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The NBS-LASL CW Microtron*

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Abstract

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

Introduction

The racetrack microtron (RTM) offers a number of unique advantages as an electron accelerator for energies above about 50 MeV. Of particular interest to the NBS-LASL project is that available high-power rf techniques offer the possibility of building a continuous-wave (cw) microtron. High-energy cw RTM's are expected to be of tremendous importance in nuclear physics.[1] At present two cw RTM's are in operation: MUSL-2, a 66 MeV, 6 pass machine at the University of Illinois which uses a superconducting accelerating section,[2] and MAMI-1, a 14 MeV, 20 pass machine at Mainz, Germany which uses a room temperature rf accelerating structure.[3] Our project is also using room temperature rf technology. With it, we expect to achieve beam currents of several hundred microamperes, limited by "beam blowup."[4,5,6] If the expected current is indeed obtained, the power conversion efficiency (from the AC power line to the beam) can be ten percent or higher, which is competitive with a modern (pulsed) electron linear accelerator (linac). Other advantages of the RTM compared to a linac are: smaller beam emittance and energy spread, much improved energy stability, and reduced construction and operating costs. The only applications for which the RTM is inferior to the linac are those requiring very high pulsed currents, such as neutron measurements in which time-of-flight techniques are used.

The impetus for the present NBS-LASL project is the perceived need for a 1 to 2 GeV, cw, high current electron accelerator for nuclear physics research.[1] The most economical way to build such a machine would be to use a recirculating scheme, either an RTM or, especially at the highest energies, a double sided microtron.[7] A recent study[8] has shown that a 2 GeV double sided microtron could be built for about one half the cost of the most promising alternative, a conventional pulsed rf linac and a pulse-stretcher storage ring. In addition, the microtron approach promises to provide better beam quality and stability, smaller energy spread, energy variability over a wider range, more total beam current (allowing several simultaneous users of the machine), and reduced operating cost. The goal of our project is to determine the feasibility of an accelerator of this type. We must determine the beam-blowup-imposed current limit of such a machine by a combination of measurements and calculations, and develop the required technology, especially a suitable rf accelerating structure. A major part of our project is to design, build, and operate a cw microtron of reasonable size in order to demonstrate viable solutions to the technological problems and make the necessary measurements of beam blowup properties. This demonstration accelerator will be an RTM with 15 passes, a final energy of at least 185 MeV and a design current capability of 550 μA. This accelerator, which will be described in this report, will be a powerful research tool in its own right for nuclear physics and other applications.

Microtron Design

In a racetrack microtron,[9] the beam is returned to the accelerating section by uniform-field end magnets, as shown in figure 1. On successive passes, the beam must pass through the accelerating section near the same "resonant" phase, ϕ_r, of the rf field. This resonance condition can be expressed by the relation[9]

$$(2\pi/c)\ \Delta V \cos\phi_r = \nu\lambda B, \qquad (1)$$

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

The choice of rf frequency in an RTM is a compromise among many factors. Lower frequency (larger λ) eases construction and operating tolerances. Higher

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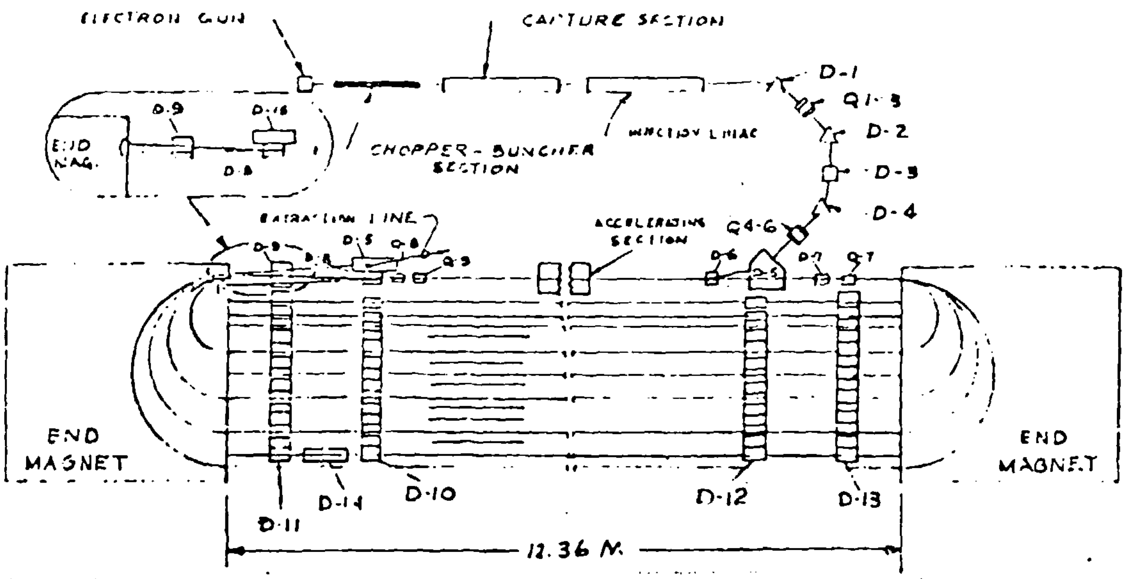

Figure 1. Layout drawing of the Microtron. Achromatic beam transport from the injection linac to the RTM is performed with the dipole magnets D1-D6 and quadrupoles Q1-Q6. Compensation for the effect of D-6 on recirculating orbits is accomplished in the chicane system consisting of D-5, D-7, and Q-7. Orbit reversal after the first pass through the accelerating section is performed by D-8, D-9, Q-8, and Q-9, as shown in the inset drawing. The array of magnets D-10 and D-11 compensate the recirculating orbits for the displacements produced in D-8 and D-9. A quadrupole doublet (not shown) at the center of each return path provides adjustable focussing. Extraction from the RTM can be obtained after any number of circulating by moving D-14 to the appropriate orbit and adjusting the field strengths of D-14 and D-15.

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

Injection into an RTM can be accomplished either by sending the incident beam into one of the end magnets, or directly into the main accelerating section. The former method, which is used in all stages of the MAMI project, requires an injection energy of about one tenth of the final energy of the RTM.[3] This would require either a very expensive injector linac (20 MeV in our case), or an injection stage microtron (like MAMI-1) adding both cost and complexity to the system. Directing the beam into the accelerating section directly, as in MUSL-2,[4] adds the complexity of an injection "chicane" where the injected orbit is merged with the recirculating orbits, and a "bypass" on at least one recirculating path, to allow the recirculation path to pass clear of the accelerating structure. In the NBS-LASL RTM we will inject the beam directly into the accelerating section and use a reverse return after the first pass through the section.[13] Thus the second and subsequent passes will be in the opposite direction from the first pass, as shown in figure 1. This is feasible because our accelerating structure is of the standing wave type. The reverse return feature simplifies the chicane design because the beam has gained energy from two passes before first encountering the chicane, and eliminates the need for bypass return orbits.

The reverse return design requires the use of auxiliary magnets to provide orbit closure on subsequent passes. The closed orbit correctors are located on the return paths as indicated in figure 1, where they do not increase the overall length of the accelerator, and can be combined in function with steering magnets which are needed in any event.

Beam quality and ease of operation in an RTM are critically dependent on the properties of the end magnets.[2] Good field uniformity is essential to maintain the resonance condition, eq. (1), yet is difficult to achieve in a conventional C-magnet having the very large ratio of gap depth to height required in an end magnet. A novel magnet design,[11] shown in figure 2, has been developed which has a calculated field uniformity of better than two parts in 10^4, not only at the nominal field strength of 1.0 Tesla, but also over a wide range up to about 1.3 Tesla. The design incorporates a reverse-field active clamp needed to eliminate undesirable vertical defocussing in the fringing field.[3] In spite of the expected excellent uniformity of the field, we plan to include correcting coils of the printed circuit board type[12] to compensate for machining errors and other imperfections that may be present in the actual magnets.

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

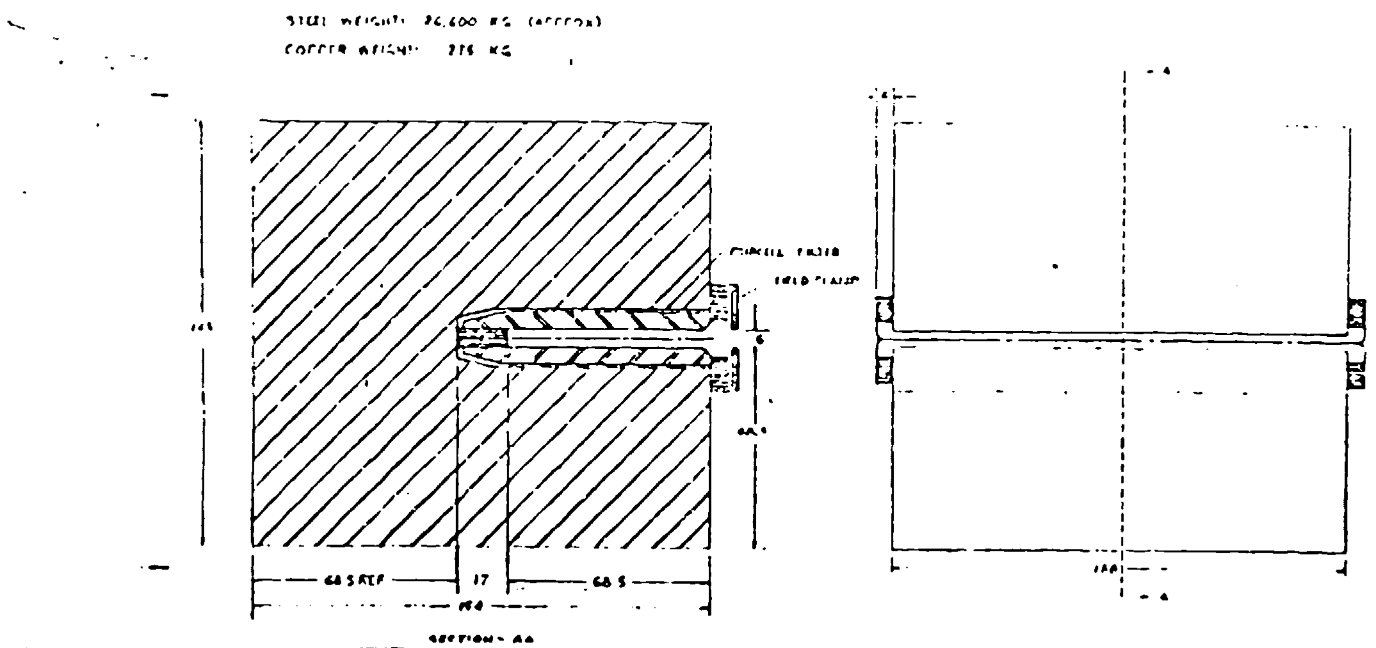

Figure 2. End-magnet design. For details, see reference 11.

schematically in figure 3 and described in detail in reference 13. The injection linac consists of two 2 meter accelerating sections of the same design as the main section of the RTM, except that the capture section has a tapered-β design (from β 0.55 at the entrance to β 0.98 at the exit) and a lower average accelerating gradient than the other sections, 1.0 MV/m compared to 1.5 MV/m.

Our design specifications for the beam out of the injection linac at 5 MeV include a normalized transverse emittance of $\epsilon_n = 5\pi$ mm mrad) ($\epsilon = 0.47\pi$ mm mrad) and a longitudinal emittance of 20π keV degrees, i.e., a full width energy spread of 40 keV (0.8%) for a phase bunch length of two degrees. These specifications allow dilution of the normalized transverse and the longitudinal emittance by factors of about two and seven, respectively, in the capture section. Our preliminary calculations indicate that these specifications are readily achievable. The Stanford superconducting recyclotron has in fact obtained considerably smaller emittances, albeit at a somewhat lower current.[14]

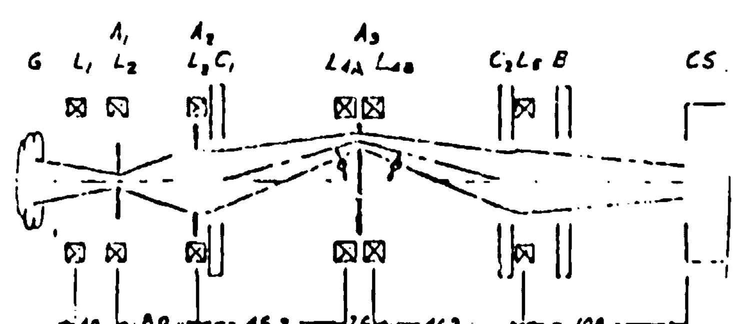

Figure 3. Schematic drawing of the chopper buncher system. G is the 100 keV electron gun. Magnetic lenses L_1 - L_5 provide focussing. Apertures A_1 and A_2 define the transverse emittance of the beam. Aperture A_3 and the rf chopper cavities C_1 and C_2 limit the beam phase spread to 60 degrees. B is the buncher cavity. CS is the capture section.

Extraction of the beam from the RTM can be accomplished after any desired number of passes by a moveable kicker magnet on the return paths. The kicker magnet deflects the beam onto a common extraction line from any return path. In this way, nominal output beam energies of 17, 29, 41, ---- 173, or 185 MeV are obtained easily and rapidly. Intermediate energies can be obtained by changing ΔV and B (in eq. (1)) proportionately and the injection energy to match. A maximum energy up to 25 percent above the nominal 185 MeV could be obtained at low beam currents with the available rf power, if the accelerating structure proves capable of an rf heating load 50 percent above the design value of 25 kW/m.

Beam Blowup

The blowup phenomenon which limits the current in recirculating electron accelerators is caused by an interaction between the beam and certain rf modes of the accelerating structure. The transverse magnetic field of the mode deflects the beam. Energy is transferred between the beam and the mode via the axial electric field, which has a node on the axis of the structure, and a linearly increasing amplitude for small displacements from the axis. On the first pass through the structure, the beam is magnetically deflected as indicated in figure 4. On the next pass the beam traverses the structure off axis. The power, P_i, transferred from the beam to the mode on the ith pass will be of the form

$$P_i = x_i I \cos \phi_i . \qquad (2)$$

where x_i is the displacement of the beam centroid, I the current and ϕ_i the phase of the rf in the mode at the time the beam interacts with it. The beam consists of repetitive bunches of electrons at the accelerating-mode frequency f_a, which is different from the blowup mode frequency, f_b. Each electron bunch will have a different value of x_i, depending on the phase of the blowup mode when that bunch passed through the structure on the (i - 1) pass. Thus x_i is correlated with ϕ_i for the different bunches, and P_i will not in general average to zero for all the bunches. On later passes, the beam will have a displacement from the axis due to the sum of all previous deflections. The total power coupled from the beam to the mode is obtained by averaging over all passes, i, in equation (2), and summing over all passes. This total power

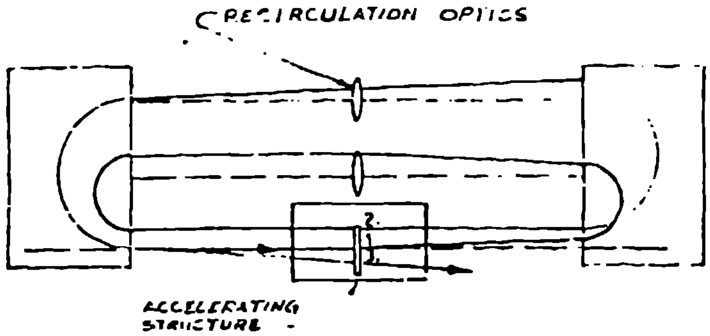

Figure 4. Schematic of the RTM, to illustrate the beam blowup phenomenon. See text for details.

will depend on the frequency ratio f_B/f_0, and the details of the recirculation optics, but in general it will not be zero, and the resulting beam displacement will increase with time, at a rate proportional to the beam current, as energy continues to be transferred from the beam to the blowup mode. The energy in the blowup mode is dissipated by the interaction of the rf with the walls of the structure at a rate inversely proportional to the quality factor, Q_B, of the blowup mode. However, for beam currents above some threshold value, I_s, the rate of dissipation will not be large enough to damp the disturbance and the deflection amplitude will grow until the beam is lost from the accelerator. In recirculating accelerators which use superconducting rf technology, the blowup phenomenon has been observed at quite low beam currents because of the very high Q values of superconducting structures.[5,15] The much lower Q values of room temperature rf structures is one of the reasons for pursuing this technology for high current applications.

Although we understand the beam blowup in principle, it is an extremely difficult task to predict the threshold current for a given accelerator design. In addition to the dependence on the frequency ratio f_B/f_0, on Q_B, and on the tune of the recirculation optics discussed above, I_s is a function of the injection energy, the number of passes, and the energy gain per pass. Some of these dependences have been studied by numerical methods.[5,6] It is clear from these studies that over a wide range of tuning conditions, I_s is inversely proportional to the number of passes. Any real rf structure will support a large number of modes that could cause beam blowup. With each mode frequency there will be a different Q_B, and a different phase shift, ϕ_B, between adjacent accelerating cavities. The last factor is significant because if ϕ_B is the same as the phase shift, ϕ_0, of the accelerating mode (and thus the beam) between adjacent cavities, the blowup effect from all the cavities in the structure will add coherently, while if $\phi_B \neq \phi_0$, the total effect will in general be smaller.

Several procedures are available to increase I_s. First, it is quite clear from general considerations of resonances in cyclic accelerators as well as from the numerical studies,[5,6] that blowup modes having f_B/f_0 close to the ratio of any two small integers (e.g. 4/3, 3/2, etc.) should be avoided. The mode frequencies can be identified in small test sections and the structure dimensions can be altered to change f_B/f_0. Obviously this procedure is not practical as an a posteriori cure. Second, stronger focussing, provided by quadrupole magnets on the return orbits, can be used to decrease the beam displacement produced by a given deflection. If beam blowup were the only consideration, one would make the focal lengths of the lenses in figure 4 equal to one-fourth of the orbit circumference, thus returning the deflected beam to the accelerator structure axis after every pass, and minimizing the blowup interaction. However this must not be done for many passes, since it corresponds to a transverse betatron oscillation phase advance of 180° per pass (or an integer multiple thereof), which corresponds to a half-integer tune resonance, a condition which will cause the beam to be lost just as surely as the beam blowup. There exists a number of other tune and coupling resonances which must also be avoided, so the focussing that can be successfully applied is not arbitrary. Nevertheless, a significant increase in I_s can be obtained by focussing. Third, the Q values of the blowup modes can be substantially reduced by external loading.[15] To be effective, this would have to be done for all the important blowup frequencies, without seriously reducing the Q of the accelerating mode.

Accelerating Structure

The performance of an RTM improves and its cost tends to decrease as the accelerating gradient is increased. Practical limitations are imposed by the available rf power and the ability to remove heat from the structure. We have begun a testing program on the disk and washer (DAW) standing wave structure,[16] which appears to be ideal for the RTM application. In addition to a high shunt impedance, it has a high cell-to-cell coupling factor which eases construction tolerances and reduces sensitivity to beam loading effects. The high cell-to-cell coupling should also make external loading of blowup modes feasible, if found to be necessary.

Figure 5 shows the DAW structure with the washers supported in pairs from T-shaped supports. (There are four supports, equally spaced azimuthally, for each pair of washers.) The radial portion of the supports lies along an equipotential of the accelerating mode electric field, and the longitudinal portion is in a region of low electric field. Consequently, this type of support minimizes the perturbation of the accelerating mode. However, these supports significantly perturb the coupling mode. Left uncompensated, these perturbations would open a stop band in the mode spectrum and create a bilevel distribution in the excitation of the accelerating cells. By experimenting with the geometry of a low-power test section, a technique has been developed to counteract these perturbations. The geometry of the DAW (without washer supports) was optimized with the aid of the

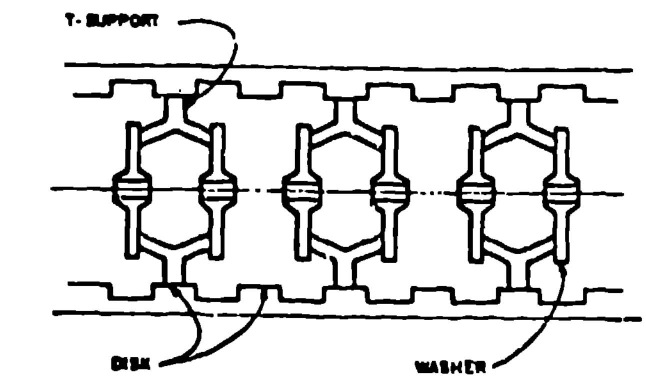

Figure 5. Disk and Washer rf structure.

computer program SUPERFISH. Then the measured perturbations caused by the supports were eliminated by a cut-and-fit procedure in which the disks which hold the supports are made thinner, and the radius of the outer wall of the cavities was made larger. The corrected low power test section exhibits a Q value of 75 percent of the theoretical value predicted by SUPERFISH. These measurements were made with the supports brazed to the washers and disks, but the rest of the structure pressed together without brazing. In the completed structure, we expect to attain a Q value of 85 percent of theory, which will provide an effective shunt impedance (ZT^2) of about 100 MΩ/m in the 2380 MHz, β = 1 structure.

In addition to supporting the washers, the supports provide channels for carrying coolant to and from the washers. Heat transfer calculations indicate that the practical limit for cooling the structure is in excess of 25 kW/m. This power level with the expected shunt impedance will result in an accelerating gradient > 1.5 MV/m. Thus the main accelerating section will be about 6 m long to provide the 12 MeV energy gain required by the design parameters. The injector linac will consist of about 4 m of DAW structure.

The low powered test section is being examined for rf modes of the type which can cause blowup. One group of these modes has been found at a frequency near 2/3 of the accelerating frequency. (In the DAW, the accelerating mode is not the lowest mode of the structure.) According to our present understanding of beam blowup, the frequency ratio of 2/3 may be dangerous and will require further study.

Summary

Initial funding for the NBS-LASL microtron was received in September 1979. The conceptual design of the RTM was completed in June 1980.[13] In addition to the rf structure development and end-magnet design effort described above, our efforts to date have concentrated on the procurement and construction of long-lead items, such as klystrons, power supplies, the control-system computer, and electron gun. Our schedule calls for first operation of the injector linac in August 1982, and completion of construction of the entire accelerator in June 1983. The total cost of the project, including a year's operation of the RTM to complete detailed performance tests, is estimated to be about $7 million, including inflation. It is important to note that this cost includes a large research and development effort. The actual cost of building the RTM is estimated to be about $2.5 million (in present dollars), which would make it an extremely inexpensive accelerator if the anticipated performance is indeed achieved.

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