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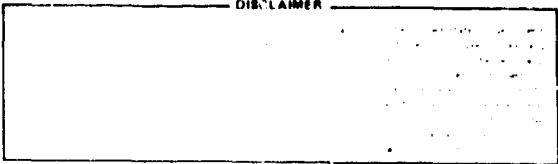
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TITLE: HIGH-INTENSITY ACCELERATORS

AUTHOR(S) E. A. Knapp



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Los Alamos Los Alamos National Laboratory Los Alamos, New Mexico 87545

HIGH-INTENSITY ACCELERATORS

E. A. Knapp

Los Alamos National Laboratory, Los Alamos, New Mexico 87545

ABSTRACT

The design of high-intensity accelerators is described, using examples of machines being built at the Los Alamos National Laboratory. The major design problem with these accelerators is associated with control of beam loss when accelerator intensity is increased. Beam dynamics, beam loss, and the radio-frequency quadrupole structure are discussed in the first part of the chapter followed by an explanation of plans to achieve high-intensity operation in three projects: the Fusion Material Irradiation Tests (a joint effort with the Hanford Development Laboratory in Richland, Washington), the Proton Storage Ring (an addition to the LAMPF accelerator), and the Racetrack Microtron Project (with the National Bureau of Standards).

1. INTRODUCTION

In this chapter I will first discuss the design of high-intensity accelerators and then give three examples of these accelerators that we are building in Los Alamos. Each has a different design problem, but in each case the major design problem is associated with control of beam loss when accelerator intensity is increased. This minimal beam loss is necessary to reduce radio-activation of accelerator parts during operation. Beam loss can occur through several different mechanisms. Beam emittance growth in the acceleration process is perhaps the most serious beam-loss mechanism, particularly for proton linacs. The injection, extraction, and instabilities in circular accelerators determine beam loss; unwanted cavity modes in electron accelerators, electron linacs, and microtrons also are a serious cause of beam loss and current intensity limitation.

2. BEAM DYNAMICS, BEAM LOSS, AND THE RFQ ACCELERATOR

For a good review of beam loss and emittance growth in linear accelerators and the limitations on intensity in ion accelerators, refer to R. A. Jameson's review talk at the March 1981 IEEE Conference, entitled "Beam Intensity Limitations in Linear Accelerators," IEEE Trans. Nucl. Sci. 28, Vol. 3, pp. 2408-12 (June 1981). He includes a good bibliography of the work done in the last few years in this field and discusses the work under way at most centers.

We have recently developed a fairly good understanding of the rms behavior of particle beams at high intensity. The halo behavior, the last few particles on the outside beam edges, is not as well understood. The beam envelope equations illustrate some of the parameters involved in these discussions.

$$\ddot{a} + (\sigma_0^t)^2 (1 - \mu_t) a = (N\beta\lambda)^2 (\epsilon_t)^2 / a^3, \text{ and} \quad (1)$$

$$\ddot{b} + (\sigma_0^l)^2 (1 - \mu_l) b = (N\beta\lambda)^2 \epsilon_l^2 / b^3,$$

where a and b are the radial and longitudinal beam rms, the derivatives are with respect to focusing period units, σ_0^t the transverse phase shift per period without space charge, σ_0^l the longitudinal phase shift per period without space charge, and

$$\left(\frac{\sigma^t}{\sigma_0^t} \right) = \sqrt{1 - \mu_t}$$

is identified as the transverse space-charge tune depression, where μ_t is the ratio of space-charge forces to focusing forces. The condition for a matched beam is that $\ddot{a} = \ddot{b} = 0$. This yields a formula for the matched beam diameter, given a beam emittance. The transverse and longitudinal motions are coupled through the space-charge parameter μ . Some understanding of this coupling has developed in the last few years and points the way to new understanding of emittance growth in linac systems.

The typical performance of existing ion accelerators (Fermilab and LAMPF) shows normalized emittance growths of between a factor of 2 and 3 from the ion source to the output (for example, into the booster at Fermilab). Modern simulation calculations, which include the space-charge effects and their coupling, show similar results and indicate that mechanisms producing this emittance growth may arise from the unequal partitioning of energy in the transverse and longitudinal emittances at injection. A curve (Fig. 1) obtained by R. Jameson (using simulation techniques) shows that with typical input beam conditions the transverse emittance grows by about a factor of 2, with simultaneous decrease of the longitudinal emittance by roughly 20%. At the same time, the transverse and longitudinal velocity spreads partition themselves during the acceleration process so that they are equal. In this example there was a space-charge tune depression of 75% with a large (factor of 5) imbalance between the initial longitudinal and transverse emittances, typical for accelerators having conventional single-frequency buncher systems at injection.

Jameson also has made calculations indicating what would happen if the input beam to the linear accelerator were balanced, or equipartitioned, in the transverse and longitudinal planes. In the case where equipartitioning is achieved for the simulated linac previously mentioned, the emittance growth through the length of the linear accelerator is virtually zero, at most 10%. This is shown in Fig. 2. If the emittances are then unbalanced with the transverse emittance smaller, the transverse emittance grows and the longitudinal emittance damps. If these conditions are reversed

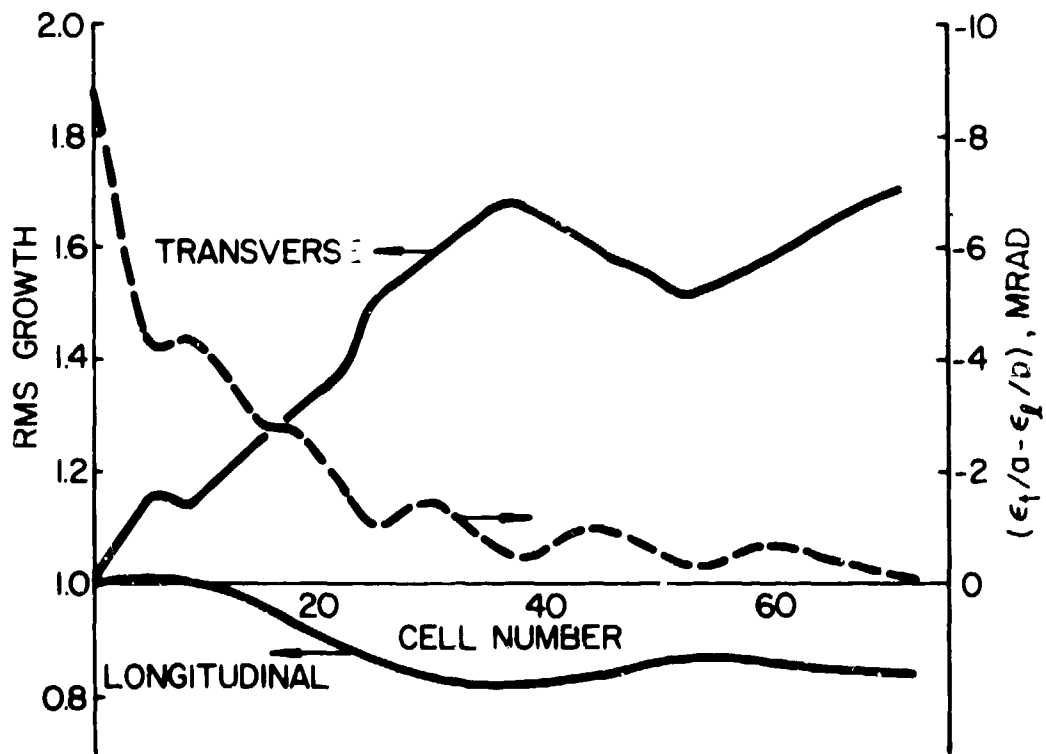


Fig. 1. Rms emittance growth and $(\epsilon_1/a - \epsilon_2/b)$ in constant $\sigma^t = 25^\circ$, constant E_0 linac. Initial $\mu^t \sim 0.75$, $\mu^l \sim 0.55$, ϵ_2/ϵ_1 .

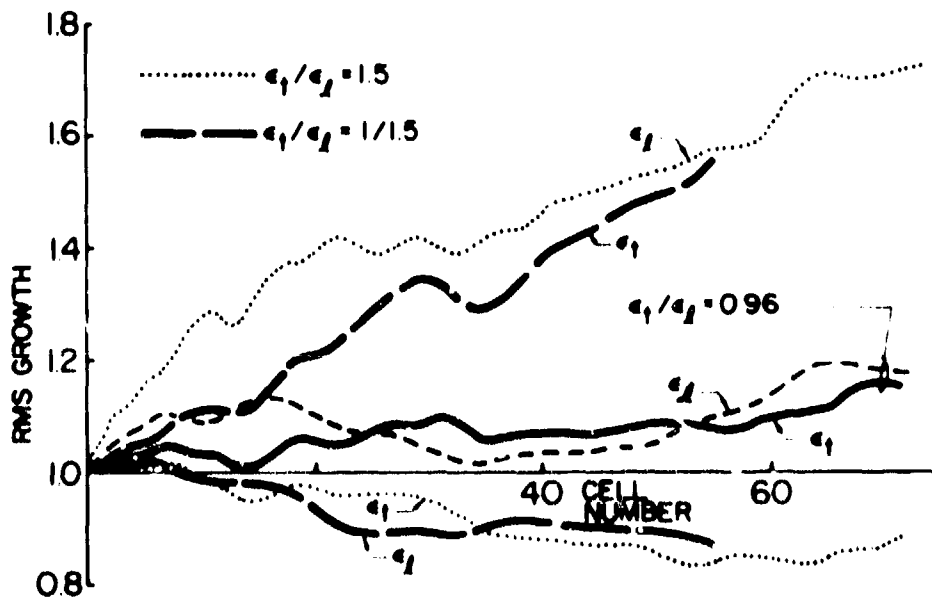


Fig. 2. Rms emittance growth in 72-cell, constant $\mu^t = 0.9$, constant E_0 linac. Initial $\mu^l \sim 0.8$.

and the emittances are unbalanced the other way, the opposite happens; that is, the emittance damps in the longitudinal case and grows in the transverse case. This would indicate, at least from the simulation calculations, that doing a very careful match and equipartitioning the energy at the input to a linear accelerator is important to keep the emittance growth low.

These matched and equally partitioned input emittances may be achieved by populating the input phase space in the six dimensions in a fairly precise way; the best way to do this might be to adiabatically capture and bunch the injector beam (dc) into the proper distributions. It is for this purpose that we think the RFQ (radio-frequency quadrupole), a new accelerator device we are developing in Los Alamos, becomes extremely important in high-current accelerator design. The RFQ solution accomplishes the task of excellent beam matching using this adiabatic capture approach, and it is an integral part of all our new high-intensity accelerator designs. I will not go into detail about the RFQ but will only indicate roughly what it is and how it works.

The RFQ is a low-velocity accelerator using rf electric field radial focusing, rather than magnetic field focusing. A view of the vane geometry at the RFQ input is shown in Fig. 3. The electric field is a quadrupole field as shown. The magnetic fields then circulate about the vanes, which are mounted on the inside of a circular pipe. Without the undulations on the vane tip, this device would be a focusing channel with no acceleration. By properly adjusting a ripple on the vane ends and phasing it properly, this structure can be made both the focusing channel and an accelerator suitable for low-velocity ions. The low-velocity ions (50- to 100-kV protons at input) can be adiabatically bunched and captured, because in a relatively short distance, many longitudinal phase-oscillation wavelengths can be included in the device design.

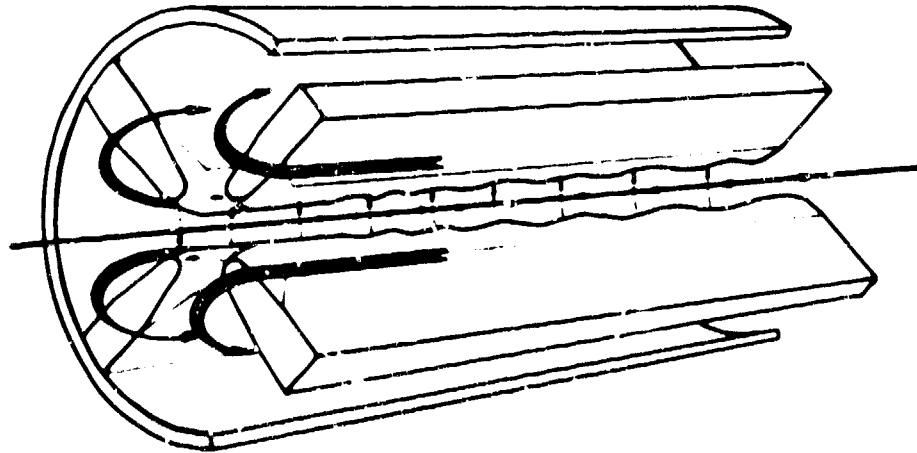


Fig. 3. Schematic view of vane geometry at the RFQ input. The heavy arrows depict the magnetic field; the dashed arrows depict the electric field lines.

In these many phase oscillations, a dc beam can be bunched with a very high-quality particle distribution in longitudinal and transverse phase space. Particle-simulation calculations of the RFQ performance show this behavior in detail. Very low emittance-growth RFQs have been designed for several of the projects described below. Future work is directed toward RFQ designs that will produce a beam optimally matched to the following stage so overall emittance growth is minimized.

3. HIGH-INTENSITY ACCELERATORS AT LOS ALAMOS

We have eight accelerator projects under way in Los Alamos. Following are three examples of high-intensity accelerators on which we are working. FMIT (Fusion Materials Irradiation Tests) is a high-current deuteron accelerator, which is to be a neutron source for radiation-damage measurements on materials that could be used primarily as liners for fusion reactors. Beam loss in this case is the major design criterion. There will be a 3.5-MW deuteron beam to be contained, and very small beam loss is required to allow hands-on accelerator maintenance. The PSR (Proton Storage Ring) is being built as an addition to the LAMPF accelerator, and because of the very high currents involved, we need to minimize loss at injection and extraction. With the National Bureau of Standards, we also are building a microtron where the cavity interactions and the excitations of transverse modes are the major problems with the intensity. Let us consider the problems associated with these three projects and discuss how we plan to achieve high-intensity operation.

The FMIT accelerator is intended to accelerate deuterons, although in the FMIT prototype at Los Alamos we will be accelerating H^{2+} ions. This system operates continuously (cw). The 80-MHz frequency is a convenient frequency for a triode rf system. There are two drift-tube resonator tanks, ending at 20 and 35 MeV, so there will be two operational energies. The maximum beam current will be 100 mA, with an energy gain of 1 MeV/m. The injection energy will be 70 kV to match the RFQ we are building as the first rf accelerator section. The RFQ output energy will be 2 MeV. The total power is a little over 5 MW, an impressive cw power.

We feel that the spill level in the accelerator has to be less than a few parts in 10^{-5} (no more), and this is our goal. We are not sure this goal can be accomplished because we have no simulation program that can track particle losses at this low level; however, we are confident we can come close to these performance levels. It is difficult to extrapolate from existing accelerators or computer codes to beam-loss levels in this range. There is a similar accelerator proposal in the USSR fusion-power program. Their position is that this can be done only if remote handling is designed into the facility.

Figure 4 shows a layout of the FMIT accelerator system. In this system there is an ion source injector and transport system,

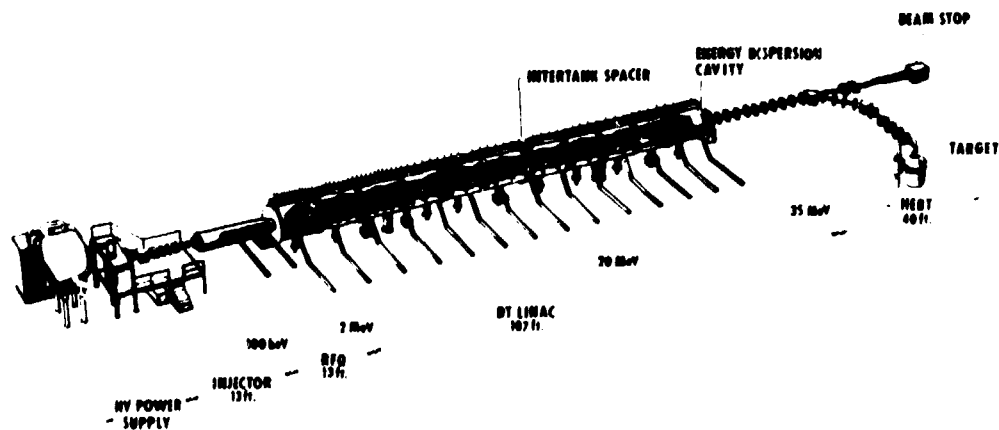


Fig. 4. The FMIT Accelerator.

a 2-MeV RFQ section, two drift-tube accelerator sections, a beam-transport system, and a target.

The ion source and injector system is operating successfully in Los Alamos. The ion source is a simple device. It is a "picket fence" ion source, consisting of a copper box with permanent magnets attached to the outside in an opposing field geometry. An arc is struck from a filament to the copper box, filling the box with a plasma, which is then extracted from a roughly 1-cm-diam hole. The injector system is shown in Fig. 5.

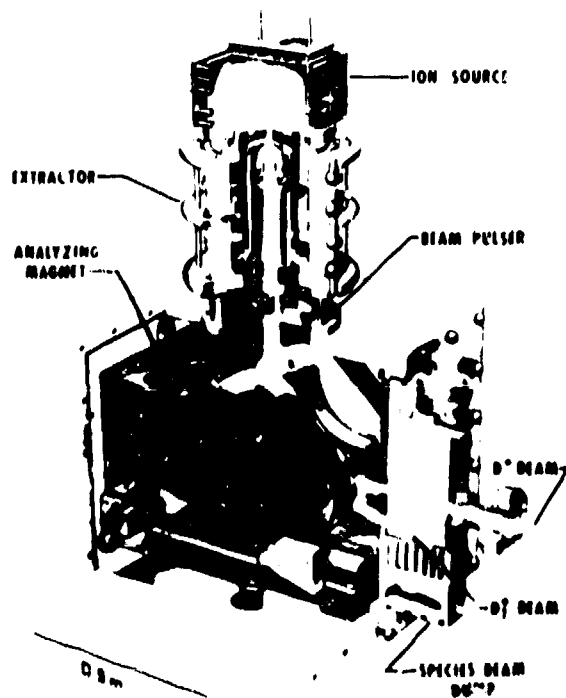


Fig. 5. Injector system.

Figure 6 is a photograph of the FMIT injector system. The beam from the ion source is clearly seen through the porthole in the beam transport tube, in the center of the picture. Ion-source operation has been successful; we have extracted 250-mA cw at 70 kV. Greater than 60 mA of current is transported through the low-energy beam-transport system with a normalized emittance of $\epsilon < 0.02\pi$ mrad-cm, which is five times better than our design requires and, additionally, is better than anyone expected.

The RFQ section is simple in principle but mechanically complex in practice. In Fig. 7, a cutaway drawing of the RFQ system for the FMIT accelerator, there is a blown-up section showing the four poles of the quadrupole system after the ripples on the tips are better developed. The RFQ is in a cylinder driven by an outer manifold, which is a coaxial cavity. There are four slots, one between each of the four vanes, located at three or four positions along the length. These slots provide electromagnetic coupling from the outer manifold into the four vanes that supply the focusing and acceleration. The slots are rotated at an angle so that the plane of the magnetic-field polarization, which in the coaxial

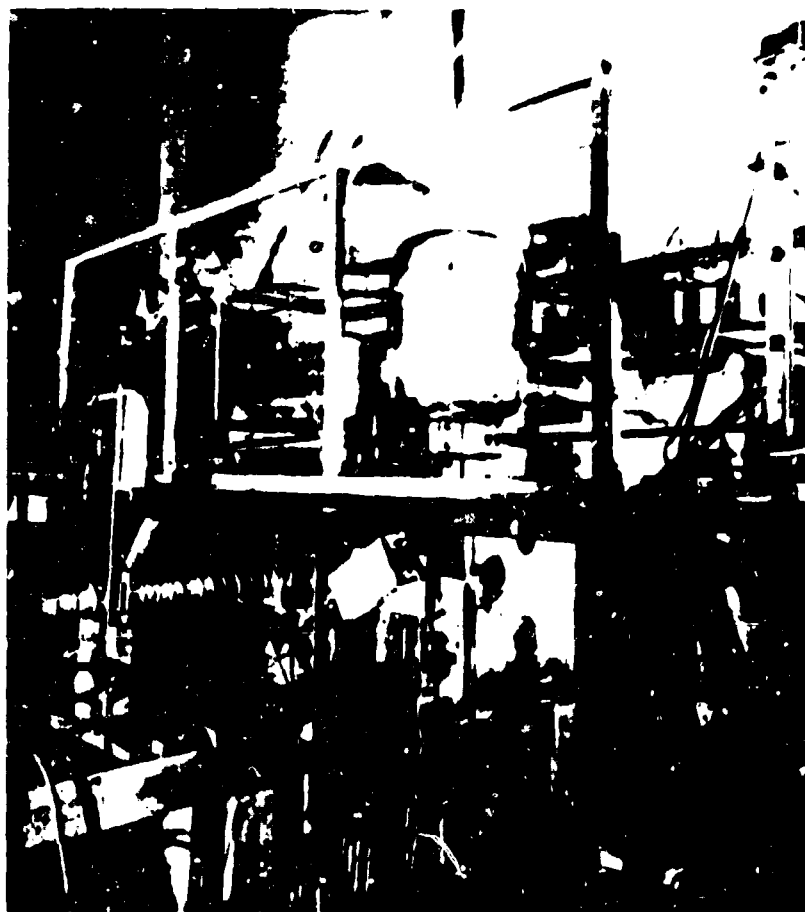


Fig. 6. FMIT injector system.

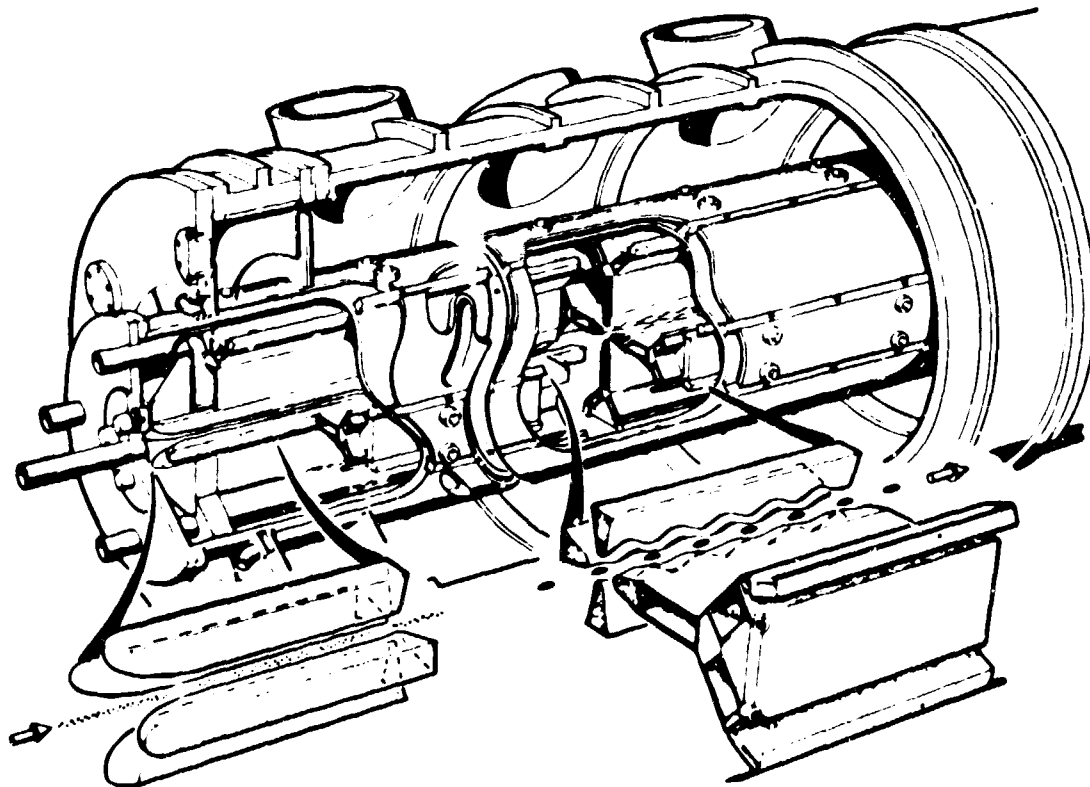


Fig. 7. RFQ system.

line is circular about the center conductor of the coaxial manifold, is rotated to be longitudinal on the inside. This is an important feature in the device development, which we think will make the fields symmetric and will allow us to drive to a high power. This system is heavily water cooled, being cw, and about 500 or 600 kw is to be dissipated in the RFQ section.

Figure 8 shows a cutaway drawing of the FMIT drift-tube accelerator that follows the RFQ section. The design is similar to the injector linac at Fermilab, LAMPF, and other places--with post couplers for field stabilization. The only unusual feature is that the system is designed so it can be taken apart with little contact with the tank interior. In case of beam-loss activation, without much difficulty the parts can be moved elsewhere for maintenance.

The beam transport system, which follows the drift-tube linac, is a periodic system designed to transport 20- and 35-MeV, 100-mA cw deuteron beams to either of two target cells and focus the beam to a 1- to 3-cm spot on the lithium target. It also will transport the beam to the beam stop during accelerator tune-up. The first section of the beam transport extends the periodic quadrupole system of the linac and is used for beam diagnostics. The remainder of that section matches the beam into the first bending magnet. The lateral displacement to the two cells is accomplished by a periodic bending system of three other bending magnets that are

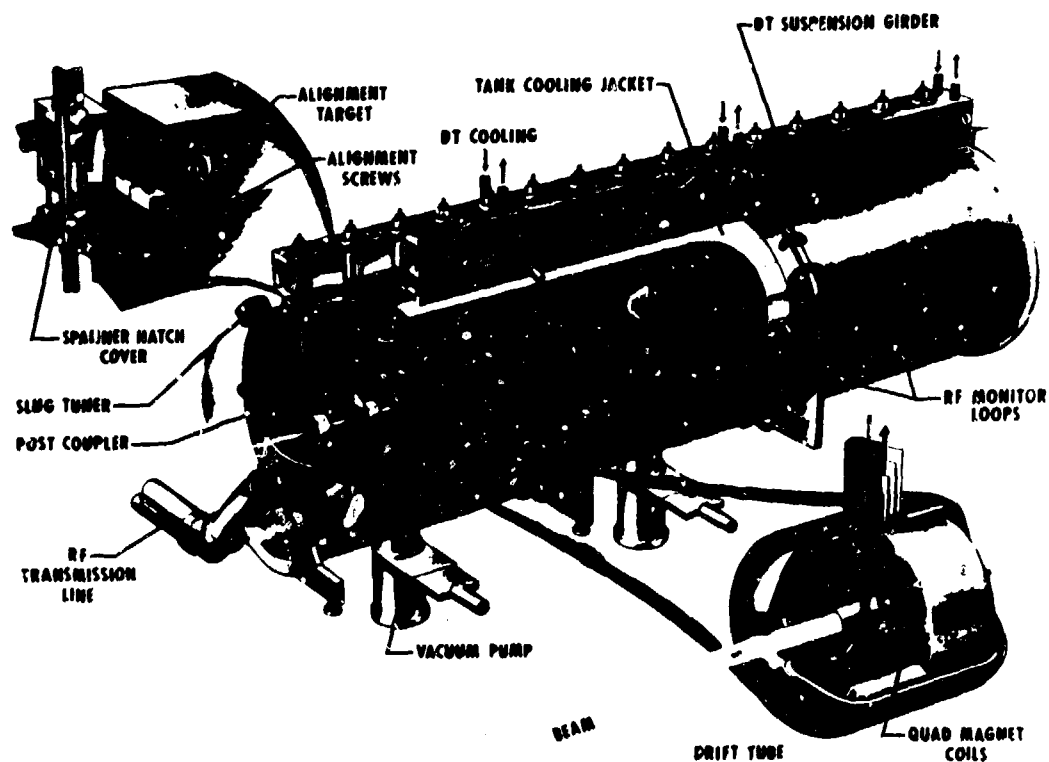


Fig. 8. Drift-tube linac.

identical but reversed for the opposite arm. The final magnet in each arm focuses the beam to a spot on the target.

Finally, the lithium target, which will dissipate about 3-MW power in a few cubic centimeters of target volume, is shown in Fig. 9. The target is unique—a flowing liquid-lithium system, presently not completely operational; it is being designed by the group that does the liquid-metal cooling for the fast-breeder reactor prototypes at the Hanford Engineering Development Laboratory in Richland, Washington. We hope to be able to absorb the 3.5 MW of beam power continuously in a very small target volume, a cubic centimeter or so. The target has a lithium electromagnetic pump, which pumps the liquid through a nozzle. The lithium is held against the back wall by centrifugal force. The neutrons are produced in the region where the beam interacts with the lithium. The beam misses the back stainless steel wall by a millimeter or less. The system cannot allow boiling in the lithium or fluctuation in the target thickness because serious problems can occur, such as melting of the back wall. This system is far from finished, but quite a bit of progress has been made recently. The pump is working; the lithium closed-loop system seems to work well.

The next high-intensity project to be discussed is the PSR, an addition for pulsed-neutron physics at LAMPF. Shown schematically in Fig. 10, it is a ten-sided "storage ring," or accumulator ring with an 8-ms storage time. It is used to compress a beam of

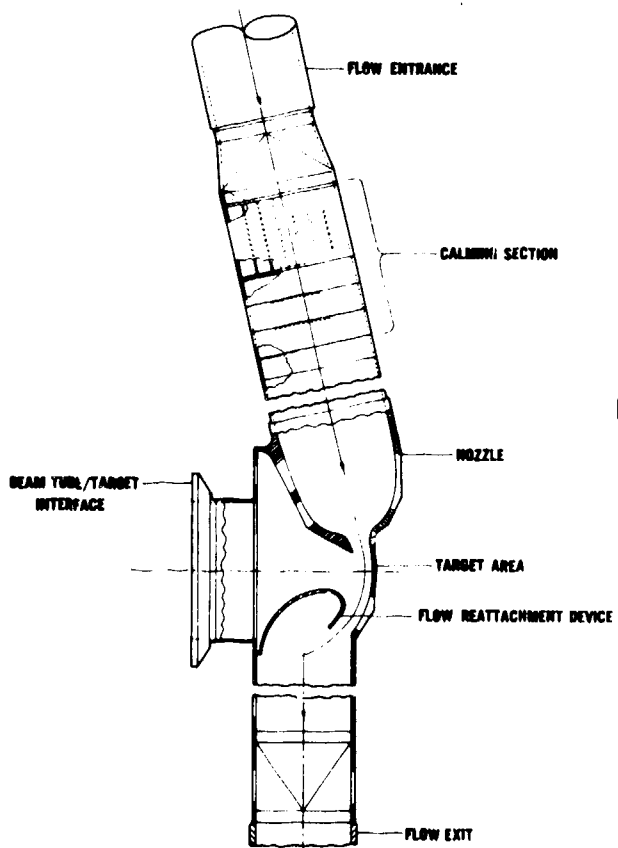


Fig. 9. FMIT lithium target.

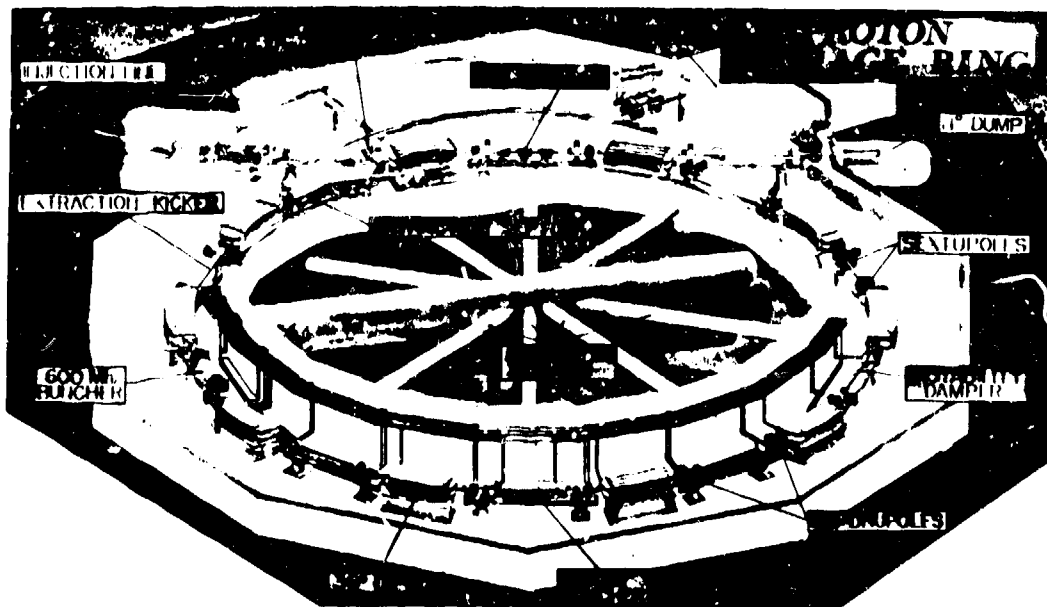


Fig. 10. Proton Storage Ring.

up to 100- μ A from the LAMPF accelerator into short bursts for neutron time-of-flight measurements. The PSR will have two modes of operation--a short-pulse mode for neutron time-of-flight measurements and a long-pulse mode for material-science studies. The short-pulse mode will feature 1-ns beam bursts at 720 pps, the long-pulse mode will be 250-ns bursts at 12 pps.

Injection and extraction make high-intensity operation difficult. For injection we use a two-step H^- stripping process-- H^- beam is converted to H^0 in a sharp-edged magnetic field outside the accelerator. It then passes through a foil on the injection orbit inside the machine for conversion to H^+ . Beams not stripped in the H^0 to H^+ stripping are then lost in a well-located beam dump; the H^0 goes straight ahead and is lost in a beam dump outside the Ring. A high space-charge limit is achieved using a large-aperture magnet system. The 300-MeV injection also minimizes the space-charge problem.

We have ample space in the straight sections for various components. The intense beam is inside the device about a millisecond, a short accumulation time. The PSR is injected with the beam already tailored into the rf bucket geometry, thus a large accelerating field in the Ring is not needed for bunching. We can extract on demand. This capability is important because in our power grid the 60 cycles on the power line are not precisely phase controlled, but a mechanical chopper for the thermal neutron measurements is quite time constant. We have to time the beam extraction to the chopper position rather than time to the 60-cycle line--an important feature.

The system status has been described recently. The magnets are out for bid. Most of the components in the Ring are in the design phase. The physics design has been set with a few components, like the rf cavities and some multipole magnets, in the R&D phase. The Storage Ring is scheduled to operate in 1985, depending upon the availability of the LAMPF accelerator switchyard modifications to allow injection.

The short-bunch mode has a 1-ns bunch width, bunched with a 600-MHz cavity system. We will store 1×10^{11} protons per bunch for a modest average current of 12 mA. In this mode, the beam comes from the LAMPF accelerator chopped in very short (1-micropulse) bunches and is injected by the H^0 to H^+ stripping mechanism as shown in Fig. 11. Bunches are injected on top of one another for many turns to build up the full current. At extraction time, the fast-kicker magnet then removes one of these bunches and leaves the rest in the Ring. These then go to a heavy-metal target, which produces the neutrons for the time-of-flight measurements.

The more difficult mode of storage-ring operation is the long-bunch mode (one bunch in the Ring), which is 270 ns long and filled to 5×10^{13} protons per bunch. The bunches are extracted in one turn, giving a high thermal neutron flux for the material science

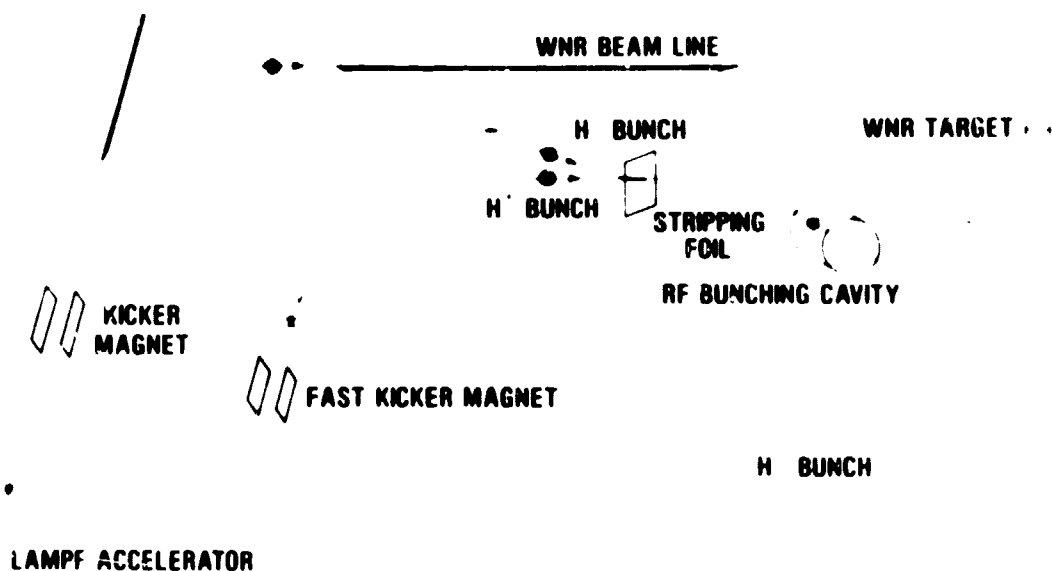


Fig. 11. The PSR increases pulse intensity 200 times and increases repetition frequency 6 times.

or thermal neutron-scattering work. This mode is being proposed at LAMPF for use as a source of neutrinos in lower energy neutrino-scattering experiments.

In this mode, the hole for extraction-magnet excitation is chopped in the beam before injection, as shown in Fig. 12. The first-harmonic bunching cavity is excited to keep the beam holes open as the beam circulates, rather than to open the holes or bunch the beam. The holes permit the fast-kicker magnet to be turned on for beam extraction with little beam loss. The system is designed for low beam loss and a large extraction kick, 9 cm, using two kicker magnets placed appropriately in the Ring. On injection, the injected phase space is trimmed so there is minimum beam size within the device. In addition, the accelerator has a very large aperture. We hope to keep the loss below 15 nA in the complicated equipment areas. The transverse area occupied by the 5×10^{13} particles to be stored in the acceptance aperture are shown in Figure 13. The limiting aperture inside the Ring can contain almost 10 times more particles than the nominal 5×10^{13} . This large acceptance should keep beam loss low.

Finally, the NBS/Los Alamos microtron project will be described. It is different from the other projects in the mechanisms involved for beam loss. It is an accelerator-technology project, not a project to build an accelerator for research. It is a precursor to building a 2-GeV, high-current, cw, electron accelerator somewhere, as yet unspecified, by the Department of Energy. The NBS/Los Alamos accelerator, however, will be a 180-MeV, cw,

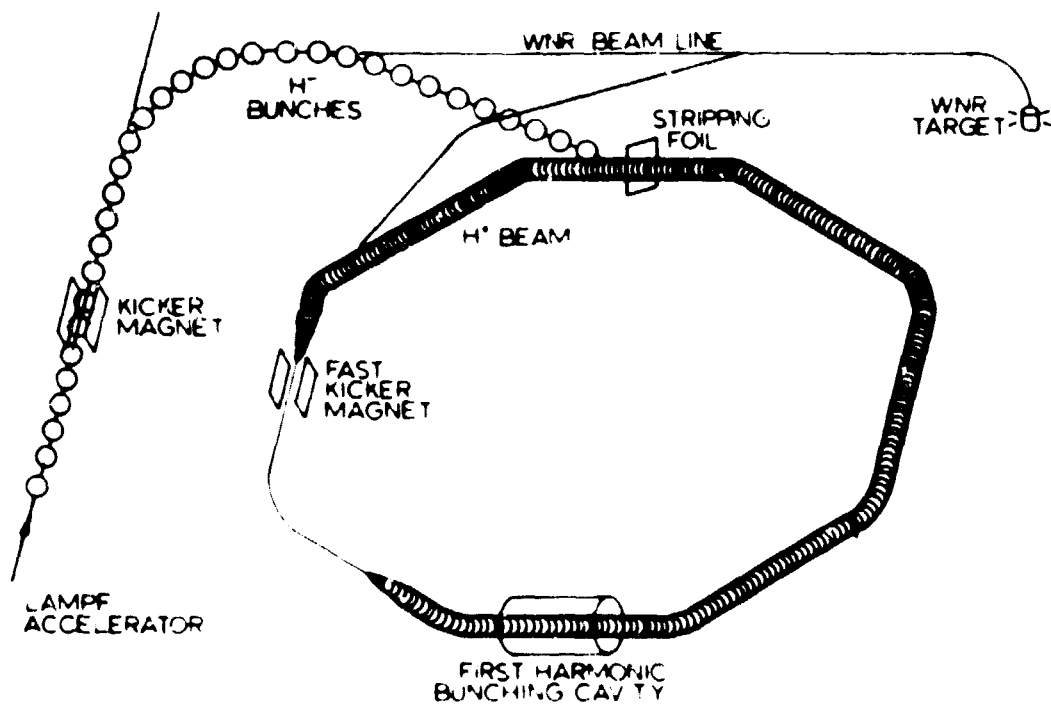


Fig. 12. The PSR long pulse mode.

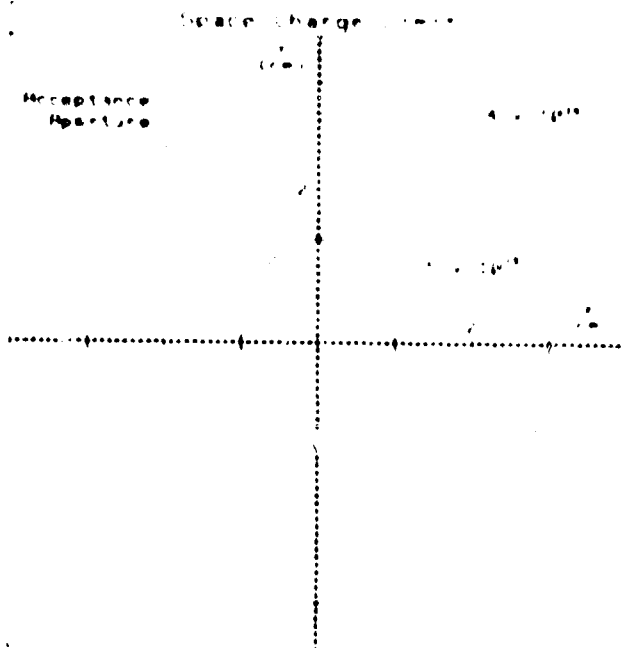


Fig. 13.
PSR acceptance and space-charge-limit at a point in the Ring lattice. The transverse acceptance of the PSR is shown by the larger ellipse and the area in which 5×10^{13} particles can be contained is shown by the inner ellipse. The acceptance aperture can contain 4×10^{14} particles.

electron accelerator and will have a beam of up to 500 μ A. We will investigate the beam breakup in microtrons and the cavity beam interactions. Cavity fabrication techniques for the disk-and-washer (DAW) system also will be engineered. The DAW has high shunt impedance and is highly coupled, suitable for microtrons and other linac-type systems operated cw. The klystron used will have a continuous output power of one-half megawatt at S-band frequency.

The microtron layout is shown in Fig. 14. An electron gun is followed by a buncher system (which bunches the electron beam to a few degrees' width), a capture section (a tapered phase-velocity system, starting at an electron velocity of ~ 0.50 and ramping up to 95% of the speed of light), a preaccelerator (which accelerates to ~ 5 MeV), and a 12-MeV accelerator section (which is used for accelerating through the 13 or 14 acceleration turns). The injection is complicated: the beam goes down through the accelerator, reverses through the accelerator without going through the end magnet, and then does the typical microtron orbits and is extracted at the end.

The accelerator sections use the DAW structure operating in the biperiodic $\pi/2$ mode. As in the case of the post-coupled drift-tube linac or the side-coupled-cavity system used at LAMPF, adjacent accelerating cavities are coupled to one another through a coupling cell, which provides efficient energy transfer. A cutaway drawing of the DAW system is shown in Fig. 15.

The washers of the DAW structure are suspended inside a disk-loaded waveguide by supports that are located so that they hardly perturb the field frequencies. Cooling is provided through the supports. The accelerating-mode field in this device has a radial zero, and the electrical field has a pi mode (oppositely directed in each cavity along the chain so that in one rf period the electron has to move). There is a zero in the electric field where the support is located, and an outside radial electric field, completing the cavity circuit. The system shunt impedance is good

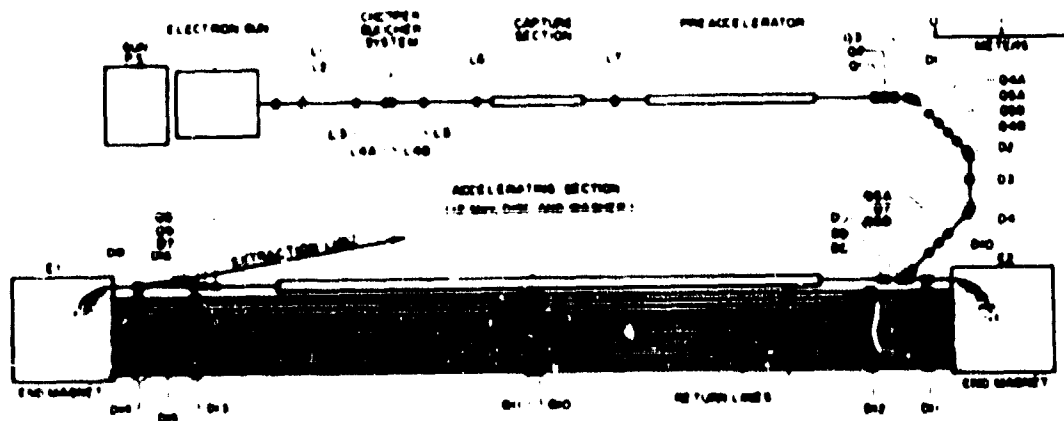


Fig. 14. NBS/Los Alamos Racetrack microtron.

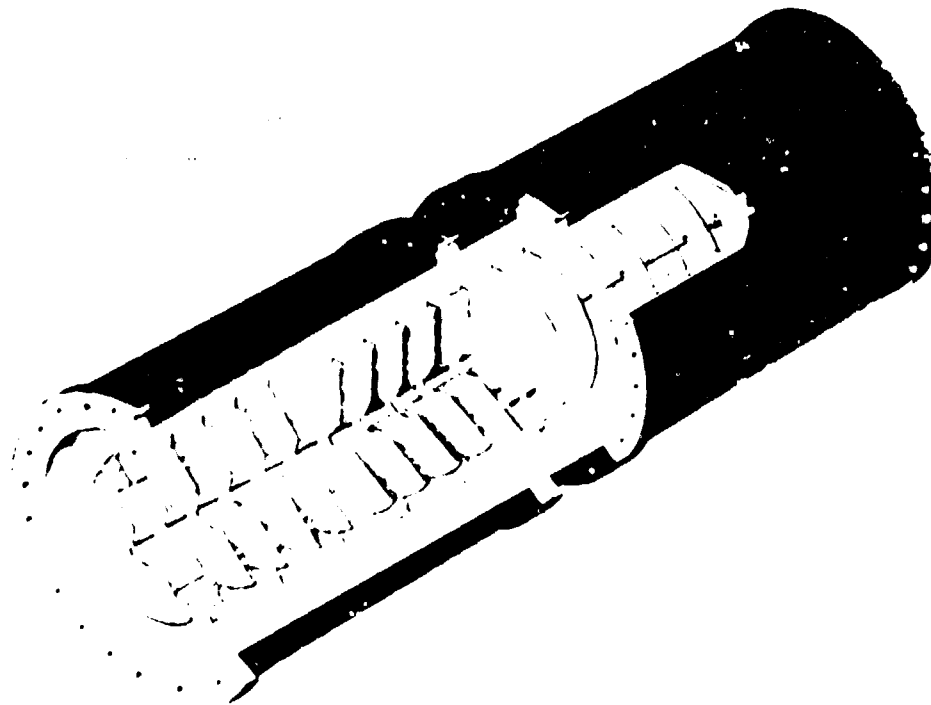


Fig. 15. Disk-and-washer system.

because the exterior wall losses, that are due to the mode configuration, are low. There is another field distribution that resonates at the same frequency as the accelerating-mode frequency. The fields are localized and have the same frequency, allowing high-power transfer between two regions; in case of field imbalance in field stability, this cavity chain operates as a $\pi/2$ mode system.

Extensive calculations have been made on this cavity with the SUPERFISH program; the zero of the electric field is in the general region where the support is placed. An interesting set of curves can be generated showing these field distributions, as shown in Fig. 16. The diagram rotates about a symmetry axis to get the complete field distribution. This complete set of modes would exist in an eight-cavity system of this kind. In such a system, the broad frequency range (1168 to 2674 MHz) from the zero mode to the π mode indicates a wide bandwidth and thus a very high group velocity for energy flow from cavity to cavity in the $\pi/2$ mode, the accelerating mode.

The cavity fabrication techniques for this accelerator structure use a step-brazing technique. Figure 17 shows a washer sub assembly for the microtron DAW accelerator system. These cavities are now in production.

4. CONCLUSION

Other accelerator systems are being considered, such as heavy ion machines, electron linacs, and programs to understand in the

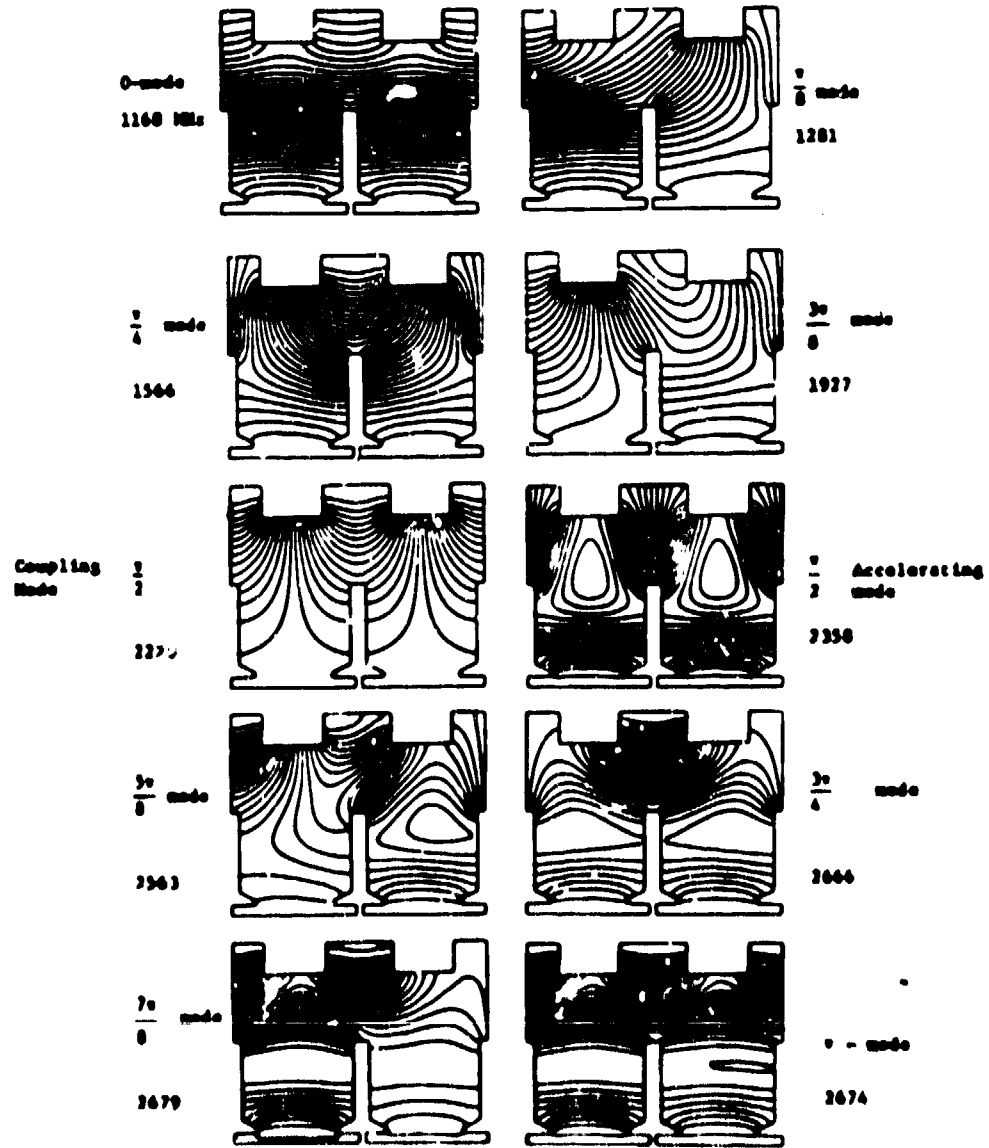


Fig. 16. Computer-generated set of curves showing field distributions.



Fig. 17. One section of a disk-and-washer.

basic physics sense the emittance growth problems of various proton accelerators.

A better understanding of beam emittance growth in an rms sense is being achieved, and application to practical devices is starting. For example, the RFQ, which carefully molds a bunched distribution and can probably be configured for optimum matching to a following system, is a device of great sophistication in terms of its beam dynamics, compared to previous machines with constant parameters along their length. Further development of these principles will be very exciting.