INITIAL OPERATION OF THE MIT ELECTRON LINEAR ACCELERATOR*

J. Haimson

Haimson Research Corporation
Burlington, Massachusetts

Summary

Initial operating experience with the various high power sub-systems is discussed, and the results of electron beam tests at progressive stages of completion of the linac are presented. A highly stable analyzed beam containing greater than 85% of the accelerated current has been demonstrated routinely using ±0.11% analyzing slits at both the 20 MeV and 120 MeV stations. Of particular importance, especially for beam transportation and future considerations of beam recirculation, has been the achievement of an extremely low emittance. Beam measurements at the 20 MeV station have confirmed that essentially all of the accelerated current is contained within an emittance of $7 \pm 2 \times 10^{-4}$ $\pi m_0 c$-cm; i.e., ~0.2 mm mrad at 20 MeV. System checkout is currently in progress to bring the linac up to its maximum operating condition of 430 MeV at a duty factor of 1.8 per cent.

Introduction

General Description of Linac System

A detailed description of this high duty factor electron linear accelerator and its associated subsystems has been presented in previously published reports,[1,2,3,4,5] therefore, only a summary of the essential technical features will be given in this introduction.

A schematic layout of the microwave distribution system, the injector linac, and the accelerator waveguide arrangement is illustrated in Figure 1. Ten high power klystrons are paired into five groups, each pair being video driven from a common hard tube modulator and RF driven from a common driver klystron. A highly stabilized master driver klystron is used to excite the five driver klystrons via a phase stabilized coaxial line.

Ten rectangular waveguide networks are utilized to interconnect the high power klystrons to 24 accelerator waveguide sections. The first klystron is reserved for the two series-connected sections of the injector linac; each of the following seven klystrons drive two waveguide sections; and each of the last two klystrons energize four accelerator sections. The use of quadruplexed waveguide sections at the end of the linac provided a satisfactory compromise between the technical desire to maximize beam energy and the economic requirement to minimize initial expenditure. This approach has an added attraction in that the machine can be up rated at a later date, without affecting the beam centerline components, by adding another transmitter and retrofitting a portion of the RWG network in the gallery.

The 24 accelerator waveguide sections comprise a 1.2 meter 7 MeV buncher section in RF series connection with a 3.7 meter section, four 3.7 meter sections, and eighteen 7.35 meter sections. The waveguide sections are traveling wave disc-loaded $2\pi/3$ mode, 2856 MHz structures which have been divided into six groups of different microwave design, as shown in Figure 1 as AA, BB, A, B, C and D, in order to (a) provide a higher gradient at the beginning of the linac and (b) elevate the threshold of beam break-up instability well above the normal operating levels of the linac.

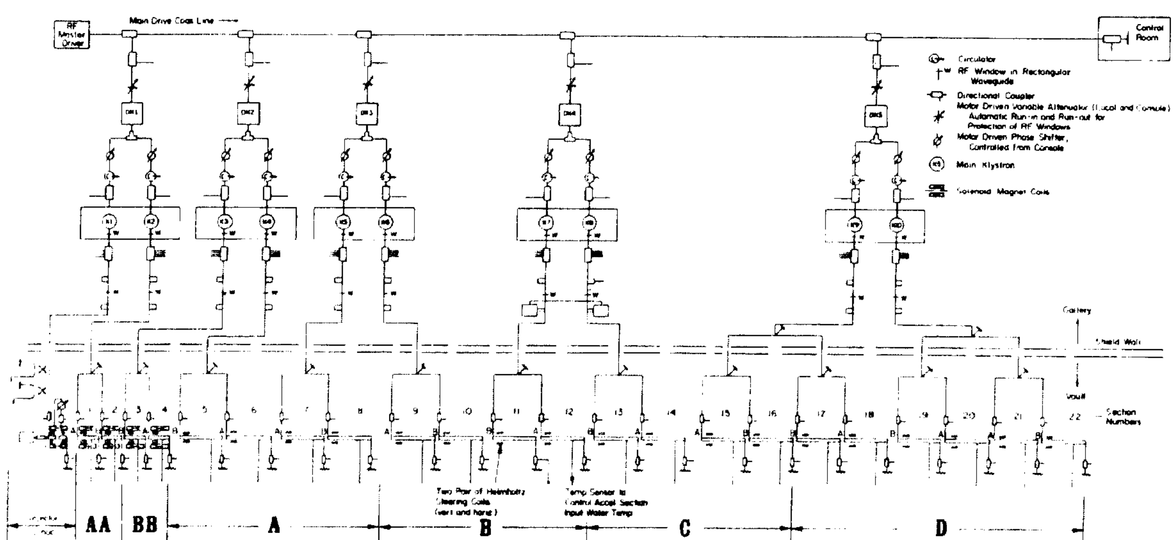


Fig. 1 Schematic Layout of Beam Centerline and RF System

*Work performed under the auspices of the U.S. Atomic Energy Commission and the Massachusetts Institute of Technology. This accelerator facility was formally named "The William H. Bates Linear Accelerator" during the dedication ceremony at Middleton, Massachusetts on April 7, 1972.

A view of the two-section 20 MeV injector linac, with its test spectrometer in the background, is shown in Figure 2; and a view of the completed beam centerline, looking toward the beam switchyard, is shown in Figure 3. The overall length of the linac beam centerline is 185 meters.

The dual transmitter systems make use of direct series switched VA938 klystrons, each of which can be operated over a 4 to 1 dynamic range to provide 80 kW of average RF power at 4 MW peak and 65 kW at 1 MW peak. Each transmitter system comprises a 400 kVA voltage controller regulator, a 170 kV 6A transformer-rectifier unit, two parallel 1 μF capacitor banks, a ball-gap crowbar and a large oil filled modulator tank containing a common hot deck, switch tubes and the klystron sockets. This direct switching concept, using high plate resistance switch tubes, has demonstrated[5] an excellent performance with less than 1° of RF phase variation over a 15 μsec pulse length at 4 MW peak power and 1000 pps (with a 0.4° bin phase variation of saturating RF drive). Figure 4 is a view of one of the transmitter systems showing the capacitor banks and the modulator tank with klystrons. It can be noted that the RWG is provided with double cooling channels to minimize RF phase variations over a wide operational range of duty factor, and that an adjustable anchor support is used to prevent stressing the klystron and to facilitate its removal. A view of the klystron gallery housing the five dual transmitters is shown in Figure 5.

With the klystrons operating at 4 MW peak power, the required performance specification for the overall linac[2] is 150 μA of average current at 400 MeV and at a beam duty factor of 1.8%, i.e., a rated peak current of 8.4 mA. At a klystron level of 1 MW, and for the same average current, the rated beam energy is 200 MeV

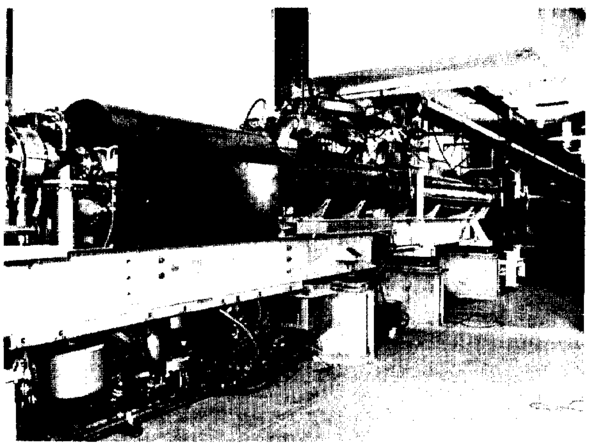


Fig. 2 View of 20 MeV Injector Linac

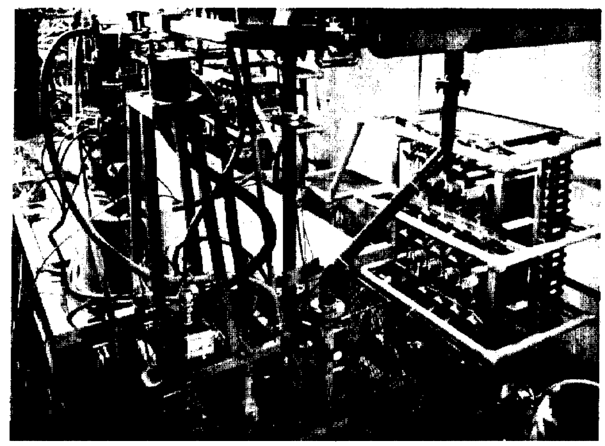


Fig. 4 Dual Transmitter System

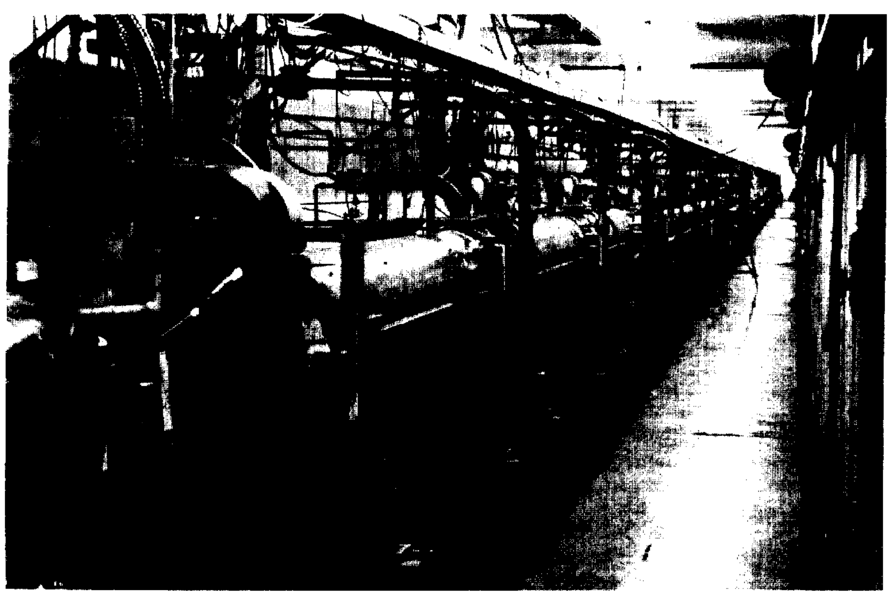


Fig. 3 View of Completed Beam Centerline Looking Toward the Beam Switchyard

at a beam duty factor of 5.8%. The performances of the individual sub-systems in meeting or exceeding the maximum duty factor requirements have been presented in previous reports, e.g., RF driver,[1] injection system[4] and high power transmitter.[5]

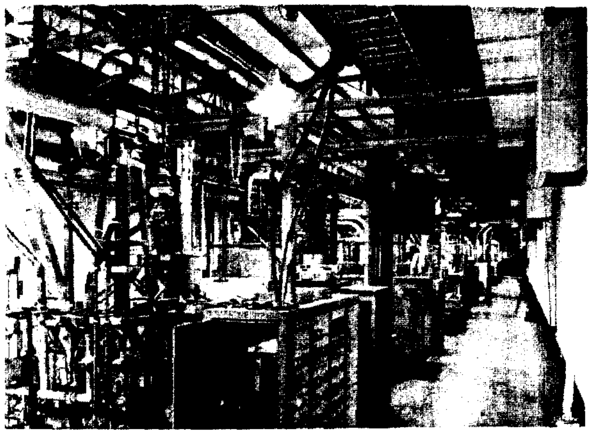


Fig. 5 View of Klystron Gallery

Initial Beam Performance

Plans for the initial beam test program included a careful evaluation of the characteristics of the injected beam at the 20 MeV level and a series of beam measurements at the 120 MeV station using 4 klystrons energized from the first two dual modulators. It was also planned that, during the 120 MeV test program, RF phase information obtained from beam loading under actual operating conditions would be used to finalize the RF phase tuning of the RWG networks, and that a study of machine performance would be made under conditions of back phasing and drifting of the beam.

The first opportunity to demonstrate an accelerated beam at Middleton occurred in September, 1971 when, immediately after completion of installation of the injector linac 1.2 meter buncher waveguide, a short series of beam tests was performed. (This occurred prior to installing the second waveguide section which was required in order to commence the main 20 MeV beam test program.)

The chopper, prebuncher and buncher structures were RF processed quickly and without difficulty; and a stable flat top beam at full rated peak current and at the buncher design energy was achieved within minutes of first switching on. Figure 6 is a record of the first accelerated beam as measured with an evacuated Faraday cup located on-axis and 2 meters beyond the 5 mm diameter output aperture of the buncher waveguide. This test run was performed at a peak current of 10 mA, a beam pulse length of 14 μsec and a repetition rate of 300 pps. A beam energy of 7.1 MeV was obtained with 2.5 MW peak RF input power to the buncher section and with an electron gun potential of 400 kV. An emergent beam diameter of approximately 2 mm was obtained using an average axial magnetic field of less than 500 gauss. Although the beam spectrum was not evaluated to any extent during this short test run, it was apparent, from the general behavior of the system and the reproducible and stable nature of the beam, that a performance of high quality had been achieved. In anticipation of obtaining definitive and exciting spectral data, the installation of the second accelerator waveguide, the high resolution spectrometer, and the emittance measuring equipment was completed expeditiously; and the 20 MeV beam test program was commenced in December, 1971.

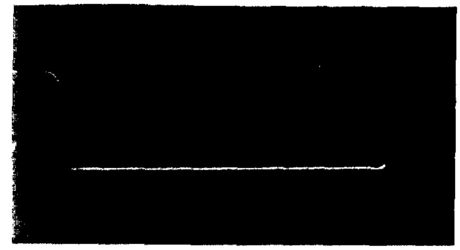


Fig. 6 First Accelerated Beam at the Middleton Facility (7.1 MeV, 10 mA, 14 μsec)

20 MeV Beam Tests

The first series of 20 MeV beam tests was performed at a klystron peak RF output power of 2.8 MW (2.5 MW at the buncher input coupler), an injection potential of 400 kV and beam pulse lengths of 10 and 15 μsec. The injection system was operated under biased (off-axis) 120^0 chopped-prebunched conditions;[2] and, contrary to previous experience with lower potential, higher current, injection systems, use of the chopper cavity resulted in a marked improvement of the accelerated beam spectra. A further operational feature which was noticed immediately, and attributed also to the high injection potential (and small beam cross-section), was the relative insensitivity of the amplitude and energy of the accelerated beam to small variations of the magnetic and RF control parameters.

Evacuated Faraday cups, and non-intercepting RF beam monitors, were used to measure both the straight ahead beam and the analyzed beam which passed through fixed tungsten slits of 0.22% resolution. (The careful field mapping and analysis of this spectrometer system by Dr. S. Kowalski is gratefully acknowledged.)

Typical high resolution performance of the injector linac is illustrated by Figures 7 and 8 which compare collected straight ahead and 0.22% analyzed beams at 23 MeV for peak current levels of 4 mA and 8 mA, respectively. It can be noted that between 80 and 90% of the time integrated, steady-state accelerated beam was contained in an energy interval of 50 keV. These double exposure photographs were obtained while operating at a pulse repetition frequency of 300 pps. The horizontal time scale calibration is 5 μsec/cm.

The transverse phase space of the 23 MeV beam was investigated by (a) observing the fraction of the beam scattered out of the straight ahead Faraday cup by a 1 mm diameter tungsten wire as a function of the wire position during traversal across the beam and (b) transmission experiments with the beam passing through widely separated small diameter apertures under different conditions of upstream focusing and steering.

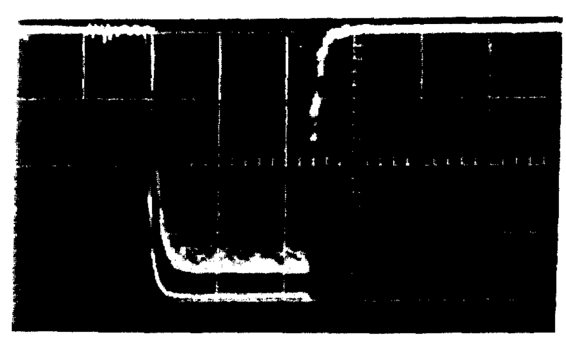


Fig. 7 Comparison of Straight Ahead Beam and Analyzed Beam Through 50 kV Slits (i_p=4mA)

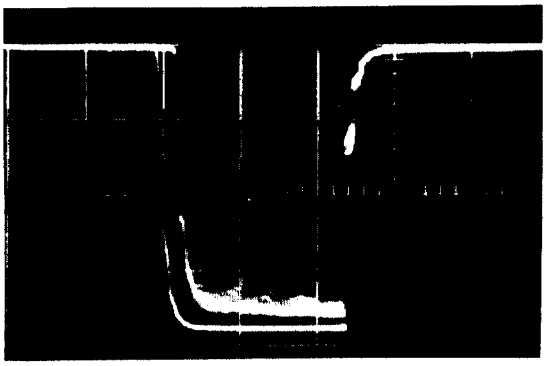


Fig. 8 Comparison of Straight Ahead Beam and Analyzed Beam Through 50 kV Slits (i_p=8mA)

With the scattered electron technique, there were two measurement locations, Station 1, just beyond the spectrometer magnet and upstream of a long evacuated drift tube, and Station 2, 4.4 meters downstream of Station 1 and about 2 meters ahead of the Faraday cup. Each station was equipped with two 1 mm diameter tungsten wire probes, one of which rotated about a horizontal axis and the other about a vertical axis. A preliminary measurement showed that 50% or higher interception could be obtained simultaneously on all four wires, indicating a transverse emittance $\leq 10^{-3}\pi$ m_oc-cm. A more precise measurement was then made but without the services of the vertical axis pair, one of which had stopped operating. The solenoids of the second waveguide section were adjusted as a lens to produce a waist in the beam by maximizing the intercepted fraction at the probes. The small size of the input collimator (5 mm), its close proximity to the lens, and the large distance from the lens to Station 2 (greater than 6 meters) implied that a beam with a waist at Station 2 is in good approximation the most parallel beam which could be produced. Care was taken during these experiments to avoid loss of beam at the input collimator. Figures 9(a) and 9(b) show typical experimental data at a fixed lens setting and at rated

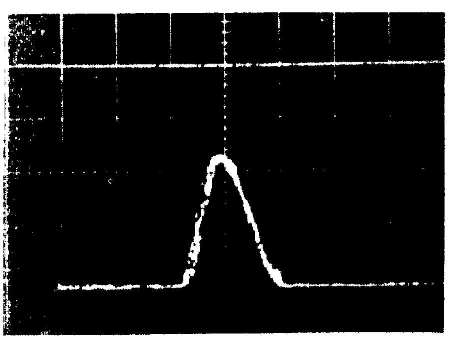


Fig. 9(a) Upstream Rotating Beam Probe (1.7 mm/cm)

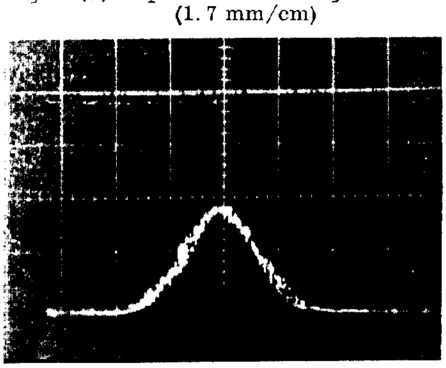


Fig. 9(b) Downstream Rotating Beam Probe

peak current for the upstream and downstream probes, respectively, as obtained with a sampling scope. The abscissa calibration scale of probe displacement is 1.7 mm/cm. Note that the percentage of beam interception varies inversely as the distance to the baseline. An analysis of the electron scattering measurements indicated a beam waist of 2 mm diameter and a radial divergence of 0.7 mm in 4.4 meters, i.e. an emittance of $7 \times 10^{-4}\pi m_oc$-cm with an estimated experimental accuracy of ±30%. (The suggestion by Dr. C. P. Sargent to utilize the rotating probes as a scattering medium and his collaboration in the evaluation of the experimental data is gratefully acknowledged.) After the rotating wire measurements were completed, a 5 mm diameter collimator was inserted just beyond the Station 2 location, 6 meters downstream of the 5 mm input collimator. Full transmission was obtained through this output collimator, even when the beam was subjected to small steering movements. The 20 MeV test program was terminated after a relatively short period to allow installation work to proceed; and the spectrometer, together with a new set of analyzing slits, for higher energy, was installed immediately beyond waveguide section No. 6, at the 120 MeV station.

120 MeV Beam Tests

These tests were scheduled for Summer, 1972; however, it was decided to interrupt the installation program for several days just before the dedication ceremony in April to attempt a "100 MeV" beam run. Klystrons 2, 3 and 4 and their associated accelerator sections were RF processed, but final RF tuning of the power dividing evacuated RWG networks was deferred until a later date. On April 5, 1972, a 107 MeV beam was achieved; and preliminary RF power measurements at the section output couplers confirmed the feasibility of tuning the RWG networks to a phase accuracy of 2^o or better using the accelerated electron beam as the standard for synchronization. Figure 10 compares the response of a section output RF monitor at constant beam current and for an input RF phase shift of 6^o (away from the optimum phase position).

The main 120 MeV test program commenced in July, 1972. The three untuned RWG networks were accurately phase synchronized to the beam (making use of a remotely operated tuning clamp), and the progressive increase of beam energy was verified spectroscopically. Figure 11 records the beam pulse, as measured with the straight ahead Faraday cup, after completion of final tuning. A beam energy of 126.5 MeV was obtained with

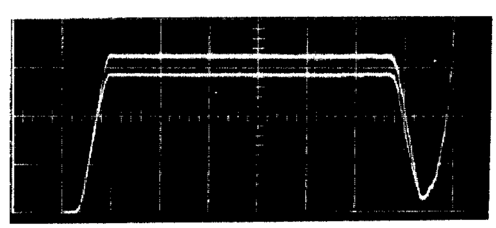


Fig. 10 Section RF Output Response for 6^o Input Phase Shift and Constant Beam Current

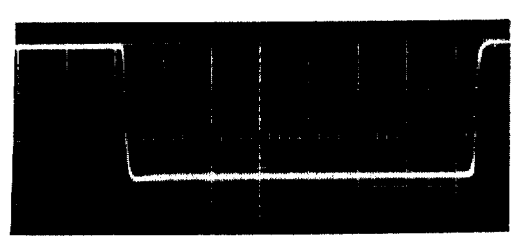
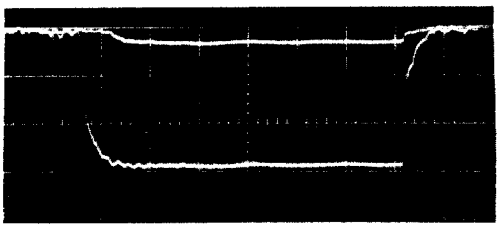
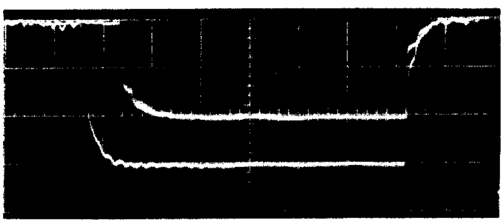


Fig. 11 Unanalyzed Beam Pulse (126.5 MeV, 9 mA, 2 μsec/cm)

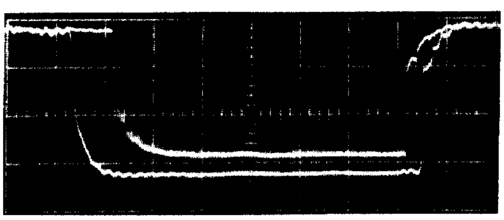
a peak current of 9 mA which is in close agreement with the 132 MeV design value[2] at zero loading and the 61 and 116 kV/mA beam loading factors for the 3.7 and 7.35 meter waveguides, respectively. As with earlier tests, even after the beam was transmitted through 0.22% analyzing slits, flat top pulse performances were achieved routinely. Figures 12(a), (b) and (c) compare the collected straight ahead and 0.22% analyzed beams for an injection potential of 400 kV and the injection conditions of (a) no prebunching or chopping, (b) prebunching with 200° chopping, and (c) prebunching with 120° chopping, respectively.



(a) No Prebunching or Chopping



(b) Prebunching with 200° Chopping



(c) Prebunching with 120° Chopping

Fig. 12 Comparison of Straight Ahead Beam and Analyzed Beam through 250 kV Slits (115 MeV, 9 mA Peak, 2 μsec/cm

Additional tests were conducted to investigate the beam performance under conditions of drifting and back phasing. It was noted, for example, that when the beam energy was reduced from 120 to 48 MeV by switching off the second transmitter, and without adjusting any of the machine parameters, full beam current could be maintained in the straight ahead cup. Also, back phasing klystrons 3 and 4 enabled the beam energy, as measured at the 120 MeV station, to be reduced to 17 MeV without difficulty. Beam spectrum measurements were obtained during the back phasing experiments to determine the longitudinal phase space.[6] An analysis of the data indicated that, at a peak current of 9 mA, essentially all of the charge was contained in a bunch width of somewhat less than 1°. This low value was consistent with (a) the injection system bunch measurements, using a rotating beam technique,[7] which confirmed visually that bunch widths of < 10° were being produced at injection to the 10:1 compression buncher, (b) the insensitivity of the spectrum width to small changes in RF phase, and (c) the ease of back phasing the beam over a wide range of operational conditions.

Two beam experiments were conducted as preliminary checks for the presence of BBU. An accelerated beam of 42 mA peak and 14 μsec pulse width was delivered to the 120 MeV station, and klystrons 3 and 4 were then switched off. Without focusing fields over the passive waveguide sections, the full beam was drifted successfully into the end cup, and at a terminal energy of 28 MeV. A low field gradient test was also conducted by reducing the klystron peak RF output level from 4 MW to 1 MW. A stable 60 MeV, 10 mA beam was demonstrated under these conditions, and this beam was also drifted successfully into the end Faraday cup when the second transmitter was de-energized. After a series of calibration measurements and phase scan tests with the prebuncher and chopper cavities, the beam test program was terminated to allow installation to proceed on the remaining portion of the beam centerline and the "Mark 1" beam switchyard. This has now been completed, and final preparations are in hand to transmit the accelerated beam along the entire system and into the main beam dump located at the 250 meter station. A portion of the switchyard showing the bent beam channel directed towards the energy-loss spectrometer hall, and the straight ahead beam dump channel can be seen in Figure 13.

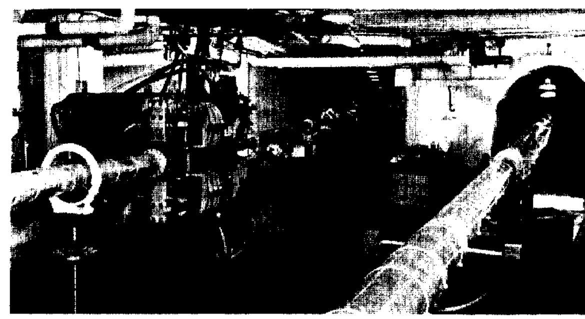


Fig. 13 View of Portion of Switchyard

Conclusions

Initial design objectives of very narrow longitudinal and transverse phase space have been demonstrated with the achievement of a small cross-section high resolution electron beam, the stability and reproducibility of which challenges the performance heretofore considered possible only with direct generation type accelerators.

References

1. J. Haimson, "A High Duty Factor 400 MeV High Resolution Electron Linear Accelerator," Proceedings of the Seventh International Conference on High Energy Accelerators, Yerevan, Vol. 1, 244, 1970.
2. "Linear Accelerators," Eds. P. Lapostolle and A. Septier, Chapter B.3.2, North Holland Publishing Co., Amsterdam, 1970.
3. R.D. Biron, H.C. Fischer, J.N. Weaver, "Some Mechanical Design and Construction Aspects of the MIT-LNS Linac," IEEE Trans. Nucl. Sci. NS-18, 589, June, 1971.
4. J. Haimson, "A Low Emittance High Duty Factor Injector Linac," IEEE Trans. Nucl. Sci. NS-18, 592, June, 1971.
5. J. Haimson, C.P. Sargent, J.N. Weaver, "Highly Stable RF Power Circuits for the MIT-LNS Linac," IEEE Trans. Nucl. Sci. NS-18, 595, June, 1971.
6. R.H. Miller, "Measurements of the SLAC Injector Emittance," Proc. 1966 Accelerator Conference, Los Alamos, LA Report 3609, 65, October, 1966.
7. J. Haimson, "Optimization Criteria for Standing Wave Transverse Magnetic Deflection Cavities," Proc. 1966 Accelerator Conference, Los Alamos, LA Report 3609, 303, October, 1966.