

THE NBS PROPOSAL FOR A ONE GEV CW RACETRACK MICROTRON FACILITY

S. Penner
National Bureau of Standards
Washington, DC 20234

Abstract

$$2.096 \Delta V \cos \phi_r = v \lambda B, \quad (1)$$

As part of a joint accelerator research project with the Los Alamos National Laboratory, NBS is now building a 200 MeV, high current, CW racetrack microtron (RTM). Upon its completion, scheduled for 1984, we propose to use this machine to provide CW electron beams to nuclear physics experimenters, and also as the injector for a second stage RTM to boost the final energy to one GeV. A building addition of 35,000 square feet will house the second stage RTM and new experimental facilities. Subharmonic RF beam splitting is planned to allow up to three simultaneous beams for experiments, with currents up to 100 μ A each. In addition, low and high energy beams at low currents for tagged-bremsstrahlung experiments can be delivered at the same time. This proposed multi-user facility is intended to be a national center for electromagnetic nuclear physics research.

Introduction

The National Bureau of Standards has proposed to the Department of Energy and the National Science Foundation to build experimental equipment and to operate a 200 MeV continuous wave electron accelerator laboratory as a user facility. NBS further proposes to construct a 1000 MeV continuous wave electron accelerator, complete with experimental equipment, and to operate this facility and the 200 MeV facility as a National Electron Accelerator Laboratory.

The accelerator for the 200 MeV program will be the Race Track Microtron (RTM) being built as an accelerator research and demonstration project jointly by NBS and the Accelerator Technology Division of the Los Alamos National Laboratory.¹ The 1000 MeV accelerator would use the 200 MeV accelerator as an injector. The basic design of this machine is quite similar to that of the 200 MeV Race Track Microtron. Beam from RTM-1 would be injected into the second-stage RTM at approximately 200 MeV and accelerated to any desired final energy up to 1.0 GeV maximum. The design current capability of RTM-2 is 300 μ A. RTM-2 would make extensive use of the technology developed in our present accelerator research project in order to minimize risk and development costs. As many as three simultaneous high current beams can be obtained from the cascaded microtrons by use of subharmonic rf beam splitting. The currents of these three beams are made independently controllable by a modification of the present rf chopper system in the injector of RTM-1. Two different beam energies can be provided simultaneously: 200 MeV from RTM-1, and the output energy of RTM-2. (We will refer to this energy as "One GeV," although it should be understood that it is continuously variable in the range 200-1000 MeV). In addition to the three high current beams, low current ($\leq 1 \mu$ A) beams for photon tagging applications can be obtained simultaneously at both 200 MeV and one GeV by magnetic separation of the low energy tails of the high current beams. Thus the facility is capable of providing up to five separate simultaneous beams at two different energies.

General Design Considerations

In the conventional RTM the beam is returned to the accelerating section by means of uniform field end magnets, as shown in Fig. 1. On successive passes, the beam must pass through the accelerating section at the same synchronous phase, ϕ_r , of the rf field. This resonance condition can be expressed by the relation²

where ΔV is the energy gain (in MeV) of the accelerating section, λ is the rf vacuum wavelength (in centimeters), and B is the field (in Tesla) of the end magnets. The parameter v is the integer number of wavelengths by which the orbit circumference increases between successive passes. It is well known that v should be as small as possible to maximize the phase stability and minimize construction and operating tolerance requirements. All existing and planned microtrons of which we are aware operate at $v = 1$ or 2. The stable range of resonant phases is given by $0 < \phi_r < \tan^{-1}(\frac{2}{\pi v})$.

An important cost consideration for a large microtron is the size of the end magnets. The radius of the final orbit in the end magnets is proportional to the final energy divided by the magnetic field. The cost of the magnets will be approximately proportional to their volume, and therefore they should be designed for the highest practical magnetic field. For the high-quality uniform fields needed here, this practical limit is in the range 1.5-1.6 Tesla.

Knowing that $v = 1$ and large B are desired, equation (1) tells us that the energy gain per pass required is proportional to the wavelength, λ . The energy gain of an accelerator section, neglecting beam loading effects, is

$$\Delta V = (P RL)^{1/2}, \quad (2)$$

where P is the input rf power (MW), R the shunt impedance ($M\Omega/m$), and L the length (m) of the accelerating section. Since rf power and accelerator length are important cost factors, equations (1) and (2) tend to require a small rf wavelength. Furthermore, a high shunt impedance is highly desirable and other factors being equal, R scales as $(\lambda)^{-1/2}$. On the other hand, as λ decreases the allowable energy gain per pass decreases, and thus the number of passes through the accelerator needed to obtain a given final energy increases. Eventually, the cost of the additional return paths (which require additional diagnostic instrumentation, steering, and focusing) will overcome the cost of the accelerating section. In addition, the spacing of successive return paths, given by

$$d = v\lambda/\pi, \quad (3)$$

will eventually become too small to allow separate steering and focusing on each orbit. Furthermore, many of the tolerances of the system will scale with λ , and the problems of producing and transmitting the rf power will be easier at longer wavelengths.

With these considerations in mind, the final choice of rf frequency is determined by the commercial availability of high-power CW klystrons. Within the frequency range suitable for an RTM, the only available high-power CW klystrons are in the 2400 MHz region (S band, $\lambda \approx 12.5$ cm). Then with $v = 1$ and $B = 1.6$ Tesla, the energy gain per pass (from equation 1) is $\Delta V \approx 10$ MeV.

The current obtainable from an RTM is known to be limited by beam blowup due to excitation by the beam of rf modes in the accelerating structure which have strong transverse magnetic fields on the structure axis. This effect has been observed in the Stanford and Illinois superconducting accelerators but never, to our knowledge, in microtrons having room-temperature accelera-

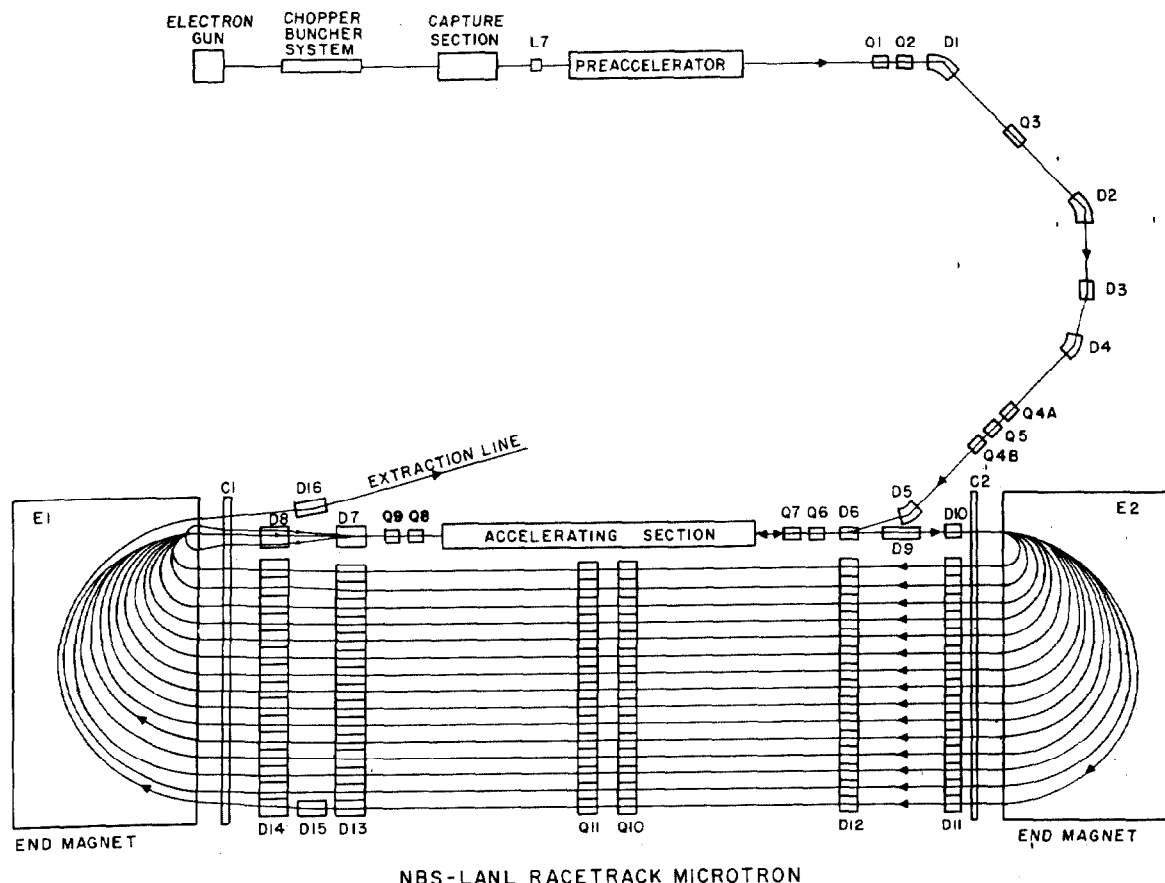


Figure 1 Schematic layout of RTM-1, not to scale. A chopped, bunched 100 keV electron beam is accelerated to 5 MeV by the injector linac consisting of a 1 MeV capture section and a 4 MeV preaccelerator. The 180° transport system, consisting of dipole magnets D1-D6 and quadrupole magnets Q1-Q5, injects the 5 MeV beam into the accelerating section. After the first pass through the accelerating section the 17 MeV beam is reversed by dipole magnets D7 and D8, end magnet E1, and active field clamp C1. The second and subsequent passes through the accelerating section are in the opposite direction from the first pass. Compensation for the effect of D6 on recirculated orbits is accomplished by the chicane system consisting of D9 and D10. The array of dipole magnets D13 and D14 compensates the recirculating orbits for the displacements produced in D7 and D8. The array of quadrupole magnets Q10 and Q11 provide adjustable focussing on the return lines. The beam can be extracted after any number of passes by moving the extraction magnet D15 to the appropriate orbit.

ting structures. However, the observation of beam blowup in superconducting accelerators together with theoretical studies of the blowup phenomenon³ predict that the starting current for beam blowup, I_s , in microtrons with room-temperature accelerating structures will be in the range 100-1000 μ A. Given that the accelerator current and energy are determined by nuclear physics requirements, and ΔV is determined by equation (1) and the ~1.6 Tesla practical limit on end-magnet field strength, the beam blowup threshold can be increased by: (1) raising the injection energy, (2) increasing the accelerating gradient, $\Delta V/L$, and (3) using stronger focussing. One of the goals of the NBS-LANL accelerator research project has been to increase the available gradient, $\Delta V/L$, by attaining the highest possible shunt impedance, R , and the dissipation limit (P/L) of the rf structure.

The important cost trade-off in the design of a large microtron is between rf power and accelerating gradient, since the energy gain per pass is determined by equation (1) together with the dependence of magnet cost on energy and field strength. The dependence of cost on rf power and rf structure length can be written

$$C = C_p P + C_L L, \quad (4)$$

where C_p is the cost per megawatt of rf power, and C_L is the cost of the machine per unit structure length. Using equation (2) to establish the relationship between P and L , a cost minimum is found for an accelerating gradient of

$$\frac{\Delta V}{L} = \frac{C_L R}{C_p}. \quad (5)$$

We have developed reasonably reliable values for the differential cost factors from our experience with the 200 MeV machine we are building. They result in a cost-optimum gradient in the range 2-2.5 MV/m if only construction costs are considered. It is more realistic to consider life-cycle costing, in which C_p includes the cost of the electrical energy to power the machine over an anticipated useful lifetime of order 5×10^4 operating hours at full power. This reduces the cost-optimum accelerating gradient to approximately 1.0 MV/m. Since the cost is a slowly varying function of gradient near the minimum and machine performance improves with increasing gradient, we have designed the one GeV RTM for a gradient of 1.25 MV/m.

Injector Microtron RTM-1

The 200 MeV RTM (1, 4) is currently under construction at NBS as part of a joint NBS-LANL accelerator research project funded by DOE. Design parameters are given in Table I. Our schedule calls for completion of the accelerator in mid-1984, to be followed by a year of beam studies which are an important part of the accelerator research project. A major effort will be made to determine the starting current, I_s , for beam blowup (BBU) over a range of beam tunes and accelerating gradients. As an injector, RTM-1 will be operated at a tune which has been found to inhibit BBU. Theoretical predictions³ of I_s for RTM-1 range from 250 to 1300 μ A. It is very unlikely that BBU will limit the achievable current to less than 300 μ A.

The only major component of RTM-1 which is still under development is the rf accelerating structure. It is a water-cooled version of the side-coupled structure.⁵ Full power rf testing of the 2.7 m long pre-accelerator section was started on February 28, 1983. After less than one day conditioning, this structure was operated at 83 kW CW power input, exceeding the design power level by 14 percent. The shunt impedance was measured to be 82.5 M Ω /m. No parasitic modes are excited near the operating frequency and no power-induced tilt in the electric field has been observed.

In the present proposal, conversion of RTM-1 to an injector will begin in mid-1985. The only modification necessary is to replace the present chopper system with a subharmonic chopper. As shown in Fig. (2), this system provides independent control of the current in three successive beam pulses which are to be split into three simultaneous beams following acceleration.

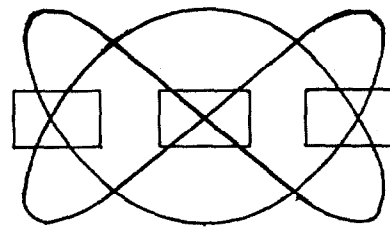


Figure 2 Beam deflection from subharmonic chopping. An rf cavity resonates at 1190 MHz and 793.5 MHz in orthogonal directions, producing the beam deflection pattern shown here. Every third beam pulse passes through the same aperture, (indicated by the rectangles). Each aperture can be adjusted independently to control the current in the pulses which it transmits.

One GeV Microtron RTM-2

The proposed 1 GeV RTM is shown schematically in Fig. (3). Design parameters of RTM-2 are given in Table I. Much of the technology and many of the components developed for the 200 MeV RTM will be utilized. This provides a firm basis for cost estimating and reduces the design effort and the risk of the project.

The accelerating section consists of two 4 m long side-coupled structures identical to those used in RTM-1. They will operate at a lower gradient than in RTM-1; 1.25 MeV/m rather than 1.5 MeV/m. The rf power source employs a 500 kW CW klystron, identical to the one used

Table I NBS CW Microtron Parameters

		RTM-1	RTM-2
Status		Construction	Proposed
Injection energy	[MeV]	5	200
Energy gain per pass	[MeV]	12	9.5
Maximum number of passes		16	87
Output energy	[MeV]	15-200	200-1000
Maximum current	[μ A]	550	300
Harmonic number		2	1
Distance between end magnets	[m]	12.4	12
Length of linac	[m]	8	8
Number of klystrons		1	1
End magnet field	[Tesla]	1.0	1.58
End magnet weight, each	[10 ³ kg]	30	300
Transverse tunes, ν_x and ν_y		0-0.25	0-0.17
Transverse emittance	[mm·mrad]	0.025 π	0.011 π
Longitudinal emittance	[keV·degree]	25 π	60 π
Energy spread (FWHM)	[keV]	40	70
Klystron type		Varian VKS-8270 500 kW CW	
Rf frequency		2380 MHz	

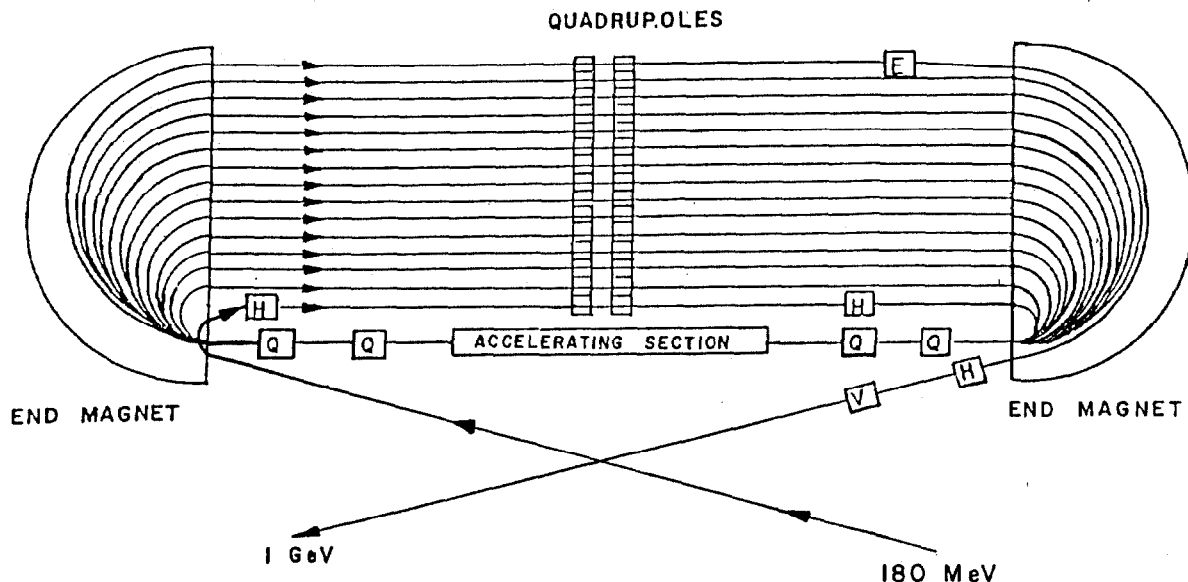
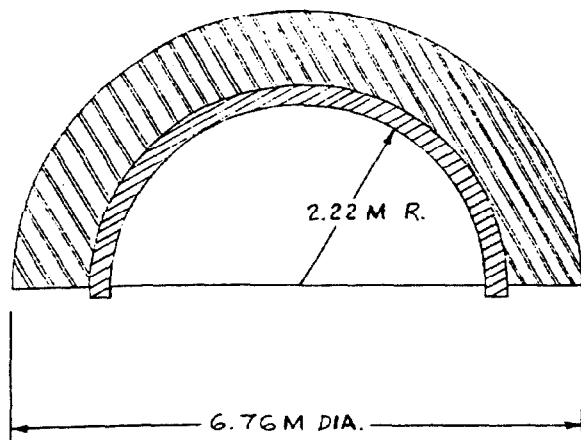


Figure 3 Schematic layout of the 1 GeV RTM, not to scale. The 180 MeV beam is injected onto the first return line using one end magnet and two small horizontal steering magnets (H), then onto the accelerator axis using the other end magnet. Transverse focussing is provided by quadrupoles on the accelerator axis (Q) and, if required, on the return lines. The beam is extracted after any number of passes by moving the extraction magnet (E) to the appropriate return line. The extracted beam is deflected by horizontal (H) and vertical (V) steering magnets to avoid the accelerating section at the injection line.

in RTM-1. The entire rf system-power supply, drive, control, and distribution will be copied from RTM-1, incorporating any modifications found necessary during testing of the first stage machine.

A preliminary design for the end magnets is shown in Fig. (4). The design is based on the same principles as the 200 MeV end magnets⁷ but is modified to a semi-circular shape to save weight. The design is suffi-

ciently symmetric that its field distribution can be calculated by using the accurate, two-dimensional codes which solve Poisson's equation (POISSON or TRIM). Results of field mapping the 200 MeV end magnets will be considered before arriving at a final design. The end magnets for RTM-2 require a field uniformity of ± 1 part in 10^4 to eliminate significant beam emittance growth. The TRIM calculations for the end magnets of RTM-1 indicate that this uniformity would be achieved in construc-



1 GeV RTM END MAGNET

WT. 300 t

POWER 300 kW @ 1.6 TESLA

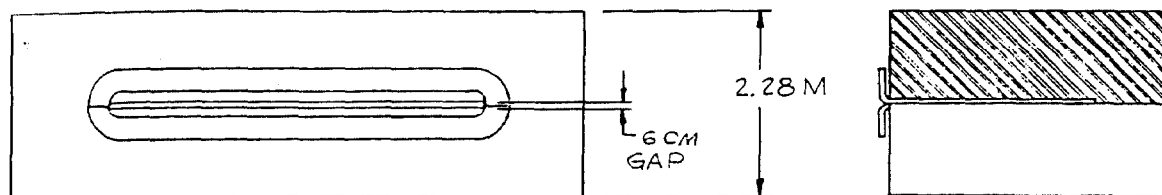


Figure 4 End magnet for RTM-2. The active field clamps to eliminate undesirable vertical defocussing are not shown. Their design is very similar to the RTM-1 design⁷. The largest orbit radius to be accommodated in the end magnets is 2.125 m.

tion, except for the effects of manufacturing tolerances and steel non-uniformity. To compensate for these imperfections, the magnetic field will be mapped using NMR probes and a computer-controlled two-dimensional scanning device.⁸ The field deviation measurements will be used to construct pole-face current sheets to reduce the non-uniformity to less than 1 part in 10^4 . We expect to use the same technique to obtain the required field uniformity in RTM-2.

The experimental studies of BBU starting current, I_s , on RTM-1 will be completed in time to aid in selecting a beam tune for operation of RTM-2. The theory of Rand et al.³ is expected to give reliable ratios of I_s in RTM's which have the same type of accelerating structure. The theory predicts a starting current in RTM-2 which is 40% above that in RTM-1 for the same tune. Thus, once a tune for RTM-1 has been determined to avoid BBU, an equal or weaker tune can be specified for RTM-2. Focussing on the return lines, if required, will be provided by quadrupole doublets of the current-sheet type⁹ which fit in the 4 cm return-line spacing.

The effects of synchrotron radiation from the beam in the end magnets has been calculated for a range of tunes. In the limiting case of no transverse focussing, the radiation causes a horizontal displacement of the central orbit from the unperturbed return lines. The displacement increases quadratically with the turn number up to a maximum displacement of 3.3 mm on the last turn. The final beam energy is simultaneously increased by 21 keV compared to the no-radiation case. With focussing on the return lines for a transverse tune of

1/8 in both x and y, the displacement is reduced to virtually zero. The main effect of the synchrotron radiation is to increase the longitudinal emittance of the beam. In the presence of return-leg quadrupoles which introduce transverse-longitudinal coupling, the horizontal-plane transverse emittance is also increased. Typically, both the horizontal and longitudinal emittance envelopes show an increase in areas of about 40 percent or less. Quantum fluctuations in the synchrotron radiation contribute an additional ~20% increase in the longitudinal emittance, and ~40% in the horizontal-plane transverse emittance. The emittances given in Table (1) for RTM-2 include the effect of the synchrotron radiation as calculated for the case $v_x = v_y = 0.25$, after arbitrarily increasing the injection emittances by 30% (transverse) and 40% (longitudinal) from the previously-calculated¹ values for RTM-1.

The control for RTM-2 will utilize components developed for the RTM-1 control system¹⁰ and will be integrated with that system.

Beam Distribution

The beam transport system shown in Fig. 5 allows as many as five beams with different currents to be sent simultaneously to the five experimental areas. At four points in the system, two-way beam splitting is achieved by a combination of an RF beam splitter, dc deflection magnets, and a septum magnet. Operating at one-third the accelerating frequency, the rf splitter may be phased to send two of three beam pulses into either of two beam lines and the third pulse into the other beam line.

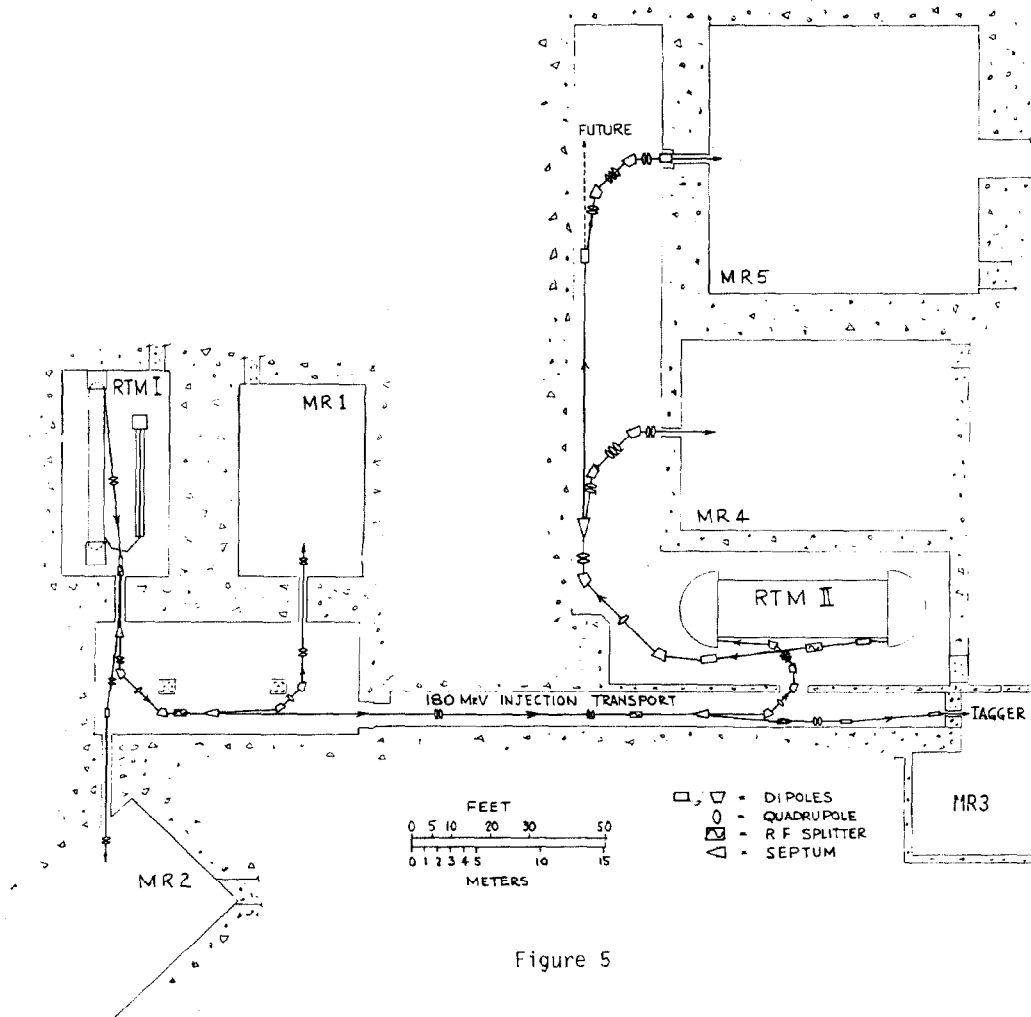


Figure 5

The chopper system described earlier allows independent control of the split beam currents, with a ratio of up to ~ 100 between beam currents. DC deflection magnets are used for operation into a single beam line, with the rf splitter turned off.

The rf beam splitters will be built of side-coupled structure tuned to operate in the TM-110 like deflecting mode at 793.3 MHz ($f_0/3$). The design calculations are based on the work of Haimson¹¹. At 200 MeV, a one-meter section driven with 20 kW rf power produces a 1.75 mrad deflection amplitude. Two splitters for the 200 MeV beam are powered from a single commercially available 50 kW transmitter. At one GeV, a 2 meter structure powered by a second 50 kW transmitter provides a 1.0 mrad deflection amplitude. Following each rf splitter, the split beams are allowed to drift until a separation of about one centimeter is obtained and then a DC septum magnet is used to further separate the beams. Because of the very small beam emittance, and especially the phase spread of $< 2^\circ$ (at f_0), degradation of the beam emittance in the rf splitters is negligible.

Each of the five 90° bends in the beam transport system is accomplished using a nondispersive DQD system.¹² The 200 MeV beam is matched into the transverse acceptance of RTM-2 with quadrupole doublets in the 200 MeV beam tunnel. For longitudinal matching, variable energy dispersion and time dispersion are provided by the quadrupole triplet in the 180° bend at 200 MeV.

In cases when one split-beam current is 100 μ A, the minimum stable current that can be provided to either of the photon-tagging areas using the adjustable chopper slits is about 1 μ A. Further reduction in beam current to meet the photon-tagging requirements is accomplished by closing adjustable slits in the 200 MeV and 1 GeV beam transport tunnels.

Buildings

For the 200 MeV program with RTM-1, only minor building modifications are needed. Structural changes to the present building required for the 1 GeV program are mainly improved utility access between existing rooms, a new fire suppression system for the existing areas being used, improvement of equipment handling capability, and relocation of the present RTM klystron power supply.

The scale of a building to house the RTM-2, two experimental halls and associated data rooms is set by the size of the accelerator and spectrometer magnets and shielding walls to contain the radiation generated by 300 kW of electron beam. The floor area of the proposed addition is approximately rectangular in shape with one side attached to the existing accelerator tunnel. See Fig. 5. The bottom floor of the reinforced concrete building is situated about 34 feet below ground level and occupies an area of 140×180 ft². The total size of the addition is approximately 35,000 square feet of floor area.

The dimensions of the two new experimental halls (MR4 and MR5 in Fig. 5) were chosen to accommodate the equipment designed for a tagged photon program (measurement room 4, a low current room) and a coincident electron scattering program (measurement room 5, a high current room).

A set-up area, served by a freight elevator, is the common access point for the high current measurement laboratory ($70' \times 70' \times 56'H$), low current measurement laboratory ($50' \times 70' \times 25'H$) and the RTM machine room. Located on the other side of these areas is the beam distribution room connecting to the RTM machine room. Above the beam distribution room, a service area is planned for the mechanical and electrical distribution of the RTM

machine and the associated laboratories. Above this service area, a counting floor is planned to house two data collecting rooms, two user rooms, a conference room and a library. Above the counting floor, a plant floor is reserved for the building mechanical and electrical services. Roof hatches are planned for equipment access to measurement rooms 4 and 5 and the RTM Machine Room.

Effective utilization of a multiple-beam research facility is greatly enhanced if all areas of the building can be occupied by the staff on a full time basis whenever there is no beam in that particular area. This was a design criterion for the existing NBS Linac facility. The shielding walls between rooms were calculated to be adequate to reduce radiation levels in all rooms not traversed by an electron (or photon, or neutron) beam to < 0.1 mrem/hr for any possible mode of linac operation up to a total beam power of 100 kW at 100 MeV. Extensive radiation surveys performed under a great variety of operating conditions have shown this goal was met. We are thus assured of the adequacy of existing shielding for RTM-1 and associated experimental areas, control rooms, and other occupiable spaces.

New shielding calculations have been performed for RTM-2, including a consideration of the radiation levels in the existing building due to sources in the new addition. The 3.6m thick concrete shielding walls which have proven to be adequate under all operating conditions for a 100 MeV, 100 kW accelerator are not sufficient by themselves for complete personnel protection at 1 GeV and 300 kW. Nevertheless, we have not used wall thicknesses greater than 3.6m (12 feet) (except for one small region around the beam dump in the high current room, MR5) because of prohibitive cost. We plan to augment the main shielding walls with auxiliary local shielding near the predictable main radiation sources such as beam dumps and collimating apertures. Since the beam quality and stability of the RTM will be so much better than older accelerators the amount of beam spill which is distributed over long beam paths (and thus not amenable to local shielding) is quite small.

A system of radiation monitoring, personnel exclusion, and area inspection modelled after the system in use at the NBS Linac will be implemented to insure radiation safety for all staff and visitors. The existing system has proven to be fully adequate and not unnecessarily restrictive in seventeen years of operating experience.

Acknowledgement

The principal authors of the proposal described here are: P. Chen, P. Debenham, W. Dodge, E. Hayward, J. Lightbody, X. Maruyama, J. O'Connell, and J. Rose.

References

1. P.H. Debenham, et al., "Progress on the NBS-LANL CW Microtron," to be published in IEEE Trans. on Nucl. Sci. NS-30, No. 2 (April 1983).
2. H. Herminghaus, et al., Nucl. Instr. & Meth. 138, 1 (1978).
3. "Beam Blowup in Race Track Microtrons," H. Herminghaus, Institut für Kernphysik, Mainz University, Internal Report KPH 15/78 (May 1978).
4. R.A. Rand, C.M. Lyneis, and H.A. Schwettman, HEPL 889 (Preliminary), High Energy Physics Laboratory, Stanford University (1981).
5. S. Penner et al., IEEE Trans. on Nucl. Sci. NS-28, 1526 (1981).

5. E.A. Knapp, B.C. Knapp, and J.M. Potter, Rev. Sci. Instr. 39, 979 (1968).
6. L.M. Young and J.M. Potter "CW Side-Coupled Linac for the Los Alamos-NBS Racetrack Microtron," paper 67, this conference.
7. P.H. Debenham, IEEE Trans. and Nucl. Sci. NS-28, 2885 (1981).
8. E.R. Lindstrom, et al., "NBS-LANL RTM End-Magnet Field Mapper," paper K30, this conference.
9. L.N. Hand & W.K.H. Panofsky, Rev. Sci. Instr. 30, 927 (1959).
10. R.E. Martin et al., Proc. of the 1981 Linear Accelerator Conference, Santa Fe, NM, R.A. Jameson and L.S. Taylor (editors), 65 (1981).
11. J. Haimson, in Proceedings of the 1966 Linear Accelerator Conference, Los Alamos, LA Report 3609, (1966) p. 303.
12. S. Penner, Rev. Sci. Instr. 32, 150 (1961).