OPERATING EXPERIENCE WITH THE NAL 200-MeV LINAC

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Introduction

The first cavity of the linac(1) produced 10-MeV beam in the temporary building in June 1969 and in April 1970 in the permanent building. The complete linac produced 200-MeV beam on November 30, 1970. The linac has served since that time as an injector for the 8-GeV booster synchrotron at the relatively low beam current of 20-25 mA (~1/3 of design current). This current level, without the buncher, has been the desired level for useful beam studies in the booster and in the main ring synchrotron while keeping down radiation levels during the running-in phase of the 200-GeV accelerator. Only for very brief intervals has the linac been run at higher current levels for linac beam studies. The maximum current accelerated to date has been 100 mA. Most operation has used a beam pulse of short duration (5-10 μs) and good quality with emphasis on high reliability. This reliability has been approximately 95% for operating periods of linac plus synchrotron during the past year.

Descriptive Features of the Linac

Figure 1 is a view of the linac with the 10-MeV first cavity in the foreground.

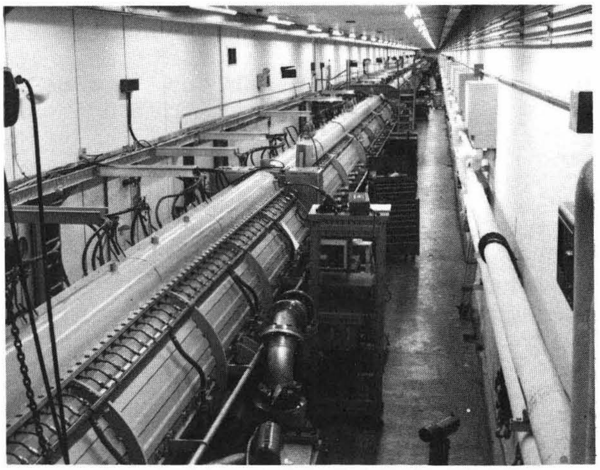

Fig. 1 View down the linac.

There is one 750-keV preaccelerator with a short beam-transport line of 3.5 meters in length.(2) The transport line includes three triplets, a single cavity buncher, and several beam-diagnostic probes. The ion source is a duo-plasmatron with large plasma expansion cup (7.5 cm in length with a 2.7 cm exit aperture). The accelerating column is of Pierce design.

The rf structure of the accelerating cavities includes post-coupler stabilization of all cavities beyond the first.(3) Each cavity is set at the resonant frequency by a coarse bulk tuner consisting of a longitudinal half-cylinder supported on posts from the cavity wall.(4) There are additional cylindrical tuners along the wall, one of which is servo-controlled in a frequency stabilization loop.

The control system is developed around an XDS Sigma 2 computer, an alphanumeric scope and a storage scope for making graphic displays.(5,6) In addition to control of any linac parameter, the computer is used for collection of data, calculation on the data and display of the results. Any reading can be plotted against any variable parameter. Currently there are about 660 analog-to-digital readout points, 100 digital-to-analog points, 800 binary sense and 375 binary command points.

Diagnostic instrumentation for proton beam measurements includes beam current transformers distributed throughout the length of the linac and beam lines. There are computer-controlled emittance-measuring probes, beam-profile single-wire scanners and multi-wire beam-profile probes in the beam-transport lines.(7) Figure 2 is a drawing of the 200-MeV diagnostic area.

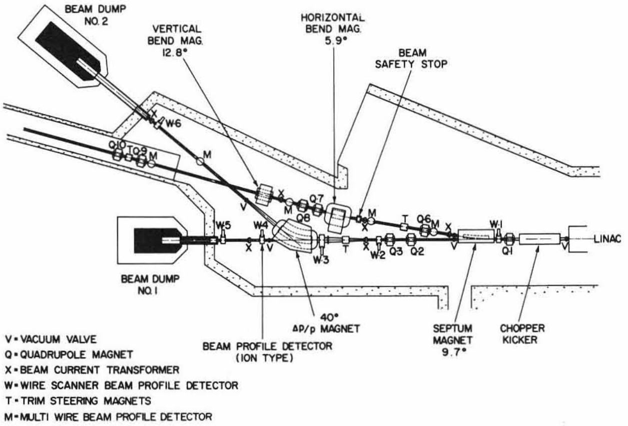

Fig. 2 200-MeV diagnostic area.

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TABLE I

200-MeV LINEAR ACCELERATOR PARAMETERS

	Design	Present Nominal Operation	Best Performance
Output energy, MeV	200.30	203	
Output momentum spread, $\Delta p/p$, total for 90% of beam (without debuncher)	2.7×10^{-3}	$2.0 \times 10^{-3\dagger}$	1.5×10^{-3} (25 mA)† 2.8×10^{-3} (80 mA)†
Peak beam current, mA (nominal)	75	25	100
Emittance at 200 MeV, mrad cm (each transverse mode, 90% of beam)	π	2.8	2.5 (25 mA) 3.4 (80 mA)
Beam pulse length, μsec	100	10	
Pulse repetition rate, pps	15	15	
Cavity resonant frequency, MHz	201.25	201.25	
rf pulse length, variable to	400 μsec		
rf duty factor, maximum	.006		
Synchronous phase angle, from rf peak	-32°	-32°	

†Estimated corrections have been made in the measured values for finite emittance.

Operating Experience and Improvements

The normal mode of operation of the NAL linac is as a component of the injection system for the 200-GeV synchrotron; hence, the linac operates at a 15-Hz rate but beam is accelerated beyond 750 keV, in the normal operating mode, only whenever the booster accelerator is ready for beam. Acceleration is achieved by activating a bypass circuit, which brings the ion source beam pulse, normally delayed by 1 msec, into time coincidence with the linac rf pulse.

The design of the NAL 200-GeV accelerator requires 12 pulses in a row at a 15-Hz rate from the linac and booster to fill the entire 6.3-kilometer circumference of the main synchrotron. In fact, this mode of operation has not been used yet in order to minimize residual radiation in the main ring during the tune-up phase. Rather, only a single pulse is normally accelerated per main-ring pulse or one 200-MeV pulse per 3 to 6 seconds. The linac, however, often accelerates at 15 pulses per second when its behavior is being investigated.

Nominal linac injection into the booster is at about 25 mA peak and this is usually achieved without the use of the buncher. Again, the value is less than design to limit radioactivation. Furthermore, the normal pulse length is shortened by the use of a biased cylinder in the ion-source extraction cup to about 5 μsec.(8) As the booster accelerator begins to operate with multi-turn injection, the beam pulse will be lengthened accordingly.

The operation of the linac is monitored by the linac control computer. Although many parameters are read on every pulse, the computer scans a table of only selected parameters and reports deviations from nominal values. A table entry can be either an analog voltage or a byte (eight bits) of binary-sense information. Any entry can be set to inhibit linac beam on the next pulse if its value drifts outside a prescribed tolerance. Under past operation the rf-gradient levels have been the primary parameters that are set to inhibit beam in this manner. Beam can also be inhibited by a hard-wire loop for such things as intertank valve closures and the safety system interlocks.

The control computer system has two monitor feedback loops for the rf-gradient level and the intertank phase of all cavities. The computer initiates action to restore the variables to their normal operating values within prescribed tolerances on a continuous basis. The computer has been programmed to reset a trip-off of a tank quadrupole pulser power supply and to bring an rf-system modulator back on from certain types of crowbar trips. In the case of a modulator crowbar, the modulator output is run to zero, the high voltage is turned on and the rf level in the cavity is automatically returned to its nominal value.

These features have made the linac system almost completely free of need for attention by an operator. In fact, the building is unattended for all but the day shifts on Monday through Friday, and even during these periods, the personnel are there only because their work benches are in that building.

Since the linac was completed in December 1970, the equipment in the linac system has operated for 13,100 hours. Over the past year, the reliability has approached 95% or better during operating periods of the entire accelerator. Of course, in a system of four accelerators in series, this factor is very important and many improvement programs are in process to improve this figure.

The reliability of the RCA 7835 tubes is of major interest due to their relatively high cost. Figure 3 is a plot of the present filament hours on the 7835 tubes now in service. To date, six 7835's have failed. Also shown in the figure are the filament hours at which each of the six tubes has failed.

Since early improvements were made in the modulator drive chain, the modulators have become increasingly reliable. The switch tube, the F11023 made by ITT, of which there are three in each modulator, have been remarkably durable. There have been no failures of these tubes at this time.

Maintenance of the NAL linac is accomplished with on the average about one 8-hour shift every second week by nominally five technicians with the help of whatever accelerator operators may be available on the maintenance day. Most diagnosis and repair of components which fail during operation is done by the operators, since no linac technicians are scheduled on off-normal working hours.

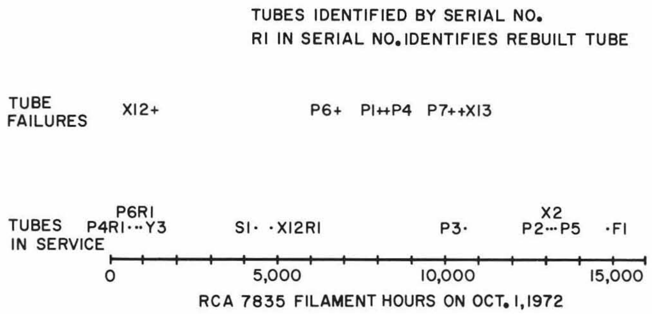

Fig. 3 Life graph of RCA 7835 triodes.

There have been several occasions where rf windows in the transmission line to the cavities have arced across and been sufficiently copper plated that they had to be cleaned. This situation was particularly persistent in tank 1 and it became necessary to replace the original 6" diameter window with a 9" window and line adaptor. Another modification has been made to help extend the life of the drive-loop vacuum barriers. The rf system modulators now have a clamp or variable-gain control. This circuit limits the amplitude of the pulse during the initial filling time of the cavity when there is a large mismatch of the drive loop.

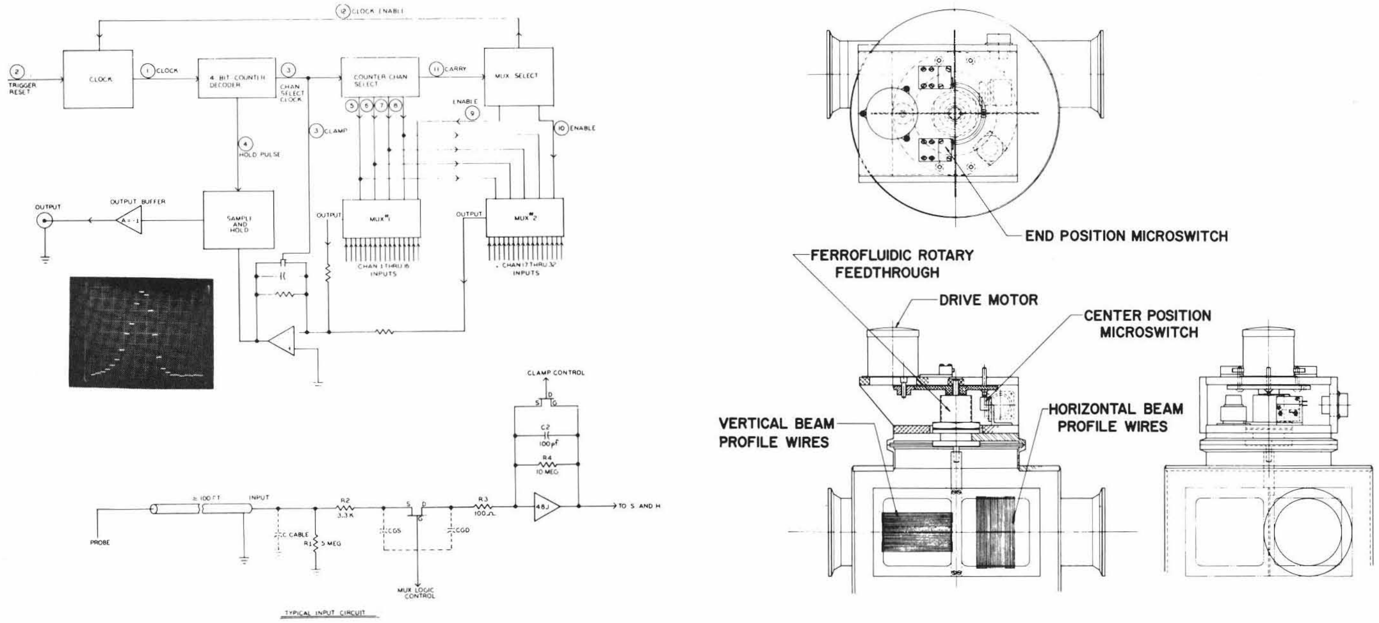

Fig. 4 Multi-wire beam-profile monitoring system.

a. Electronic circuit and momentum profile. b. Mechanical assembly of the detector.

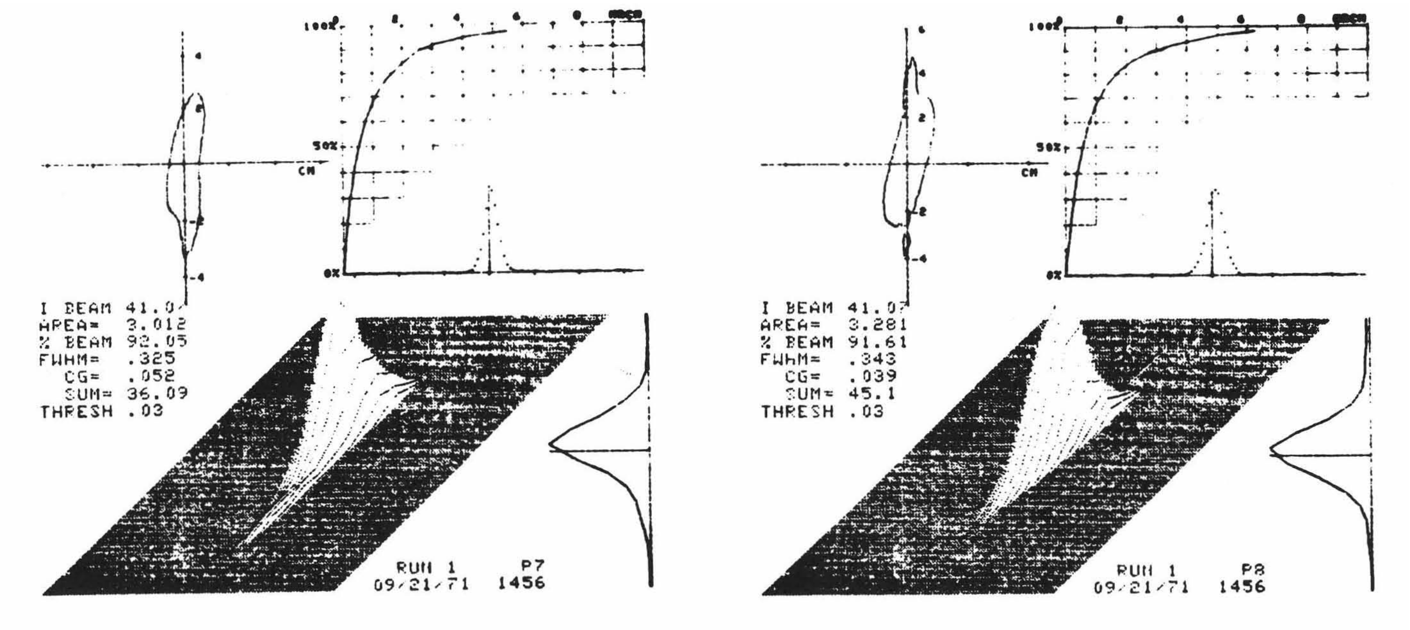

Fig. 5 200-MeV emittance display for 41 mA beam.

a. X plane b. Y plane

One drift tube quadrupole in tank 3 was shorted internally by a water leak in the drift tube cooling circuit. The linac was operated for several weeks this way, while a new drift tube assembly was made, with only a small beam-current loss at the low nominal beam current. Attempts at high currents with this power supply off gave a substantial beam loss. No attempt to match the beam around the turned-off quads was made. At the time this assembly was installed, this cavity was inspected internally and no deterioration of coupling loops, tuners or drift tubes was observed. To allow for any future shorts, several semifinished spare drift tubes of various sizes are being fabricated.

The beam diagnostic systems are essentially unchanged from those described elsewhere(7,9)--except for the addition of a multi-wire profile monitor, enabling single-pulse beam-profile observation. The mechanical assembly and associated electronics for this monitor are shown in Fig. 4. The horizontal and vertical wires are connected together in pairs and the desired profile is selected by physically rotating the appropriate wire plane into the beam. Following a beam pulse, coaxial cables attached to the individual wires are left with a charge proportional to the amount of beam intercepted by the wires. The electronics sequentially integrates this charge and produces an analog histogram of the beam profile. The addition of a modular A to D unit and a local first-in first-out memory will soon make profile information available to the control computers. By multiplexing this information at low level, one eliminates a preamplifier on each channel.

These monitors are being used in the 200-MeV momentum analyzing line and at eight locations in the transfer line to the booster accelerator.

Beam Properties

At low beam currents (15-30 mA) the operating 200-MeV emittance area, not normalized, is typically somewhat less than π cm-mrad for 90% of the beam.(10) Somewhat smaller emittance is obtained when the ion source parameters are adjusted for smaller emittance from the column, showing the value of a brighter source. Adjustment of the 750-keV triplets can give a smaller 200-MeV emittance in either plane with a corresponding larger emittance in the other plane.

The 200-MeV emittance increases quite slowly with beam current to an area of approximately 3.6 mrad-cm for 90% of the beam at 80 mA. This observation is with the linac quadrupole strengths as well as rf-field levels for all cavities left unchanged for all beam currents. The 750-keV transport triplets are generally readjusted for extremes of beam current. Beyond this tuning, little systematic variation of linac quadrupoles has been attempted to reduce 200-MeV emittance. A few changes in the 10-MeV cavity quads did not significantly reduce emittance growth for low beam intensity. Figures 5 and 6 show

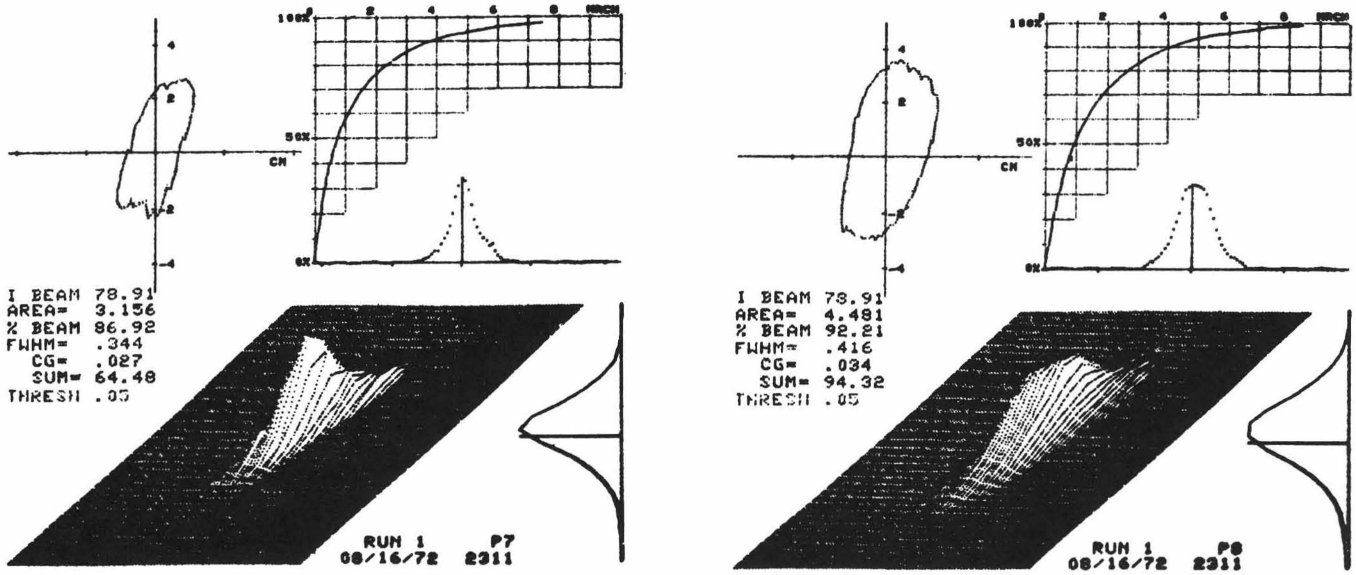

Fig. 6 200-MeV emittance display for 79 mA beam.

a. X plane b. Y plane

higher current emittance displays. Shown in clockwise order beginning at the lower center are: the beam density in phase space in three dimensions, a contour in the phase plane, the emittance versus percentage of beam curve, the beam profile and the beam angular distribution. Emittance versus beam current is shown in Fig. 7. It is interesting to note that the ion-source plasma expansion cup gives a beam emittance at 750 keV nearly independent of beam current(11) (see Fig. 8). The slow increase in 200-MeV beam emittance with beam current, therefore, means increasing emittance growth, which possibly can be attributed to space charge effects in the linac. One notes that the brightest 200-MeV beam, however, is the highest current beam. The brightness of the ion source is, of course, proportional to beam current for the present design.

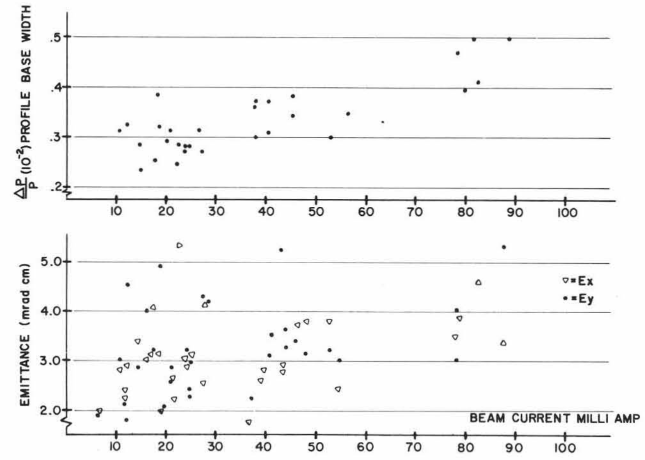

Fig. 7 Emittance and momentum spread, Δp/p, as a function of 200-MeV beam current.

There is always an emittance growth through the linac,(2,8) typically a factor of two and variable with beam matching at the linac input. Emittance growth is here defined as the ratio of final to initial normalized emittance. The growth is present for all beam currents and takes place almost totally within the 10-MeV first cavity for low beam currents.

A sample of emittance growth curves is shown in Figure 9 for beam currents of 38, 55 and 78 mA. Although there can be large variations in these curves, depending on adjustment of beam match, there are a few qualitative generalizations which apply to most curves. These features are exemplified, in part, by Figure 9. Emittance growth is shown as a function of percentage of beam within emittance contours. As a first feature, the growth curve slopes upward toward higher percentage of beam in almost all observations for

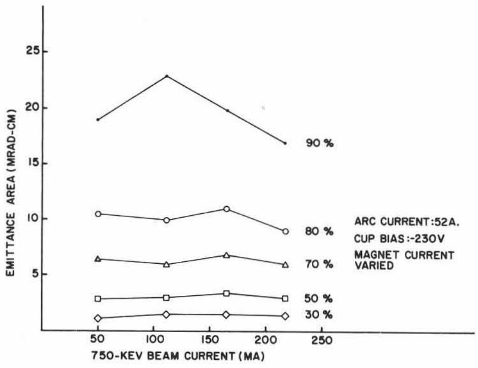

Fig. 8 Emittance versus beam current for 750-keV beam.

the 750-keV to 10-MeV range. In the 10-MeV to 200-MeV range, either the reverse is true or the curve has zero slope: This may imply that the fringes of the beam undergo more growth than the core below 10 MeV, while above 10 MeV, in those cases with growth, either the core undergoes relatively more growth or the beam as a whole grows uniformly. A second feature is that differential growth between low and high current beams is not observed consistently below 10 MeV while there tends to be more growth for the high current beams above 10 MeV. A third feature, frequently observed, is the essentially constant overall growth to 200 MeV for a given beam current as the relative growths below and above 10 MeV change with variation in 750-keV beam matching.

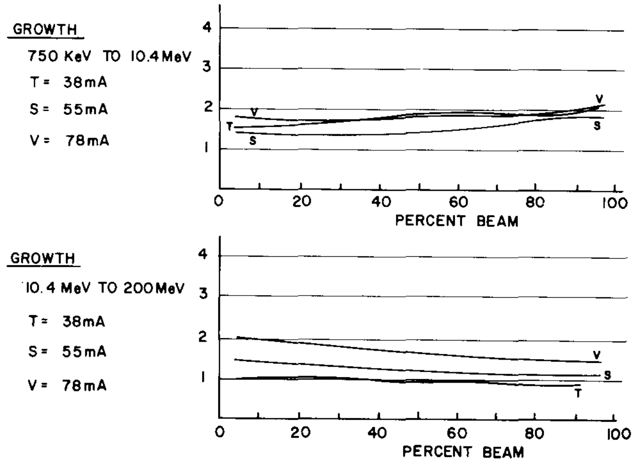

Fig. 9 Emittance growth in the linac.

The output beam energy from the linac is adjusted and the energy spread minimized by the method described in March 1971.(10) The rf-phase adjustment of the last cavity, number nine, minimizes energy spread while phase adjustment of the last two cavities sets precisely the energy. Momentum spread as well as emittance are routinely measured and calculated on line while the accelerator is operating as an injector to the booster. Measurements have been made at other times for a range of beam currents as seen in Fig. 7. The momentum spread, Δp/p, is seen to increase slowly on the average with increasing beam current to a value of approximately 0.35% at 80 mA for 90% of the beam, uncorrected for finite emittance of the total beam. The 90% widths are smaller than the total widths plotted in the figure. The correction for emittance depends on the relative value of momentum spread and emittance but studies have indicated a correction downward of 20-25% of the 90% width for typical cases with a larger correction for the smallest values of Δp/p.

Figure 10 shows a comparison of uncorrected momentum sprectra for beam currents of 82 mA and 43 mA. These were obtained with buncher on and buncher off, respectively, and no retuning of other linac parameters. A slight increase in total spread is observed at the higher current. At beam currents of 40 mA and 20 mA the buncher-on and buncher-off widths were equal.

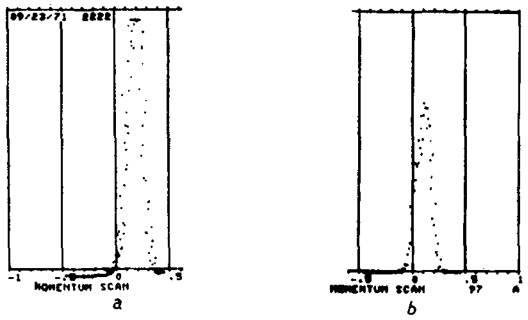

Fig. 10 200-MeV momentum spectrum showing effect of buncher.

a. Buncher on, 82 mA b. Buncher off, 43 mA

Another momentum spread comparison is shown in Fig. 11. Of the two spectra at the same beam current of approximately 20 mA, one was obtained with nominal linac-cavity rf-field levels and the buncher off, the other was obtained with the first cavity field reduced and the buncher turned on. The reduction of energy excursion in the first cavity resulted in smaller momentum spread at 200 MeV. The 200-MeV emittance was not reduced. Consequently, the emittance correction to Δp/p would be greater for the narrower spectrum, and the difference in corrected widths would be enhanced.

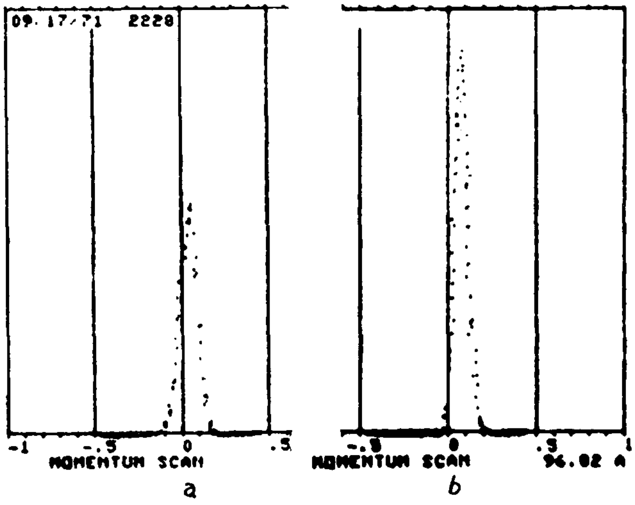

Fig. 11 200-MeV momentum spectrum at 20 mA showing effect of cavity #1 rf gradient.

a. Nominal gradient, buncher off.
b. Reduced gradient, buncher on.

It should, perhaps, be pointed out that the momentum spread and emittance data at the highest currents in this report were obtained with incomplete compensation of droop in a few of the cavity-rf gradients due to beam loading. Although sufficient rf power was available, the beam-derived feedback signals for a few rf systems had picked up sufficient noise to cause unstable operation at full feedback level. Hence, some droop was tolerated on these systems together with any deleterious effects on beam properties that may have resulted. It is believed, however, that the trend of increase in $\Delta p/p$ and emittance with beam current shown in Fig. 7 is valid.

The effect on 200-MeV emittance by slit reduction of emittance at 750 keV was tested briefly. Table II shows results of this experiment. The 200-MeV emittance is reduced in both planes by the slit, which collimated in the X-plane only. There is apparent X-Y coupling above 10 MeV.

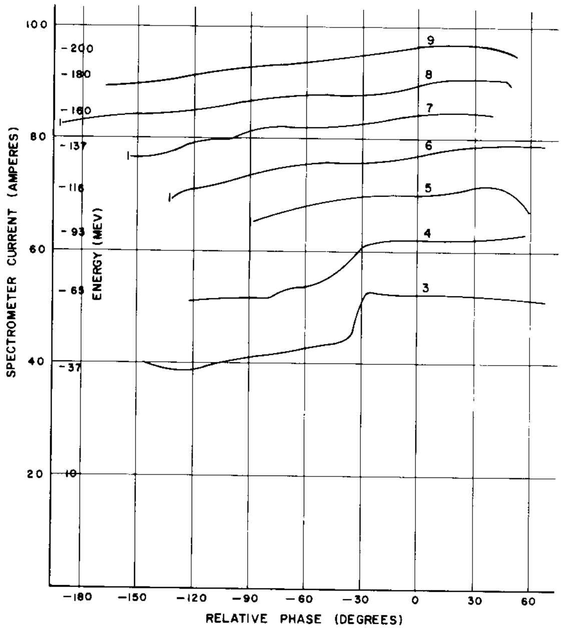

Fig. 12 Linac output energy variation. Number on each curve represents last operating cavity.

TABLE II

EFFECT OF 750-keV BEAM COLLIMATION

X-Slit	Beam Current	80% Emittance Area (mrad-cm) 10 MeV X	 Y	 200 MeV X	 Y
Out	22.9 mA	9.4	5.2	2.8	2.0
In	14.5	6.75	5.2	1.9	1.65

It is of some interest to see over what energy range the linac beam can be varied. This question arose in connection with potential use of the proton beam for radiation therapy during that part of each acceleration cycle of the main synchrotron when the linac is not needed as an injector. A method of energy variation, alternate to the use of absorbers, is shown in Fig. 12. In normal operation, the energy gain per cavity beyond the first is in the range of 17 to 29 MeV. Clearly, energy steps of this magnitude are possible by inhibiting or by shifting in time the rf pulse of each cavity, one at a time. Intermediate energies can be reached by shifting the rf phase of the last operating cavity, which results in synchrotron oscillation of the proton bunch about the synchronous energy and phase. Use of this technique of turning off cavities and phasing demonstrated that one can reach a continuous range of energy from the maximum down to at least 37 MeV. The number on each curve refers to the last cavity whose phase is being varied. The beam energy was always measured by drifting the beam through the unused cavities to the spectrometer in the 200-MeV diagnostic area.

Summary

Reliability of the linac operation as an injector has been about 95%. Beam emittance and momentum spread are within the design range at currents below 30 to 40 mA but increase slowly with beam current to somewhat larger than design values at 80 mA at the present time. Emittance growth through the linac is typically a factor of two, occurring principally between 750 keV and 10 MeV for low currents, but with significant growth between 10 MeV and 200 MeV for high currents. The brightest beams are the high-current beams. Coupling between transverse planes is indicated. Further study of the high-current beams is needed.

Acknowledgements

The authors wish to acknowledge all the NAL people who worked to construct the linac and bring it into operation, especially all the engineers, machinists, technicians and draftsmen of the old Linac Section. The beam measurements of this report were possible because of the valuable work, in particular, of Mr. G. M. Lee on mechanical design of the diagnostic equipment and of Mr. R. W. Goodwin on writing the computer programs.

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DISCUSSION

Swenson, LASL: Cy, you described the phase and amplitude control to be closed-loop through the computer. Could you amplify on that a bit?

Curtis: Well, there is a closed-loop hardware-loop. The loop through the computer is a very slow one. If there happens to be some drift, then the computer sets to work and brings the reading back within certain tolerance limits. It can run without it, but it has been a convenience, particularly in the early stages when our feedback loops weren't quite so good. This became a convenience and we still leave it in there.

Batchelor, BNL: Do you have a separate extractor electrode on your source?

Curtis: We have an extractor electrode in the Pierce geometry, but I'm not sure what you mean by separate. We have not been varying the voltage on that electrode for different beam currents, so running at something less than 250 mA, we are not truly in the Pierce geometry as far as having a parallel beam the way we are presently running.

Bohne, GSI Darmstadt: Can you give some figures about the loss in beam quality in terms of energy spread and time resolution in the case of the variable energy operation?

Curtis: I'm sorry I can't do that. I did all this in one afternoon and then the booster was ready to run again. I did drift the beam through the rest of the linac when I turned off the high energy tanks to put the beam through the spectrometer to determine the energy spectrum. The energy spread was increasing for certain tanks and decreasing for others. This does not mean that one could not, by phasing the individual tanks, narrow that energy spread down to some optimum value, but I did not do that.

Featherstone, Central Engineering Co.: Pursuing the matter of tube life, I have two questions: One is, I believe you are also using the 4616 tubes on which we have heard rather different results from two laboratories. We'd be interested in yours. The other question is, are you running your 7835's at reduced filament voltage?

Curtis: Let me answer the second one first. Yes, we are reducing the filament current. We are typically running at 6400 A in the filaments, whereas the nominal current is 6800 A. In the last tube to fail, we increased the filament current to 6800 A, which was as high as the power supply would go at that moment. All the other tubes failed by grid-to-cathode short. There have been no failures of 4616's. I should mention another tube, a rather important one, the switch tubes in the modulators, of which there are three in each system. We are using ITT tubes and some of us were surprised to learn the other day that there had been no failures.

Witkover, BNL: Regarding the growth in the energy spread with beam current and the emittance with beam current: First, did you use a slit in the energy spread measurements; and if not, was the growth in the energy spread corrected for the increase in the emittance?

Curtis: No. We did not use a slit and the growth in energy spread was not corrected for emittance of the beam, in the curve that I showed. If you apply a correction it does appear that the growth is still there. That correction is a difficult one but it is not too far above our initial design figure, operating without a debuncher.