EXPERIENCE GAINED FROM THE NEW U.S. LINEAR ACCELERATORS*

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Abstract

Three new proton linear accelerators in the U.S. are coming into operation. Several new features have been incorporated in these machines, the most important being the field stabilization by means of coupling mechanisms between cells. Initial performance of the machines agrees in general very well with the design calculations. Available data are presented but more measurements are needed for complete comparison with the theory. While results are encouraging, peak design performance has not yet been achieved.

1. Introduction

Three large proton linear accelerators have been under construction in the United States for several years and are now coming into operation. They are the 200 MeV injector linacs at the Brookhaven National Laboratory and the National Accelerator Laboratory and the 800 MeV meson factory, LAMPF at the Los Alamos Scientific Laboratory. The injector linacs are essentially complete. Their first full energy beams were achieved in November 1970 and they are now injecting regularly into their respective synchrotrons. LAMPF accelerated beam to 211 MeV in August of this year and is scheduled to achieve 800 MeV next July.

These machines represent a third generation of proton linacs in the United States and incorporate some completely new concepts as well as the latest general advances in accelerator technology. They have been extensively described in the literature[1-5]) nevertheless the major parameters are reproduced in Table I for reference. The similarity between the two injectors is not coincidental as both machines were built from the same basic drift tube table. In fact, throughout the design and construction there has been the closest cooperation between all three laboratories. Figures 1 and 2 show views of the linacs at BNL and NAL. Figures 3 and 4 show the drift tube and side coupled structures at LASL.

2. Preaccelerators

The three preaccelerators each consist of a duoplasmatron ion source, a Haefely Cockcroft-Walton generator of 800 keV rating, a high gradient accelerating column and a low energy beam transport line to the first tank of the linac. Some detailed data concerning these systems are contained in Tables II, III and IV. The considerable advances which have been made in sources and high gradient columns in recent years have been incorporated in these systems making possible substantial increases in peak and average currents.

While increases in current, and in stability and reliability have been large, the hoped for increases in beam brightness have not been as well realized. There is clear need for continued source development work particularly in the region of the plasma expansion cup.

The high gradient column at BNL[6]) uses an accelerating gradient in excess of 47 kV/cm when operating at a typical level of 780 kV. Breakdowns, inside or outside are rare and the required conditioning time after the column has been up to air is usually only a few minutes. This performance is attributed to the exclusive use of titanium for all interior metallic surfaces and to the clean high vacuum produced by the ion pumps. There is little indication of beam phase space dilution in the column. Generally similar performance has been observed at NAL[7]) and LASL[8]). At the present time, the BNL preaccelerator has not been able to reach full current (400 mA) for the full pulse length (200 μs) because of a pulse shortening phenomenon. Apparently at high currents, some beam from the source is intercepted on the early accelerating electrodes in sufficient quantity to seriously perturb the field distribution with a time constant which is characteristic of the bleeder resistor.

The importance of the low energy beam transport sections has been clearly demonstrated. It is not sufficient to have the proper emittance area at the linac but the emittance shape must be carefully matched in detail to the linac admittance in order to achieve the maximum intensity and beam quality. This observation is in agreement with the theoretical predictions[9]) and at BNL the transport system has, in fact, operated as the calculations had indicated. However, an adequate number of lenses for transverse control and a substantial amount of beam diagnostic equipment are required. To date, serious space charge effects have not been observed in the BNL system, but this may be due to the brightness being lower than expected.

The low energy transport system for LAMPF is necessarily more complex than those required for the injector linacs with one or two ion sources. The LAMPF injection system includes three ion sources, each with its own accelerating column and high voltage supply (750 kV). One ion source produces a 25 mA beam of protons in a transverse phase space ($A\beta\gamma$) of 1.5 π (.04) cm mrad with a 6% duty cycle. The other two ion sources will produce H^- beams, one of which will be unpolarized with a current of a few milliamperes, and the other will be polarized with a current of one microampere. The low-energy transport systems must guide the proton beam and one of the negative beams to the linac, and combine them for simultaneous acceleration to 800 MeV. The portion of the transport system required for the proton beam has been in operation

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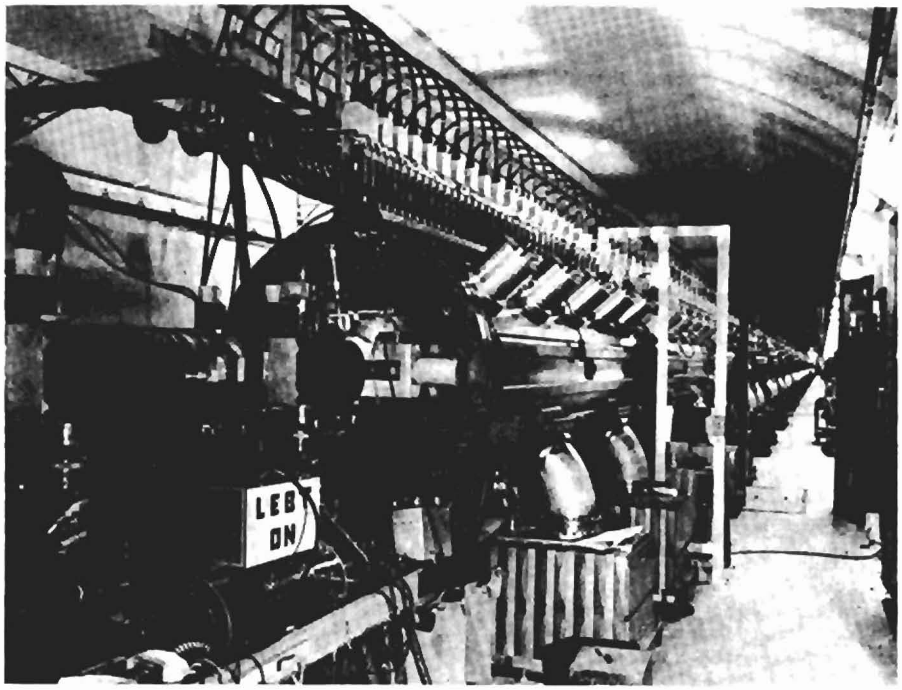

Fig. 1. The 200 MeV Proton Linac at Brookhaven National Laboratory View From the Low Energy End.

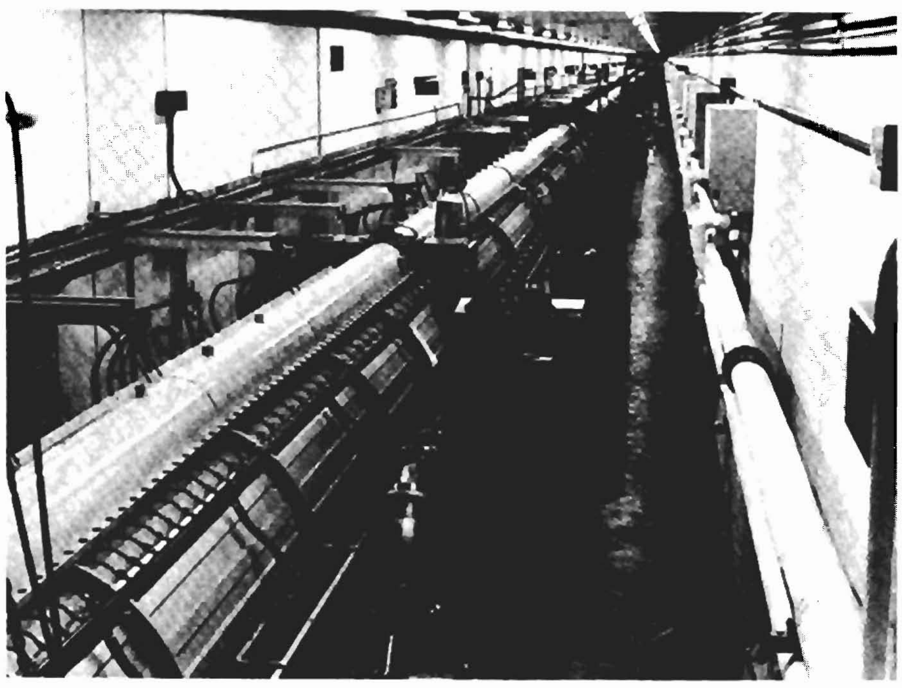

Fig. 2. The 200 MeV Proton Linac at National Accelerator Laboratory.

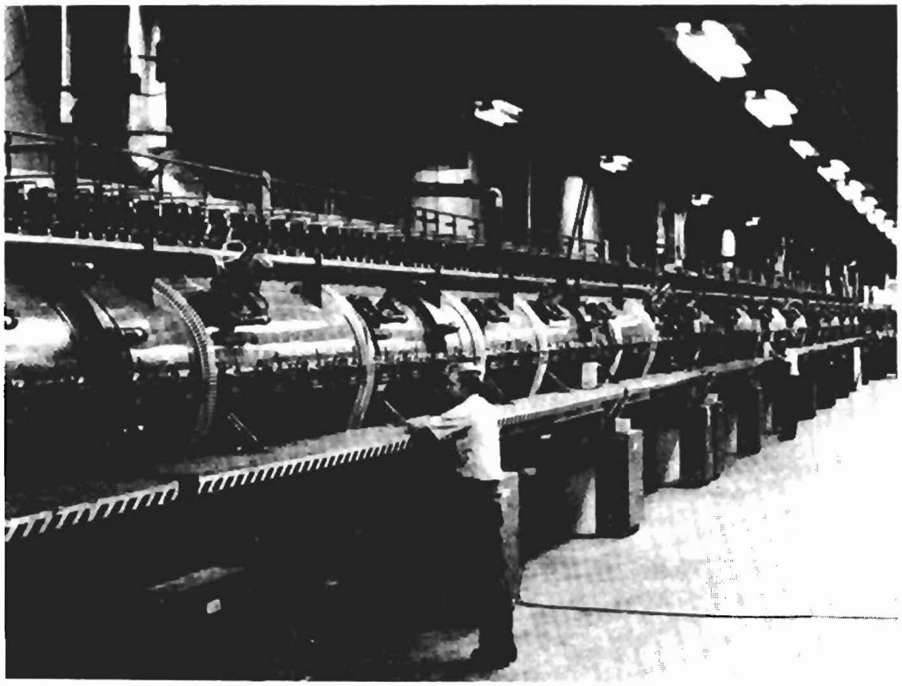

Fig. 3. The 100 MeV Drift Tube Linac at Los Alamos Scientific Laboratory.

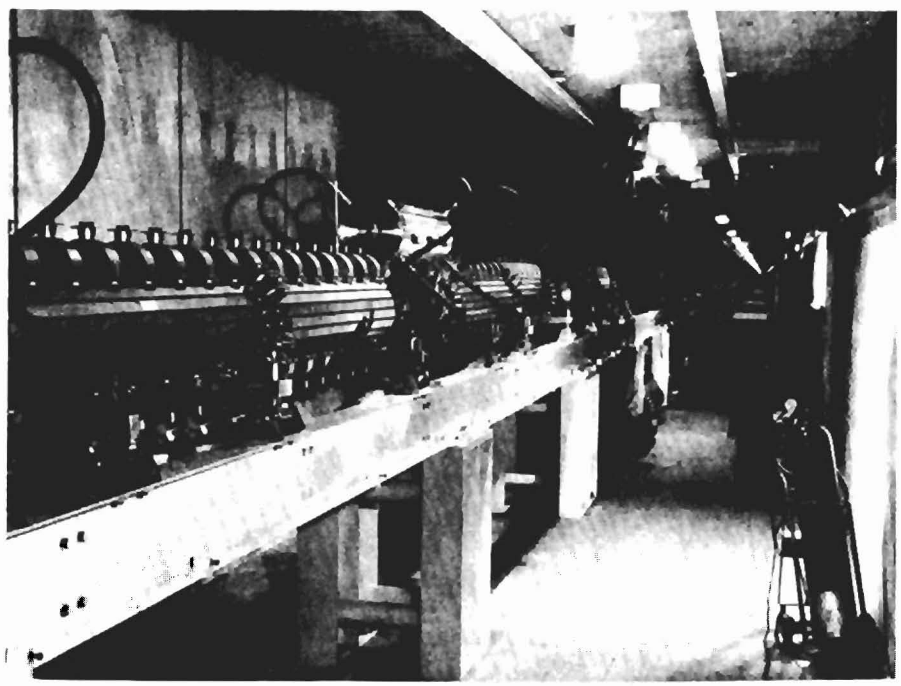

Fig. 4. A Section of the Side Coupled Linac at Los Alamos Scientific Laboratory.

TABLE I, MAJOR PARAMETERS OF THREE NEW PROTON LINACS

	BNL	NAL	LASL
Type of Service	Injector	Injector	Meson Factory
Final Energy (MeV)	200	200	800
Peak Current (mA)	100-(200)	100	17
Injection Energy (keV)	750	750	750
Beam Duty Cycle (%)	0.2	0.15	6-12
Beam Pulse Length (μs)	200	100	500-1000
Pulse Rate (pps)	10	15	120
Operating Frequency (MHz)	201.25	201.25	201.25 805.00
Length (m)	145	145	794
Structure	Multistem Drift Tube	Post Coupled Drift Tube	Post Coupled Drift Tube to 100 MeV then Side Coupled Cavity to 800 MeV
Number of Cavities	9	9	4 (Drift Tube) and 44 (Side Coupled)

TABLE II, PARAMETERS OF ION SOURCES

Machine	BNL	NAL	LASL
Cathode Type	Oxide	Oxide	Oxide
Cathode Power (W)	75	60	25
Cathode Life (h)	>3000	-	1000
Arc Current (A)	28	40	8-16
Arc Voltage (V)	120	230	100-180
Snout Voltage (V)	50	70	-
Max. Magn. Field (kG)	2.5	3.0	2.0
Snout Channel (dia. x length) (mm)	5x10	5x1.6*	4.5x11
Anode Aperture (mm)	1.2	1.3	0.62
Snout Anode Distance (mm)	8	13*	0.64
Plasma Expansion Cup (exit dia. x length) (mm)**	20x37	28x75†	14x9
Extraction Geometry	Pierce	Pierce	Pierce
Extraction Voltage (kV)	125	43	27
Operational Ion Current (mA) for ()mA linac beam	~300 (100)	~250 (100)	48 (17)
Proton Percentage (%)	75	85	75-80
Emittance (area x $\beta\gamma$ cm-mrad)††	1.2	0.8	0.25
Gas Pressure (Torr)	~.5	.15	.3
Gas Consumption (cm^3 atm/min)	>5	2.5	2
Pulse Length (μs)	100	20	500
Frequency (Hz)	10	15	120

* Unconventional snout design affects these dimensions
** Each cup has different inside geometries
† Biassed -50V cup wall
†† Measured at linac input and 90% of total beam

for more than a year. Space charge effects play a significant role in the beam dynamics of the system. It is necessary to evoke some neutralization of the space charge in order to get agreement between beam measurements and calculations. It is also believed that insertions of diagnostic probes into the beam can change the degree of neutralization of the beam both upstream and downstream from the probes. A positive bias (+100V) on the probes eliminates this effect in a satisfactory manner.

3. Cavity Performance

Perhaps the major recent advance in linac technology is the use of accelerating field stabilization techniques. The drift tube linacs, operating in the TM_0-mode, employ coupling circuits between the cells inside the cavity. At BNL, the multistem[10] system is used. Figure 5 shows the arrangement in Tank 3 at BNL. The NAL and LASL drift tube linacs use the tunable post couplers[11,12]. Figure 6 shows the arrangement inside Tanks 3 at LASL. Both methods were extensively modeled and calculated and in practice, both methods have worked exactly as predicted. The field stability is excellent and no multipactoring nor electrical breakdown problems have been encountered. There is, of course, some lowering of the Q in these cavities due to stabilization devices particularly the multistems. In the BNL linac, Qs of 50,000 are typical for the cavities which have an unloaded Q of about 80,000. The mechanical simplicity and lower losses of the post couplers recommend them strongly. The field distributions in the stabilized structures are so stiff that no modification of the field distribution can be made by tuning. Frequency tuning over a wide range can be accomplished with a single tuner without any effect on the flatness. In order to do the gross tuning and preliminary field smoothing it was necessary to work with the stems or posts removed. Final field flatness to about 1% was achieved throughout the three linacs.

At BNL, measurements are being made to observe the phase shift of the RF field along the length of the stabilized cavities, both with and without beam. In Tank 3 which is about 16 m long a maximum phase shift of about 3^o is observed from the center to either end without beam (the cavity is fed at the 1/4 and 3/4 points). Reliable measurements with the beam on have not yet been obtained.

The portions of LAMPF above 110 MeV utilize the side coupled linac structure [13] which was the first of the "stabilized" linac structures developed, and shows the same characteristics cited for the drift tube linac cavities above: that is, exceptional field stiffness, good beam loading response characteristics, and loose tolerance requirements. Operation of LAMPF at 211 MeV has demonstrated the soundness of this design. High power checkout of each of the 805 MHz tanks has shown field stability of better than ± 2% for average power dissipations ranging from 0 to 12% duty.

4. Beam Performance

All three linacs have been brought into operation with a minimum of confusion. When RF amplitudes and phases and quadrupole gradients have been set to the computed values, the accelerated beam has been detected almost at once. The performance of the first tank of each machine has been covered else-

Fig. 5. The Interior of Cavity #3 of the BNL Linac, Showing the Multistem Arrangement.

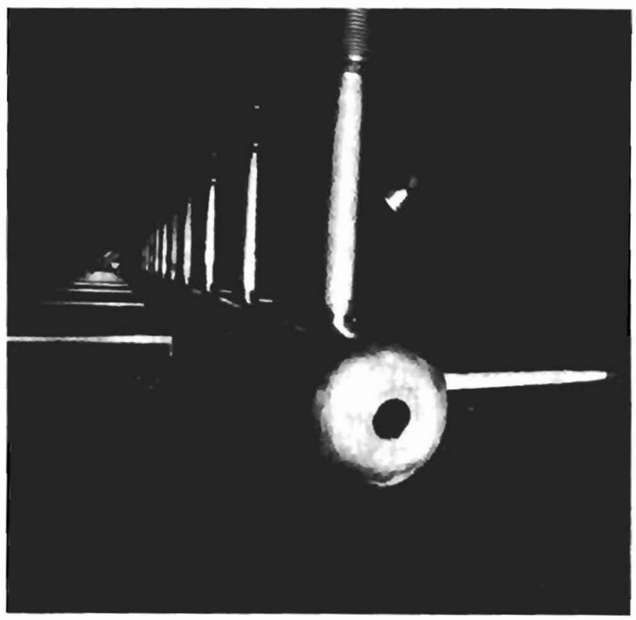

Fig. 6. The Interior of Cavity #3 of LAMPF Showing the Post Couplers in Place.

TABLE III, MAIN CHARACTERISTICS OF 750 kV HIGH GRADIENT ACCELERATING COLUMNS

Machine	BNL	NAL	LASL
Insulation Material/Pressure	Air/1 Atm.	SF_6/2.1 Atm.	SF_6/1.3 Atm.
Outer Envelope Height (cm)	120	182	306
Outer Envelope Diam. (Ø cm)	63	112	122
Gradient on Envelope (kV/cm)	6.5	4.1	2.5
Accelerating Distance (cm)	16.5	30	31
Mean Accelerating Gradient (kV/cm)	47	25	25
Number of Internal Gaps	6	8	10
Beam Hole Vac. Electrode (Ø cm)	2.5/3.5	2.8	1.4/2.0
Material Vac. Electrode	Ti	Ti	Ti
Inner Tube Height (cm)	120	51	56
Inner Tube Diameter (Ø cm)	63	51	38
Number of Sections	18	8	16
Section Height (cm)	6.4	2.5	3.2
Section Voltage (kV)	42	100	54
Mean Gradient 1 sect. (kV/cm)	6.5	40	17
Assembling Technique	Cold Epoxy + Indium O-rings. Modules	Vinyl Acetate	Polycarbonate in oven
d.c. Divider	Carbon resistance in epoxy	Water resistor	RPC carbon film resistor
d.c. Divider - drain (μA)	140	1500	1080
Pumps ℓ/s (ionic for air)	2x2000	1x2200	2x1200
Pressure with source on (Torr)	1×10^{-5}	1×10^{-5}	2×10^{-5}
X-rays with beam at 4 m (mR/h)	<50	<10	10
Generator (kHz)	8	8	5
Voltage Stability	$<5.10^{-4}$	-	10^{-4}
Maximum Accelerated Beam (mA)	500	320	53
Operational Accelerated Beam (mA)	300	250	48
Operational Pulse Length (μs)	100	20	500

where[4,7,14]. Nevertheless, a typical example of the excellent agreement which can be obtained between calculated and observed performance is shown in Fig. 7 for the 5 MeV section of the LASL machine. In this figure, energy spread at 5 MeV is shown as a function of cavity excitation level with the bunchers off. At BNL, a current of 210 mA was accelerated to 10 MeV and it appears that only lack of RF power prevents the acceleration of 200 mA to 200 MeV. Also at BNL, 18 mA of deuterons were accelerated to 5 MeV and acceleration of deuterons to 100 MeV will be attempted.

Both at NAL and BNL, currents up to about 100 mA have been accelerated to 200 MeV but data are available only at lower currents. Deliberate efforts have been made to do all preliminary tune up and running at low currents, short pulse lengths and slow repetition rates in order to minimize induced radioactivity. A few short runs have been made at BNL using about 50 μA average proton current and the activation in the beam stop area was extremely severe.

The method used for setting up the linac at NAL is generally typical for the three machines. For each successive cavity, the accelerated beam current is observed as a function of cavity phase and RF amplitude. Comparison of these plots with the calculated values yields quite closely the proper settings for the phase and amplitude. Agreement in the lower energy cavities is excellent but some smearing of the data are observed for the higher energy cavities. With the beam set up in this manner, the momentum spread is measured by a magnetic spectrometer in the high energy beam transport line. The momentum spread may then be minimized by proper adjustment of the phase of cavity 9[15]. In practice, both beam energy and momentum spread are adjusted by varying the phases of two cavities, usually the last two, (for the injectors, the exact value of output energy is not important). This method is simply an adjustment of the phase oscillations in the linac so as to pick the minimum momentum spread point on the last oscillation. Values of $\Delta p/p = 0.2\%$ have been achieved for a beam of about 30 mA.

TABLE IV, LOW ENERGY BEAM TRANSPORT SYSTEMS

Machine	BNL	NAL	LASL
Number of Channels	1	1	2
Length (m)	7.5	3.5	12.5
Mode, Number of Periods (+-+-)	8	3	5
No. of bending magnets (aperture cm)	0	0	4 (5)
No. of quadruplets (aperture ∅ cm) (length cm)	1 (4) (10,10,10,10)	0	2 (7.5) (15,15,15,15)
No. of triplets (aperture ∅ cm) (length cm)	7 (7.5) (8.75,17.5,8.75)	3 (8) (12,24,12)	2 (7.5) (15,30,15)
No. of doublets (aperture ∅ cm) (length cm)	0	0	2 (5) (10,10)
Peak magnetic gradients (kG/cm)	.68	.7	1.0
Pulsed or d.c.	Pulsed	d.c.	d.c.
Sets of Steering Magnets	2	0	5
No. of bunchers (MHz)	2 (201)	1 (201)	1 (201)
No. of Pumps (speed ℓ/s)	1 (2000)	0	6 (200)
Pressure (Torr)	$2x10^{-7}$	$4x10^{-6}$	$2x10^{-7}$
Aperture/beam ratio	2	2	2 (doublet) 3 (others)
Monitoring:			
No. of beam transformers	6	4	6
Sets of emittance scanners	2	2	3 + 2
No. of position monitors	0	0	3
Beam Transmission (mA)	280	280	32
Emittance growth in transport line	10-20%	none	0.5 cm mrad

Emittance probes of the type used at low energies are not practical at 200 MeV so values are determined from beam profiles measured by wire scanners at three (or more) points in the transport system beyond the linac. From these profiles, the emittance may be reconstructed by the computer[16]. At 15 mA, NAL observes emittance areas from 0.4π to 1.3π cm-mrad for 90% of the beam as compared to the design goal of 0.5π to π cm-mrad for 100 mA. A typical emittance plot as produced by the NAL computer is shown in Fig. 8. At BNL, for currents of 20 and 35 mA, emittances of 0.6π and 0.8π cm-mrad containing 90% of the beam have been observed. A value of ΔE = 600 keV at 200 MeV is associated with these values. Based on the observed emittance at 10 MeV, these figures indicate that there is no further emittance blow up in the accelerator beyond 10 MeV, as has been predicted. On the other hand, the brightness is still below the design value, which calls for 100 mA in 1.0π cm-mrad. It is felt that this is largely due to imperfect phase space matching of the beam into the linac[17].

5. Summary

In general, the initial performance of these linacs has been very gratifying. The experience to date can be summarized as follows:

1. The measured performance agrees very well in general with the design calculations indicating that the calculations are realistic and reliable and that the machines have been built to closely approach the design figures. There have been substantial improvements in preaccelerators and in phase space matching techniques which have resulted in less dilution of the beam from the preaccelerator through the first cavity. Although the data are still sparse, it is indicated that there is no phase space dilution from 10 MeV to 200 MeV at least for modest currents.
2. Space charge effects in these beams have not yet been investigated in any detail. There has been very little operation at high currents and there is essentially no data to compare with the predictions. Confirmation of these predictions will have to await further operations.
3. The stability of the beams both during a pulse and from pulse to pulse is much greater than in earlier machines. This feature was strongly considered in the designs and it is encouraging that it has been achieved.
4. Although the final level of design performance has not yet been reached, there appears to be no fundamental reason why these linacs should not meet or exceed their design specifications.
5. Extensive and sophisticated diagnostic equipment is essential to optimize the performance and it appears that these machines have no more than the minimum needed.
6. Also essential for optimized operation is computerized control and surveillance of the linac.

Acknowledgements

It is impossible to acknowledge individually all those who have contributed to the design and construction of these machines. However, I am particularly indebted to the following people who contributed specifically to the preparation of this report: K. Batchelor, J. Sheehan, and Th. J.M. Sluyters from BNL, C. Curtis, P. Livdahl and D.Young from NAL and D. Swenson and E. Knapp from LASL.

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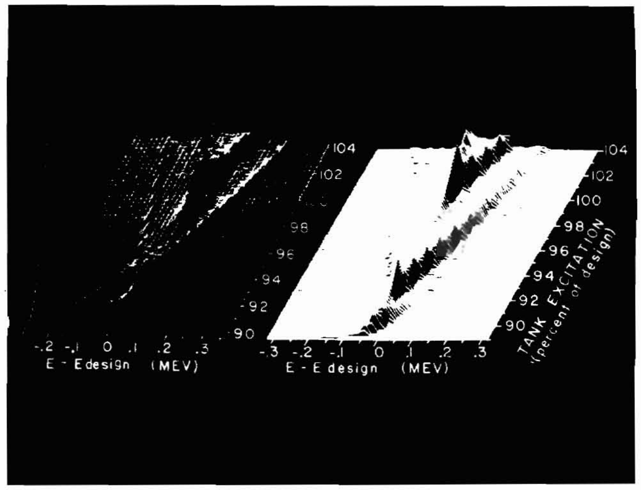

Fig. 7. Calculated and Measured Energy Spread at 5 MeV as a Function of the Cavity Excitation for the LASL Linac. Calculated Spectrum on the Right.

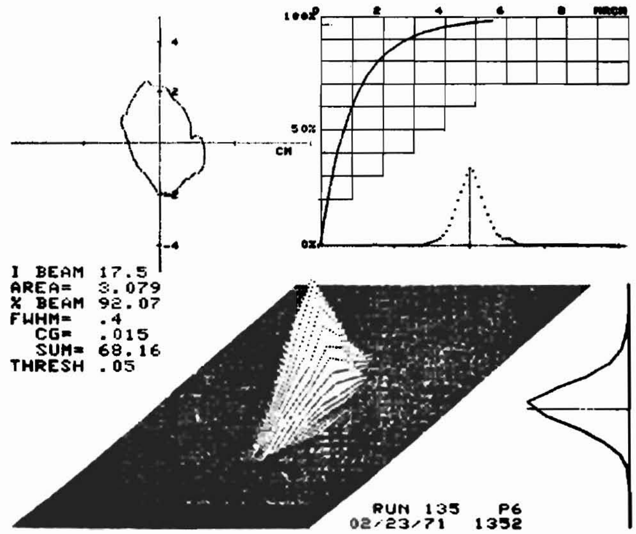

Fig. 8. A 200 MeV Emittance Plot Measured on the NAL Linac and Produced by the Computer.

DISCUSSION

L. SMITH: In the LASL accelerator, is there a difficulty in the transition from 200 to 800 MHz?

G. W. WHEELER: The matching section is not yet installed, and no measurements have yet been made. Perhaps Swenson could comment.

D. SWENSON: We have no indications of problems resulting from the frequency shift by a factor of four at 100 MeV. The longitudinal phase space will be tight at that point, and will require careful tuning of both the drift-tube linac and the side-coupled linac to achieve 100% capture in the latter accelerator. Our 5-MeV measurements suggest strongly that our calculations are valid, and our calculations demonstrate a suitable match.

E. F. PARKER: What specific steps are being taken at BNL to improve source brightness?

G. W. WHEELER: We are starting to set up a program and hope to develop more plans from the forthcoming Ion Source Conference at BNL.

C. D. CURTIS: With respect to the NAL emittance values at 200 MeV, which you quoted, more recent measurements indicate a value of about 1.2 π mrad-cm for 90% of the beam at 55 mA. However, we have not yet optimized the match into the linac for this current. More work remains to be done.

P. M. LAPOSTOLLE: Could you comment about the choice of pre-injection energy?

G. W. WHEELER: I believe that all three laboratories are quite satisfied with the injection performance at 750 keV. The drift-tube structures operate quite satisfactorily at this energy. The required matching is somewhat easier at 750 keV than at a higher energy and we believe that space-charge blow up in the transport line can be controlled at 750 keV. In addition, the loss of longitudinal damping at higher energies could be troublesome, particularly for LAMPF.

D. SWENSON: The injection energy of 750 keV seems quite satisfactory for such linacs. The damping of the phase coordinate, which is important for LASL, would be reduced by injection at higher energies. The new batch of linacs have been designed with a low gradient ($\sim$ 1 mV/m) for the first few MeV, and run reliably without breakdown.

T. NISHIKAWA: In Brookhaven, you have a quite flexible matching section between the pre-injector and the linac tank. Can you tell me how you can find the matching condition practically?

G. W. WHEELER: The actual emittance at the base of the column is measured in both planes. These emittances are then used in the six-dimensional program with space charge (of R. Chasman) to calculate the proper quadrupole setting to produce the match. The emittances at the entrance of the linac are then checked by direct measurement. The fields in the first few quadrupoles of tank 1 are slightly modified to produce the match in the centre of drift tube 3.

S. SUWA: Are the figures which you gave normalized emittance or just area?

G. W. WHEELER: They are not normalized.