beam-current measurements,
4. beam-current transformer measurements,
5. direct viewing of beam spot size,
6. momentum analysis,

7. discriminator-foil energy analysis,
8. four-jaw aperturing, and
9. horizontal and vertical steering.

All of the above equipment, much of which is shown in Fig. 1, is mounted on pneumatic or stepping-motor actuators, and is operated under computer control from an operator's console. A large package of software has been written and implemented that supports a wide variety of beam and accelerator measurements and data analyses. The entire system has been reliable, responsive, and easy to use.

During the tests of the APF structure, the accelerated beam was dumped in a special Faraday cup mounted inside a dummy drift tube at the interface between the APF cavity and the high field gradient test cavity (PIGLET) through which the power was provided. This special Faraday cup was fitted with an energy-discriminating foil window. High-energy electrons were magnetically suppressed, whereas secondaries originating in the copper were electrically suppressed. The cup therefore provided a measure of accelerated beam current only.

During tests of the RFQ structure, the PIGLET cavity again was used to supply rf power to the accelerating structure; however, this time in a coaxial manifold mode. In this case, the accelerated beam that emerged from the structure was expected to be small and bright in emittance, at an energy of only 640 keV. A transport system was designed and assembled from available components, which would allow both emittance and momentum measurements. The system includes a quadrupole doublet, a 45° analyzing magnet, beam-diagnostic boxes, beam dump, and vacuum system.

V. APF ACCELERATOR PROTOTYPE

All four PIGMI prototype tanks were delivered. The first section, the APF, has been loaded with drift tubes and tested under power with beam. The APF tank contains 28 drift tubes, each with a unique length. Each drift tube was fabricated from mild steel and fitted with three hollow mounting stems for support and to provide water cooling. Following an initial copperplating, all drift tubes were mounted in the tank and aligned. Frequency measurements indicated that a thicker plating was required. Two subsequent plating jobs were required to bring the assembly into resonance at the proper frequency.

Fig. 1.
PIGMI diagnostic equipment.

Each drift tube was aligned transversely in a conventional way using a transit and a target inserted in the bore of each drift tube. A special depth guage was developed for measuring the longitudinal positioning of each drift tube. Working on the principle of electrical continuity, the guage did not require a solid mechanical contact, thereby minimizing the drift-tube deflection during the measurement of its position. Stems were manually bent to correct the longitudinal position of the drift tubes.

The APF tank was bolted to an adapter ring mounted on the upstream end of the PIGLET high-power test cavity, using elastimer O-rings for vacuum, and gold wire for electrical integrity. Power was coupled into the APF cavity from PIGLET, used primarily because of its existing rf drive configuration and rf window. A special dummy drift tube was fabricated to provide a match between the two dissimilar cavities. Bead pulls indicated flat fields in the APF structure, but somewhat higher fields in the gap between the final APF drift tube and the first dummy drift tube. The design fields were ultimately exceeded by about 10%, but the field level was constrained by this gap.

Initial operation of the APF structure was plagued by vacuum difficulties associated with water leaks in the stem to drift-tube body joints. This problem, associated with long-term crevice corrosion of the braze material because of incomplete washing after copper plating operations, was extremely elusive and is detailed in a separate series of memos. Leaks were plugged using a commercial epoxy-base preparation designed for such applications. To further avoid such problems, the tank was operated at reduced duty using air cooling only.

The APF linac structure was developed for the acceleration and focusing role in the low-beta portion of PIGMI. In this structure, the transverse, as well as the longitudinal, focusing forces are produced by the rf electric fields. By arranging the drift-tube lengths in a conventional standing-wave drift-tube linac (DTL) structure, the gaps can be positioned to provide acceleration, as well as a succession of focusing and defocusing forces. These forces result in satisfactory containment of the beam in the six-dimensional phase space without requiring additional focusing fields.

Fig. 2.
APF Cavity.

Figure 2 shows the APF portion of the PIGMI prototype. It is 63 cm long, 46 cm in diameter, and contains 28 drift tubes, none of which contain quadrupole lenses. The drift-tube bodies vary in length from a minimum of 0.690 cm to a maximum of 3.003 cm, and are 8 cm in diameter. The bore-hole radius increases from 0.402 cm in the first drift tube to 0.487 cm in the 28th drift tube. The APF operates at 450 MHz and accelerates a proton beam from 250 keV to 1.011 MeV.

Preliminary performance tests of the APF linac structure were made in the following way. The APF section, which has no provisions for rf excitation, was bolted to another short linac section that does have such provisions. A

special drift tube, containing an energy-discrimination foil (600 keV) followed by a Faraday cup, was installed between the structures to adjust the resonant frequency of the combination and to provide a minimal beam-diagnostics capability. The combined structure requires a total rf power of about 700 kW to reach the design excitation.

The combined structure was driven to a peak power of about 850 kW, corresponding to an average axial electric field approximately 10% higher than the design value of 6 MV/m. The maximum surface fields were in the vicinity of 28 MV/m.

The 250-keV proton beam from the PIGMI injector was used for the preliminary beam tests. The net current signals from a Faraday cup at the entrance to the linac, the energy-discrimination foil in the special drift tube, and the Faraday cup in the special drift tube were monitored as a function of rf power, injector voltage, solenoid current, steering current, buncher excitation, buncher phase, and ion-source parameters. Some of these data are presented in Fig. 3.

Fig. 3.
The APF performance data.

When protons with an energy < 600 keV enter the special drift tube, they are absorbed in the foil and contribute to the signal from that element. Protons entering the special drift tube, with an energy > 600 keV, pass through the absorber and contribute to the signal from the Faraday cup within the drift tube. Stray electrons from the foil and Faraday cup are returned to their original element by a high-voltage suppression ring. High-energy electrons originating in the accelerator are excluded by a 1-kG magnetic field produced by a pair of permanent magnets. The signal from the Faraday cup is taken as a measure of the accelerated beam current.

Figure 3 shows the dependence of accelerated current, I_b , on rf power. The threshold for acceleration (1.75 in the arbitrary units given here) corresponds to an rf power of 750 kW, and the peak acceptance corresponds to an rf power of 850 kW. These data are in fair agreement with our expectations.

At the optimum excitation, the percentage capture of a well-collimated beam is 15.7% or ± 28 degrees of phase. This is in good agreement with the expected performance.

The dependence of accelerated beam on injector voltage is shown in Fig. 3, revealing a rather sharp peak at 248 kV. The width of the peak agrees with the design calculations. The apparent deviation of the peak position from the design value of 250 kV may be real or may be due to an error in the calibration of the voltage measurement. Figure 3 also shows the dependence of accelerated beam on buncher phase for the buncher excitation that produces the maximum accelerated beam at the optimum phase. The general features of this phase-scan look correct, but the detailed shape has not been analyzed.

The maximum current accelerated to date is 3 mA. There are a number of hardware problems and it is hoped that this limit can be raised in the future.

VI. DEVELOPMENT OF THE RADIO-FREQUENCY QUADRUPOLE STRUCTURE

The second linear accelerator structure studied on the PIGMI test stand was the RFQ. Its function is to accept the 0.10-MeV unbunched deuteron beam from the injector, to bunch, and to accelerate it to an energy of 0.640 MeV. The RFQ is a new concept that has not heretofore been used outside the USSR. It promises to fulfill the above functions with little loss of beam intensity and minimal increase of beam emittance.

The RFQ generates time-varying electric quadrupole fields that provide radial focusing forces to contain the ion motion. In contrast to the magnetic force that is proportional to ion velocity, the electric force is velocity independent and is particularly useful in focusing low-velocity ions. The electric quadrupole fields in the RFQ are generated by producing opposite-polarity voltages on two pairs of conducting poles that surround the z-axis. The time-varying voltages are produced by rf currents that flow in the transverse direction. If the pole tips do not vary in radius, the structure provides only radial focusing. If the pole tips are modulated in radius, they also produce longitudinal electric fields. These longitudinal fields are used

to bunch and to accelerate the ion beam. By appropriately varying the magnitude of the pole-tip modulation, the longitudinal fields gradually can be increased from zero at the input of the RFQ to their final value near the RFQ output. In this way, the ions are captured and bunched with high efficiency, and during the acceleration only a small percentage is lost by striking the RFQ poles.

The first objective in developing the RFQ accelerator was to construct a new version of the beam dynamics simulation code PARMILA that was capable of describing the ion motion. As a basis for this, we chose to use the lowest order potential function from which RFQ electric fields can be obtained in the quasi-static approximation. This potential function is three-dimensional in character, obeys Laplace's equation, and contains only the lowest order Fourier component of the longitudinal space dependence. The quasi-static approximation is well fulfilled because the aperture of the RFQ and the pole-tip radii are very small compared to the $\lambda/2$ conductor length in the transverse plane between two adjacent pole tips. Two important and self-consistent quantities are calculated from the potential function: first, by performing the gradient operation, we obtain a complete three-dimensional description of the electric fields; second, by setting the potential function equal to a constant, we obtain a three-dimensional description of isopotential surfaces, which are then the shapes of the conducting pole tips required to produce the electric fields. In practice, the poles are constructed to have the pole-tip radius exactly equal to that specified by the potential function. In the transverse plane at each value of z , the pole tips are made to have a constant radius of curvature specified by the potential function for the pole tip. This is a sufficiently good approximation to the exact hyperbola-like shape. The machining of the pole tips with a computer-controlled milling machine is described later.

The RFQ electric fields obtained from the potential function were used to construct transformations for the six-dimensional phase space, consisting of the coordinates x , x' , y , y' , ϕ , and W . These transformations, as well as a space-charge impulse, were incorporated into a beam-dynamics program called PARMTEQ. This program has been extensively used to analyze the performance of many RFQ accelerator designs. Usually, the input ion beam is described as a random distribution of particles in the four-dimensional phase space x , x' , y ,

and y' . In addition, the input particles are usually assumed to be mono-energetic and also to be uniformly distributed in phase through 360° , to represent a dc beam. For a specified beam current, the beam particles are transformed through the array of cells that represents the RFQ accelerator. Particles that strike the vanes or fall out of synchronism are eliminated and the radial and longitudinal phase-space distributions of the transmitted beam are generated at the output.

Our method for the analysis of specific RFQ accelerator designs is the PARMTEQ beam-dynamics simulation program described above. We now discuss the procedures we have developed for the synthesis of RFQ designs. We will describe in more detail the functions that a typical RFQ is required to perform. These functions can be divided into four parts. First is the radial matching of the dc beam from the injector to the input of the RFQ. Because the electric fields of the RFQ vary with time, to obtain a high acceptance of the input beam we introduce the radial focusing forces gradually enough to allow the beam to adapt itself to the RFQ time-varying focusing fields. We call this process adiabatic radial matching. The RFQ pole tips start with a large radius, and over a length of about 5 cm, the radii of the poles are reduced to a much smaller value. We assume that the intervane voltage does not vary with z , so that reducing the pole-tip radius increases the focusing forces to their full strength at the end of the radial matching section. From the end of the radial matching section, we usually hold the average radius of the pole tips constant. This means the time-varying, electric focusing amplitudes are constant for all values of z . This feature, together with the velocity independence of the electric force, means that the RFQ has excellent radial focusing characteristics.

The next section is called the shaper. In the shaper we begin to introduce the longitudinal field very gradually, and, beginning with a synchronous phase of -90° , we begin to bunch the beam. By the end of the shaper, we have formed a phase-stable bucket in which we have a specified distribution of particles. After the shaper section is the gentle buncher, which continues the bunching process in a sufficiently gradual manner, so that in the presence of space-charge forces, only a minimal radial-emittance growth occurs. The gentle buncher makes the transition from a condition of low-acceleration efficiency to a condition of high-acceleration efficiency,

with the synchronous phase having its final value. The last section is the accelerator in which acceleration of the ions is continued at a constant synchronous phase and high efficiency.

In addition to the design requirements discussed above, we impose additional constraints that are obtained from space-charge scaling laws.

It was highly desirable to provide an early experimental verification of the RFQ principle, as well as our ability to design working RFQ resonators. A plan was devised to test an RFQ resonator by injecting it with 0.1-MeV protons from an existing injector, and to power the resonator with an existing 425-MHz klystron. Besides these constraints, the RFQ wavelength was dictated to be 1.1 m by an existing tank to which the klystron waveguide was attached. With these restrictions, we made a beam-dynamics design that emphasized proper radial matching and bunching, rather than maximum energy gain. The aperture of this RFQ was small, as determined by the rather high frequency and the use of a conservative peak surface field of 30 MV/m. The aperture diameter ranged from 0.4 cm at the shaper input to 0.26 cm at the accelerator output. With the restrictions imposed by existing equipment, the output energy was limited to 0.64 MeV. The nominal input-beam current was considered to be 15 mA, which gave a predicted output current of 14.4 mA and a small radial emittance growth. However, with an input current of 30 mA, the output current was predicted to be 25.9 mA and the radial emittance growth was still expected to be small.

VII. BEAM DYNAMICS

The particle-dynamics program, PARMTEQ, is a program similar to PARMILA, and is designed and written for studying RFQ linacs. Like PARMILA, PARMTEQ allows much flexibility, particularly in the specification of input-particle distributions and in output formats.

The RFQ Linac (or the Space-Uniform Focusing Linac, as it is called by the Russians) has some unique properties that should allow a high-capture efficiency of low-velocity beams. The transverse focusing strength is approximately independent of position along the structure, but varies sinusoidally in time. High focusing can be achieved and, because it is electrostatic, can be independent of particle velocity. At any given instant the beam would appear to have approximately the same elliptical cross section throughout the linac.

The acceleration and the rf defocusing forces both depend on position along the linac, as well as on time.

Because of these differing properties, one wonders whether to use time or distance along the linac as the independent variable. In a conventional linac, one would naturally use distance, and PARMILA is structured to do so. Being similar to PARMILA, PARMTEQ is also structured this way, and the coordinates of all the particles are calculated at discrete points along the linac. But to properly calculate the space-charge forces, one needs to know all the particle coordinates at a given instant.

Consequently, before the space-charge impulses are applied in PARMTEQ, the transverse coordinates of each particle are transformed to their values corresponding to a specific time, assuming that the particle feels only the local rf quadrupole field. After applying the space-charge impulse, the coordinates are transformed back to their values corresponding to a specific location along the linac.

For beam-dynamics purposes, each linac cell is divided into N segments, where N is typically 4. The space-charge impulses are applied once per cell at the time when the electric field is zero, at which time the "matched" beam would have a nearly circular cross section. In computing the space-charge forces, the effects of an arbitrary number (typically 5) of adjacent bunches on each side of the particle bunch is included. This requires a recalculation of the space-charge table every few cells, depending on how rapidly B_r is changing. The CDC 6600 computing time required for 500 particles, when each cell is divided into 4 segments when space charge is included, is about 1 minute for 10 cells.

VIII. RFQ FABRICATION

Copper tubing, 6.125-in. o.d. by 0.192-in. wall, was chosen as the main structural element for the cavity. Square ends were brazed to the tube, then accurately machined and faced to length. The ends form three mutually perpendicular planes; two are parallel to, and equidistant from, the cavity center line. In this form, the part is easily indexed and clamped in jig boring and other machine tools, where dowel pin and screw holes can be accurately located and drilled.

The vane bases are machined from solid OFHC copper. Slots are made to receive copper tubing for cooling water. The bases, including water tubes,

are located in the cavity with dowels and screws and the whole assembly is then furnace brazed.

The RFQ is suspended inside another cylindrical rf cavity by means of two copper disks. Contact fingers connect the inner surface of the outer cavity through the disks to the outer surface of the RFQ, forming a coaxial line terminated at each end by an electrical short circuit. The outer cavity, or manifold tank, is connected to vacuum and cooling-water services.

The rf power is fed through a wave guide to the manifold tank. The magnetic field couples through the angled slots in the RFQ side walls to magnetic fields inside the RFQ. Power is uniformly distributed to all four chambers of the RFQ.

Each end of the cavity is closed by a disk assembly containing four small tuning slugs, as shown in Fig. 4. The slugs vary the capacitance between the vane ends and the cavity and they are used to adjust the electrical field distribution along the axis of the RFQ.

Fig. 4.
Low-power RFQ test cavity.

Fabrication of the vanes incorporates a three-axis, numerically controlled, vertical mill. Normally, this machine reads its control data from a punched paper tape that has a capacity of about 800 data blocks. The vanes require approximately 20 000 data blocks for an adequate description.

A spherical tool is used to cut the vanes. The path that the tool center follows is in the xy-plane and must consist only of straight lines and circular arcs. As each cross section is cut, the machine table moves an increment Δz along the vane's longitudinal axis. The process is slow ($\Delta z = 0.020$ in.), moving 1-2 inches per hour in the z-direction.

If the radius of the tool were zero, the tool path would be identical to the cross section of the vane. However, with a finite tool radius, the cutting path of the tool is not always in the same plane that the tool travels. The deviation depends on both the cutter radius and the slope of the vane. The program that computes the machine instructions compensates for this error.

IX. RFQ MEASUREMENTS

Two separate techniques have been used to establish the accelerated beam's energy. For the initial measurements, a special Faraday cup was prepared with a thin, nickel-foil window covering its entrance aperture. The thickness of the foil was selected from available stock (0.1 mil or 2.2 mg/cm^2) and had a proton range of 450 keV. In this measurement, high-energy electrons were suppressed by a permanent magnet dipole built into the Faraday cup. Any signal seen in the cup would therefore result from protons, having > 450 -keV energies, that have penetrated the foil.

Typical measurements using this technique indicated that 12.5 mA or 52% of the injected beam was accelerated to energies > 450 keV. Parametric studies of accelerated-beam current as a function of cavity field indicated the expected behavior; that is, current being a strong function of rf field above a well-defined cutoff.

In the second series of energy measurements, the beam from the RFQ was transported through a quadrupole doublet and a 45° analyzing magnet. Although not all of the beam is accepted by this line, its central momentum was easily established. The calculated field required to bend a 640-keV beam through the 45° magnet is 770 G. The measured field corresponding to the centroid of the energy spectrum was 765 G, well within experimental error at

this point, and therefore the final energy is very close to the design energy. The current levels and transmission efficiencies were as reported in the following section.

To determine what fraction of the beam transmitted by the RFQ was indeed accelerated to 650 keV, the following measurement was performed. By reducing the rf field level to about one-quarter of the design value, one is assured that only 100-keV beam is transmitted. This was verified by tuning the doublet and bending magnet for maximum transmission to the beam stop. The bending field should scale with the square root of the energies, which we have verified. Having optimized the analyzing line for 100-keV beam, the rf fields were returned to the operating level. No 100-keV beam was observed at the beam dump (strongly suggesting that everything that comes out of the linac is accelerated beam). In fact, no beam was detectable at any energy except ~640 keV. This is consistent with beam dynamic calculations, which indicate that for significant space-charge levels the majority of the unaccelerated beam is not transmitted. This is further confirmed by an emittance measurement at the exit of the RFQ (EM-2) in the following way; the slits and collectors of EM-2 straddle a quadrupole doublet, which is turned off for normal measurements; if any low-energy beam or heavier ions were transmitted, they could be detected easily by making an emittance measurement with a quadrupole slightly excited and this would apparently rotate the emittance of the different beam components. This measurement was done and none were observed.

Transmission measurements of beam, accelerated and focused through the RFQ, have been made at several input currents (shown in the table below). The input beam was measured on the Faraday cup inserted just in front of the RFQ (FC-02), and the output current was measured on the Faraday cup inserted just after the RFQ (FC-04). Both Faraday cups have electron suppression rings, and measurements were made to insure that the electron suppression voltage was sufficient to suppress all secondary electrons from leaving the cup. The first four measurements in the table were made at approximately the same rf power level, and the last measurement was made with a slightly higher rf power level.

$I_{in}(mA)$	$I_{out}(mA)$	Trans.
30	26	86.7
27	26	81.5
15	12	80.0
9.8	7.5	76.5
9.2	8.2	89.1

The emittance was measured at two stations: the first located between the injector and the solenoid (EM-1), and the second located just downstream of the RFQ (EM-2). The results, discussed below, were obtained when the beam current at FC-02 (the Faraday cup located just ahead of the RFQ) was 32 mA (no apertures were inserted), and the RFQ output current was 25 mA at FC-04. The results of the emittance measurements are given in the table below, where E is the emittance area in $cm \cdot mrad$, and the normalized emittance is defined as $\eta = \beta \gamma E / \pi$. The table values are the emittances that contain the specified fraction of the total beam.

Beam Fraction	EM-1 ($cm \cdot mrad$)		EM-2 ($cm \cdot mrad$)		Growth Factor
	E	η	E	η	
0.90	1.49 π	0.022	1.52 π	0.056	2.58
0.95	1.94 π	0.028	1.97 π	0.073	2.57
0.985	2.44 π	0.036	2.40 π	0.089	2.49
rms	0.53 π	0.008	0.31 π	0.011	1.48

Several comments seem pertinent when interpreting these results. The beam at the first emittance station consisted partly of H_2^+ and H_3^+ (~10 to 15%). Earlier measurements indicate that the emittance of all three species overlap. Consequently, we believe that the emittance of the proton fraction was essentially the same as the measured quantity.

From emittance measurements made before the RFQ was installed, we saw that the beam radius became quite large in the solenoid, and that the emittance pattern measured near the RFQ entrance showed a propeller-like distortion, with a total emittance increase by a factor from 1.5 to 2. We therefore conclude that the emittance growths, as measured at the present emittance stations, are not entirely caused by the RFQ and that a significant fraction can probably be attributed to the effects of the solenoid.

Operation of the RFQ has been extremely reliable, with the number of good beam pulses certainly exceeding 90%. The only observed mode of failure is caused by sparking on the vane tips at high power levels. As the vacuum and rf conditioning continue to improve, so does the operational stability.

X. LOW-BETA STRUCTURE SELECTED FOR TREATMENT FACILITY

Two novel low-beta accelerators have now been designed, built, and tested in the PIGMI laboratory. Initial tests of the APF structure indicated that the dynamics were performing as expected, although the full beam current was not attained. The APF test accelerator was temporarily dismantled in preparation for a test of the RFQ structure. The tests of the latter accelerator benefited from experience gained during the previous experimental program, and when the RFQ was turned on in mid-February of 1980, it performed extremely well.

The results of the measurement program will be reported in the next reporting period. We can now say, however, that the RFQ performs so well and has so many redeeming features--lower injection energy, higher final energy, higher capture efficiency and current limit, lower emittance growth, tolerance to fabrication errors, and operational stability--that it is the clear choice for the low-beta section of any future PIGMI accelerator.

XI. DTL SECTION

The PIGMI Quad Ramp Tank was completed and delivered at the same time as the APF Tank. Fabrication of the nonmagnet-loaded drift tubes (three-stemmed) was completed, except for copperplating. Fabrication of the magnet-loaded drift tubes was completed and they are now ready to load in the magnets. All drift-tube stem hardware was completed.

The PIGMI Phase Ramp and DTL tanks were completed and delivered in December 1979. The tuning-slug/vacuum port for the Phase Ramp tank was modified to allow placement of the ion pump on top of the tank. All nonmagnet-loaded (single-stemmed) drift tubes for the Phase Ramp and DTL tanks were completed, except for final stem machining and copperplating. All magnet-loaded drift tubes were completed to the point of being ready to receive the magnets. All drift-tube stem-termination hardware was completed.

The PIGMI DTL tank is being assembled. The DTL tank has been mounted on an alignment stand and the downstream tankhead installed. The tank will

contain one nonmagnet-loaded drift tube and two magnet-loaded drift tubes. The nonmagnet-loaded drift tube is complete except for copperplating, and is installed temporarily in the DTL tank. The magnet-loaded drift tubes are ready to receive the magnets, which also are ready. Loading and quadrupole field measurements will commence as soon as manpower is available, probably not before the summer of 1980.

Alignment stands and other miscellaneous components, fabricated for the Quad Ramp, Phase Ramp, and DTL tanks, are being used for the RFQ POP tests.

XII. PERMANENT-MAGNET QUADRUPOLES

The PIEMI Prototype design calls for 18 quadrupole-loaded drift tubes, each quadrupole having a unique length and strength. For fabrication purposes each quadrupole falls into one of six geometry groups. The gradient of each assembly is adjusted by grinding flats to an appropriate depth on each of the four circular pole pieces. The geometry of each assembly is common within a group, in the spacing of the pole pieces, and in the shape of the yoke.

One assembly from each quadrupole group has been fabricated and assembled. The pole pieces for each assembly have been ground, measured, and reground until the proper gradient was obtained. This process required the development of a grinding fixture that could hold a pole piece to reproduce the same orientation for the removal of a few mils of material. In addition, a bookkeeping system kept track of the numerous pieces during the grinding and measuring operations. After each grinding operation, the magnetic properties of the assembly were measured: the transverse gradient in four orientations, the effective length at four points, and the harmonic content of the field. Transverse fields and effective length were measured with a Hall-effect probe, the harmonic content of the field was measured, using a rotating coil and spectrum analyzer.

Following each grinding and measuring operation, the data were analyzed to predict how much more material should be removed to achieve the required properties. This process was completed for one quadrupole assembly in each geometry group.

XIII. DISK-AND-WASHER LINAC STRUCTURE

Development of the disk-and-washer linac structure for the PIGMI applications has continued throughout the present reporting period. The structure is a standing-wave linac and offers efficient acceleration at proton energies > 150 MeV. The structure's field distribution is extremely stable as a result of the strong intercell coupling and the $\pi/2$ nature of the operating mode.

The once-favored radial-washer supports have proven to be too lossy for further consideration. Current efforts are directed toward the development of T-shaped washer supports because of their minimal perturbation of the cavity fields and their fore/aft symmetry. Techniques are being developed to counteract the perturbations that they introduce into the structure and coupling.

The geometry of the DAW linac structure (without washer supports) has been optimized with the aid of the rf cavity calculational program, SUPERFISH. The half-cell geometry, shown in Fig. 5, is characterized by the 10 quantities L , G , R_C , R_D , T_D , R_W , T_W , R_H , R_N , and θ . A list of these quantities, optimized for the PIGMI application at 1320 MHz are given in Table I for a range of beta from 0.4 to 1.0 in steps of 0.05. For this application, a number of quantities were held constant, independent of beta; namely, R_C , T_W , R_H , R_N , and θ . Figure 6 shows typical sections of this structure for beta equal to 0.5 and 0.8.

Fig. 5.
DAW half-cell geometry.

The washers are supported in pairs from a number of T-shaped supports. The radial portion of these supports lies along an equipotential of the cavity fields, and the longitudinal portion of these supports lies in regions of low electric field. Consequently, this support geometry represents a minimal perturbation to the frequency of the accelerating mode.

On the other hand, these supports do represent a significant perturbation to the frequency of the coupling mode and to the cell-to-cell coupling

TABLE I
PARAMETERS FOR THE PIGMI DAW LINAC STRUCTURE AS A FUNCTION OF BETA
(FREQUENCY = 1320 MHz, WAVELENGTH = 22.712 cm)

$$R_C = 16.600, T_W = 0.400, R_H = 1.111, R_N = 0.250, \theta = 30^\circ$$

Beta	L	G/L	G	R_D	T_D	R_W	ZT^2
0.4	2.271	0.306	0.695	11.71	0.36	11.27	32.25
0.5	2.839	0.363	1.031	12.06	0.61	10.95	45.37
0.6	3.407	0.415	1.414	12.45	0.92	10.63	56.87
0.7	3.975	0.462	1.836	12.87	1.30	10.31	66.42
0.8	4.542	0.504	2.289	13.32	1.72	9.94	75.17
0.9	5.110	0.545	2.785	13.86	2.18	9.52	82.80
1.0	5.678	0.582	3.304	14.54	2.71	9.94	88.03

constants. Left uncompensated, these perturbations would open a stopband in the mode spectrum, jeopardizing the structure stability, and would create

a bilevel distribution in the excitation of the accelerating cells. Fortunately, it is possible to compensate these perturbations by minor changes in the geometry so as to retain a closed stopband, with its implied stability, and a uniform distribution of accelerating fields.

The magnitude of these perturbations, and the changes required to compensate for them, cannot be determined solely from SUPERFISH results, but depend in part on information gained from model cavity measurements. One approach is to measure the magnitude of the perturbations on the model cavity, and to learn from SUPERFISH the nature of the geometrical changes that are required to compensate for the effects

Fig. 6.

Typical DAW sections for $\beta = 0.5$ and $\beta = 0.8$.

of the perturbations. Armed with this information, it is a straightforward process to alter the cavity geometry so as to converge on the desired results.

Figure 7 shows some of the model's cavity hardware fabricated during this reporting period. Additional hardware is being fabricated from aluminum for $\beta = 0.5, 0.6, 0.7$, and 0.8 . For fabrication and handling convenience, this hardware is being scaled down from 1320 MHz to 2380 MHz.

XIV. BRIDGE COUPLERS FOR THE DAW LINAC STRUCTURE

In long linac structures such as PIGMI, there is the need to break the structure into shorter sections to allow for the introduction of auxiliary apparatus such as beam-focusing quadrupoles, beam-diagnostic equipment, vacuum-isolation valves, etc. In many cases, it is desirable to couple these sections into larger resonant units to reduce the required number of rf power drive points and to lock the relative phase and amplitude of the fields in adjacent sections. Such couplers in LAMPF have been called bridge couplers, because

Fig. 7.
DAW model cavity.

they bridge the resonant properties of the linac structure around the auxiliary apparatus.

The DAW linac structure is a resonantly coupled ($\pi/2$ mode) linac structure with very large coupling constants. To take optimum advantage of the superior properties of this structure, any required bridge couplers also should be of the resonantly coupled type with large coupling constants. For practical structure tuning, the coupling of the bridge coupler to the linac structure should represent a minimum distortion of the field patterns in either element.

It was recognized several years ago that the field patterns in the coaxial TEM mode were very similar to the field patterns in the plane of the washer of the DAW structure. A family of coaxial bridge couplers based on this geometry were proposed by J. J. Manca and E. A. Knapp. The couplers in this family do not, in general, satisfy all the requirements of resonant coupling, which requires that resonance be maintained for both the accelerating mode and the coupling mode of the structure.

For accelerator applications, resonantly coupled bridge couplers must satisfy one beam-dynamics constraint and two rf constraints; the former requires that the length of the bridge coupler, as defined in Fig. 8, be equal to $N\beta\lambda/2$, where N is an integer; the latter requires proper accommodation for both degenerate modes of the linac structure. Until recently, we did not know how to satisfy both of these constraints simultaneously for an arbitrary particle velocity β .

Fig. 8.
Resonantly coupled coaxial
bridge coupler.

For a simple cylindrical coaxial cavity, shown in Fig. 8, the rf constraints require that the bridge-coupler length be $M\lambda/2$, where M is an integer. Furthermore, the beam dynamics requires that M be of the same parity as N ; that is, if N is odd, M must be odd, and if N is even, M must be even. This constraint on bridge-coupler length is incompatible with the beam-dynamics constraint on

bridge-coupler length except for a few discrete values of β . Therefore, the simple cylindrical coaxial cavity is not a suitable solution for the general resonantly coupled bridge coupler.

One alternative is to choose the bridge-coupler length so as to satisfy the beam-dynamics constraint exactly, and to tune the resulting coaxial cavity so as to satisfy both rf constraints simultaneously. Two recently conceived schemes achieve these constraints.

The first scheme is based on our recent observation that there is a class of tuning perturbations that affects both modes in exactly the same manner. This class of perturbations guarantees that when one of the rf constraints is satisfied, the other also will be satisfied.

The second scheme is based on the use of two different perturbations that affect the two modes differently, and the adjustment of these perturbations, in concert, until both rf constraints are satisfied. This scheme, although slightly more complex, may yield more appropriate geometries.

In either case, we can treat the bridge coupler as M identical sections, where M is chosen to be close to βN and of the same parity as N . Thus, the basic section length is $(\beta N/M)\lambda/2$. If M is greater than βN , perturbations are required that lower the frequency of the two modes, and if M is less than βN , perturbations are required that raise the frequency of the two modes. In practice, it may be desirable to constrain M to be either greater than βN or less than βN , so that only one type of perturbation is required.

The class of perturbations, having identical effects of both modes, is limited to symmetrical perturbations centered on the $1/4$ and $3/4$ locations within the basic bridge-coupler section. This implies a fundamental periodicity of the bridge-coupler geometry of one-half the basic section length.

Figure 9 shows a bridge coupler of the type for $N = 7$, $\beta = 0.6$, and $M = 5$. The power dissipation of the accelerating mode in this bridge coupler is 1.15 times the dissipation in the accelerating cavity.

Figure 10 shows a bridge coupler of the second type for the same values of N , β , and M , where two different perturbations are used and adjusted, to satisfy the two rf constraints simultaneously. The power dissipation of the accelerating mode in this bridge coupler is 1.21 times the dissipation in the accelerating cavity.

Fig. 9.
Type 1 bridge coupler.

Fig. 10.
Type 2 bridge coupler.

For the PIGMI application, it appears that single-cell bridge couplers ($N = 1$) may be adequate to house the required apparatus within the linac structure. Figure 11 shows the $N = 1$, $M = 1$ bridge couplers of the second type for the values of β equal to 0.5, 0.6, 0.7, and 0.8. The power dissipations of the accelerating mode in these bridge couplers are 0.60, 0.64, 0.67, and 0.68 times the dissipations in their respective accelerating cavities.

Figure 12 shows the field distribution for the accelerating mode and the coupling mode for the some four values of β . The resonant frequency in each case is 1320 MHz.

If the power dissipation in the bridge couplers is considered excessive, it should be possible to modify the geometry at each

end of the bridge coupler so as to reduce the excitation of the bridge coupler without affecting the excitation of the accelerating structures. It should also be possible to implement a movable perturbation that would affect the relative excitations of the adjacent accelerating structures.

In the center of each of the M identical bridge coupler sections is a region of high magnetic field and zero electric field. The effect of a radial short in this plane on the accelerating and coupling modes is equivalent to the effect of the tank and terminations on the two modes. Conducting radial supports in this plane have a negligible effect on the accelerating mode and a tolerable effect on the coupling mode.

Fig. 11.
Single-cell bridge-coupler geometry
for $\beta = 0.5, 0.7$, and 0.8 .

Hollow conducting radial supports provide a suitable channel for the services required by the auxiliary apparatus housed inside the bridge coupler, such as cooling water for the bridge parts, power leads for electromagnets, signal leads for beam diagnostic devices, and control rods for mechanical devices. There may be some advantage in selecting M (and hence N) to be odd. With this constraint, midplane of the bridge coupler is a suitable plane for the support structure.

Fig. 12.
Single-cell bridge coupler field
distribution for $\beta = 0.5, 0.6, 0.7$,
and 0.8 .

XV. FIELD GRADIENT AND AVERAGE POWER ACCELERATOR STRUCTURE TEST

Essential to the PIGMI concept is the demonstration of the viability of the selected design acceleration gradients, and the accelerator structure compatibility with the related average power. Both of these parameters have been affirmed, using structures typical of those required for the low-frequency, low beta portion of the PIGMI accelerator. These tests included both the Alvarez and RFQ structures. Similar testing of the DAW structure proposed for use in the higher frequency, higher beta portion remains. The 22-cell, $\beta = 0.7$, DAW structure, as shown in Fig. 13, will be used for this test. The selected PIGMI design gradient (9.0 MV/m) implies a maximum surface gradient somewhat in excess (15%) of the Kilpatrick Criterion, a semiempirical guide to sparking threshold. For the selected test structure, a peak rf power of 1.4 MW at an average rf power of 5 kW, represents the minimum requirements. Ideally, one would push the structure to sparking, with the rf power requirement increasing with the square of the gradient.

Two high-power, pulsed, klystron tube types are available for application to these tests. Both of the available klystron types satisfy the peak- and average-power requirements of the planned tests. However, they differ significantly in their modulator requirements. One type, the L-3707, uses a nonintercepting, modulating anode. As such, the tube operates with a dc potential applied across the tube, which in turn is gated on and off by an essentially zero-power pulse applied to the modulating anode. For experimental application, this type of modulation offers maximum operating flexibility. The pulse length and pulse-repetition rate can readily be varied. The effective tube perveance and the tube operating voltage can be varied, so as to

Fig. 13.
DAW power test assembly geometry.

readily and efficiently tailor the power output to any changes in the experimental requirements. Additionally, the technology for this modulator type is well developed and was employed in the aforementioned low-frequency, low-beta-structure tests.

The second klystron tube type available for use is the L-3661, which requires cathode modulation; that is, the full tube voltage and current must be gated. As such, the modulator must switch megawatts, as opposed to the essentially zero power required when using a modulating anode. On the other hand, the required dc voltages differ significantly with the cathode type, representing the more conservative stance. Conventionally, the cathode modulation is provided by a resonantly charged pulse-forming network driving a step-up pulse transformer. The pulse length and pulse repetition rate are relatively fixed. Potentially more serious, this type of modulator is more difficult to engineer because of the long pulse ($\sim 60 \mu s$) requirement. The cathode-pulsed tube type is the more attractive choice for PIGMI application because commercially available cathode-pulsed klystrons offer significantly higher unit peak-power output. This in turn offers lower construction cost and increased operating reliability.

Because the cathode-pulsed tube was the preferred choice for an operational PIGMI facility, we decided to pursue the development of the required technology for this approach. While satisfying the basic requirements of the experiment, it will also provide an opportunity to develop the hardware and software unique to this approach and required for an operational facility. A resonantly charged pulse-forming network and pulse-transformer modulator has been designed. In combination with the L-3661 klystron, the program can test the 22-cell structure at gradients of up to 2.5 times the Kilpatrick criterion and at average powers of up to four times that projected by the design. The equipment required for this test will be assembled in space recently made available to the program by the Laboratory. The L-3707 klystron, the combination with the previously used PIGMI modulator, will be used as a contingency backup.

XVI. PION CHANNEL DESIGN

For the treatment of tumors with pi-minus mesons (pions), a pion channel with a large solid angle is essential. A parallel beam of uniform density and reasonable size at the patient position is favored, from the practical point

of view. A new pion channel with sixty toroidal current sheets and some solenoids is shown to meet these requirements. It would also be useful for some physics experiments using low-energy pion and muon beams.

The pion channel used at LAMPF consists of two bending magnets and eight quadrupole lenses and has a solid angle of about 15 msr. Even with a proton beam of 500 μ A, it takes a fairly long time to treat a patient (15-20 min). Therefore, it is of interest to consider pion channels with a larger solid angle.

So far, two kinds of pion channels with a solid angle of 0.5 to 1.0 sr have been constructed for medical application. One is the double orange-sector pion channel at Stanford and SIN. The other is one with a shaped solenoidal field developed at Dubna. The latter type has recently been considered at TRIUMPF. In these channels, pions from the target are refocused to a point in space. However, treatment experience at LASL suggests that a parallel beam of uniform density is to be preferred because of its ease of use. The channel with an orange sector can collect many pions. We propose and analyze a new pion channel design where the pions are collected with an orange-sector magnet, and then made into a parallel beam by running the pions outside a special solenoid field.

Figure 14 displays an overview of the practical situation in the treatment of a patient. The position of the patient can be adjusted, depending on where the tumor is in the body. For a tumor lying near the surface of the body, the patient can be placed nearer to the main solenoids, whereas for a deep-seated tumor, he should be placed a little downstream to make use of the more parallel beam.

After bombarding the target, the proton beam is guided outside. This makes it easier to reduce neutron and γ -ray background at the patient position from beam dump, as compared with the situation at SIN, where the proton beam is stopped between target and patient.

The pion-production angle of $\theta_{\pi} \cong (85 \pm 15^{\circ})$ is selected in the present channel. It is probably the best choice, considering the angular dependence of pion-production cross section and a tolerable contamination of muons and electrons.

Fig. 14.

Practical situation of the present pion channel in the treatment of a patient.

are appropriate, whereas the remaining solenoids can be made with conventional copper wire.

3) By tuning the shape of the current sheets, a sharper focus can be obtained. Refinement of solenoids would result in a larger effective solid-angle.

4) It is estimated that an energy degrader can be used to reduce the energy width of particles at the patient position. The original particle distribution of the parallelogram can be converted into the rectangular form. Energy loss, straggling and variation in trajectory angle for each particle at the degrader will cause some variation from the rectangular form. The loss of

The present channel would be useful for some physics experiments. In fact, if we do not mind the beam size of $r \approx 20$ cm, we can attain a solid angle of more than 2 sr, while the resulting beam with a selected energy is fairly parallel.

In the present work, some basic characteristics of the current sheet and solenoid pion channel are explored in fair detail. However, prior to practical design considerations, additional work must be done. Some considerations are discussed below:

1) The bending magnets for the incident proton beam should be designed so that they do not interfere magnetically with the arrangement of the sector magnets and solenoids.

2) It should be established from what material each solenoid must be made. For the two main solenoids, superconducting coils

beam intensity from multiple scattering in the degrader should be analyzed quantitatively.

5) It would be interesting to investigate the possibility of some kind of dynamic treatment. As the pion energy is increased, the layer where the pions are stopping goes deeper and deeper. The shape of each layer should be exactly matched to that of the tumor at that point. This can be done by changing the shape of the slit on the patient as we change the pion energy.

XVII. ACHROMATIC BENDING SYSTEM

A PIGMI accelerator would be 130 m long. One possibility of reducing the total length of the facility is to bend the linac back on itself at the halfway point. However, the 180° bending system used for this purpose must have the very special properties of being both achromatic and isochronous, to transport the proton beam without destroying the transverse or longitudinal dimensions of the bunch.

Two such systems have been studied. We expect the 180° bending system to be positioned at about the halfway point in the linac structure, corresponding to an energy of 250 MeV. The bending system would consist of several bending and quadrupole magnets. The problem is to find an appropriate combination of these magnets to satisfy both the achromatic and the isochronous conditions.

A flat, semicircular bending magnet can achieve isochronous, but not achromatic, bending. When two identical 90° bending magnets with a quadrupole magnet located between them are used, a system can be made either achromatic or isochronous (depending on the field strength of the quadrupole magnet), but it cannot be made simultaneously achromatic and isochronous. Therefore, three or more separate bending magnets are necessary to build the desired system. Two possible systems were studied.

Figure 15 shows an achromatic and isochronous system, consisting of three bending-magnets. This system satisfies all of the necessary constraints. Particle trajectories of special interest are shown in Fig. 16. The z-axis coincides with the central ray. The x- and y-axes indicate the deviation from the central ray in horizontal and vertical motions, respectively. A monochromatic beam, diverging at the entrance, forms an intermediate double-focusing image at the symmetry center of the second bending magnet B_B , and converges again to the exit.

Fig. 15.

An achromatic and isochronous bending system --- System 1. (The bend radius of each magnet is 1.4 m).

the exit. A typical trajectory for $\Delta p/p = 0.2$ is shown as a solid line in the xz -plane, labeled $\delta = 0.2$. A relatively large dispersion at the symmetry center is necessary to make the system isochronous.

For this system, the separation between the incoming and outgoing beams is 5.6 m, which makes it unattractive for some applications. To build a system with smaller separation, it is necessary to use more magnets involving bends to both directions.

A somewhat more complicated system, consisting of eight bending magnets, is shown in Fig. 17. Involving bends in both directions, this system is relatively large, but the separation between the incoming and the outgoing beams is only 2 m. In the first half of the system, optical properties of point-to-point imaging and parallel-to-parallel transformation again are realized for the monochromatic beam. Therefore, any monochromatic beam can be transported to the one with the same phase space in the full system. Off-momentum particles, incoming on the central trajectory, are dispersed horizontally by the first bending magnet B_1 to an intermediate image near the quadrupole Q_5 . The angular dispersion at this point can yield a large

A representative trajectory of $\theta_0 = 4 \text{ mrad}$ and $\phi_0 = 4 \text{ mrad}$ is drawn with solid lines in Fig. 16. An incoming monochromatic beam, parallel to the central ray, again becomes parallel at the symmetry center and is transported to an outgoing parallel beam at the exit. A representative trajectory of $x_0 = 5 \text{ mm}$ and $y_0 = 5 \text{ mm}$ is drawn with dotted lines. An off-momentum particle, incoming on the central ray at the entrance, deviates horizontally from the central ray in the first bending magnet and travels on a dispersive trajectory, which becomes parallel to the central ray at the symmetry center, so the particle is again on the central ray at

Fig. 16.

Particle trajectories of special interest in System 2. (The solid line and the dotted line show trajectories of particles of central momentum. The solid line labeled $\delta = 0.2$ is that of an off-momentum particle.)

Fig. 17.

An achromatic and isochronous bending system that involves bends in both directions—System 2. (The bend angle of each magnet is 45° ; the bend radius is 1.4 m. All bending magnets are identical.)

spatial dispersion at the symmetry center and sufficient path-length difference to realize the desired isochronous condition in the full system.

The 2-m separation between the input and output beams will facilitate installation of both halves of the accelerator in the same beam channel, and this system can readily be designed for even smaller separations. Finally, it should be pointed out that all bending magnets are identical, which would be advantageous from the cost aspect.