THE LIVERMORE MTA PROJECT AND ITS INFLUENCE ON MODERN LINACS

Philip V. Livdahl
Fermi National Accelerator Laboratory
P. O. Box 500
Batavia, Illinois 60510

In the early 1950's a series of linear accelerators were built at Livermore, California which constituted part of the Material Testing Accelerator (MTA) Program. These linear accelerators, and subsequent development activities which derived therefrom, will be discussed.

Introduction

In the late 1940's a program was initiated by Professor Ernest O. Lawrence and the University of California Radiation Laboratory (now known as the Lawrence Berkeley Laboratory) and the United States Atomic Energy Commission to investigate the possibilities of electronuclear breeding of Pu^{239}, U^{233} and Tritium by irradiation of depleted uranium with accelerator-produced neutrons. A summary of the objectives of the entire program was written by C. M. Van Atta in 1977.[1] A major component of the program was research and development of high current accelerators.

Since the program objectives were classified at the time of inception (declassified in 1957), as well as a production process being a goal, a site apart from the University of California, and an industrial partner were sought. The site selected was a World War II Naval Reserve Training Station at Livermore, California (this site is now known as the Lawrence Livermore National Laboratory). The Standard Oil Company of California formed a subsidiary called the California Research and Development Corporation (CR&D) to be the industrial partner.

The role of CR&D was to produce the engineering designs for the accelerators as well as the supporting facilities, and to construct and operate the MTA accelerators.

The MTA program was terminated in the mid 1950's with the discovery of what was then regarded as ample uranium deposits to meet the needs of the nuclear program. Thus the role for CR&D came to an end and the Corporation was disbanded.

The combination of the demise of the corporation, with the consequent dispersal of much of the staff, as well as the long delay in declassification of the corporation reports, etc., have conspired to keep much of this program from coming to the attention of any large section of the linear accelerator designers.

These factors have made the documented characteristics and performance of the prototype accelerators built during this program sketchy at best. This paper must therefore be viewed as a compilation of data available from the few actual reports I have and my recollections relative to the project.

I worked as an accelerator physicist on the prototype accelerators of the MTA program. In the course of design and construction of subsequent linacs I have discussed some of the features of the MTA machines with other linear accelerator specialists. Such discussions, coupled with a curiosity about the MTA accelerators, have motivated the Program Committee for this conference to invite me to prepare this paper.

To achieve the ultimate electronuclear breeding capability it was realized that the deuteron energy would need to be in the range of 350 MeV with average beam currents of at least tenths of an ampere. Since these requirements were far beyond any previous experience, it was determined that the Mark I accelerator would be constructed to investigate high current ion production at lower energies. Thus Mark I was a prototype for a much larger facility which was concurrently being planned for construction at Weldon Springs, Missouri.[2]

MTA Linear Accelerators

There were a series of linear accelerators built and tested during the MTA program. This section of this paper will record the characteristics and performance of the prototypes, and how the prototype experience influenced future linacs.

MTA Preaccelerator

The limitation imposed by available high-voltage, high-current, dc power supply technology determined many of the characteristics of the preaccelerator. The development of the ion source and pre-accelerator has been described in the technical literature by Lamb and Lofgren.[3] Figure 1 is a drawing of the Mark I preaccelerator.

Parameters for operation of the ion injector at the largest dc beam currents of protons that were maintained over periods of hours, are shown in Table 1. Maximum deuteron beam obtained was about 10% smaller. Much larger beam intensities were achieved for short periods of time.

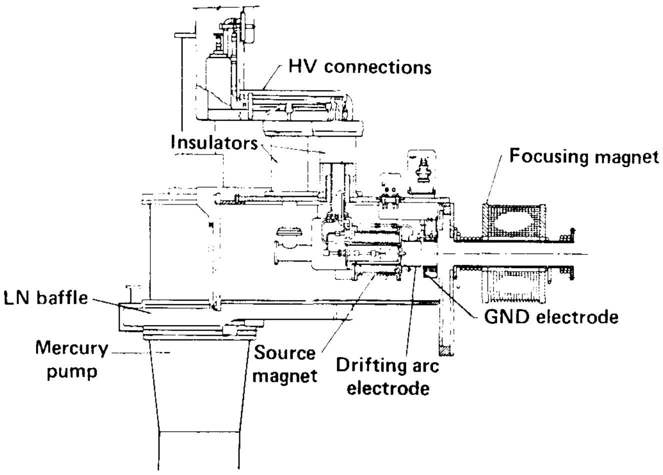

Fig. 1. The Mark I pre-Accelerator.

The Mark I pre injector was common to each of the MTA linear accelerators.

Its operation and continued development lead to: a) the development of more reliable and better regulated high voltage dc power supplies; b) a more complete understanding of the behavior of electrical discharges in vacuum; c) a realization that very high currents of ion beams can be achieved reliably and with ion beam characteristics that would be useful for not only the MTA program but for future generations of accelerators and plasma devices as well.

Mark I Accelerator

The first linear accelerator built as a part of the MTA program was called the Mark I accelerator. The design criteria for this accelerator were determined from what was deemed at that time to be practical from the point of view of the state of the art of existing hardware and technology.

The only linear accelerator which had previously been built was the 32 MeV linac built at UCRL in Berkeley by Luis Alvarez.[4] The accelerating cavity of that machine resonated at 200 MHz and the rf excitation power was supplied by surplus World War II radar transmitters. The tubes for these transmitters were unreliable and were severely limited by average power and duty cycle ratings.

Another 200 MHz, 68 MeV linac was concurrently being built at the University of Minnesota.[5] Its construction was started in 1949 but completion was substantially delayed by difficulties in the development of a suitable rf power source. Before the "resonatrons" for this machine were available the first cavity (10 MeV) was operated with "Frank" oscillators.

The Radio Corporation of America (RCA), had by the late 1940's produced prototype triodes for CW operation in the range of kW of rf power output per tube with an upper frequency limit of 12 MHz. Figure 2 is a photograph of the RCA 5831, which was commonly - but not necessarily endearingly - called the "bucket-of-bolts," due to its method of construction. The anticipated availability of those tubes determined the operating frequency - 12 MHz. This, together with the desired output energy - 15 MeV protons - determined the design dimensions of the cavity.

The Mark I linac cavity was a single resonant structure, 60' in diameter and 60' long, containing 8 full drift tubes, with 1 half drift tube at the low energy end of the cavity. Magnetic focusing was provided which was produced by solenoidal magnets housed in each drift tube. The shell of the resonant cavity was constructed of a water-cooled copper liner which was housed in a vacuum enclosure made of welded and reinforced 1/2" thick steel plate. Figure 3 is a photograph of the vacuum tank for Mark I with the building being constructed around it.

Figure 4 is a photograph of the inside of the Mark I accelerating cavity and Figure 5 is a cross sectional drawing of the Mark I accelerator.[6]

	Continuous Operation No Grid	Pulsed Operation Ground Electrode Grid Used
Beam current	3/4 A at 100 kV	~2.0 A at 100 kV
Beam diameter	3/4 A at 100 kV	~2.0 A at 100 kV
	70 in. from the source	20 in. from the source
Beam divergence, 1/2 angle	<5°	~10°
Accelerating power supply current	1.1 A	~ 10°
Arc chamber hydrogen pressure	50 μ	20 μ
Arc voltage	35 V	150 V
Arc current	80 A	125 A
Source magnet	3200 gauss	6000 gauss
Ground electrode magnet	200 gauss	800 gauss
Focusing magnet	3000 gauss	None
Vacuum tank pressure	2×10^{-5} mm Hg	2×10^{-5} mm Hg

Table 1

Proton performance of the MTA preaccelerator.

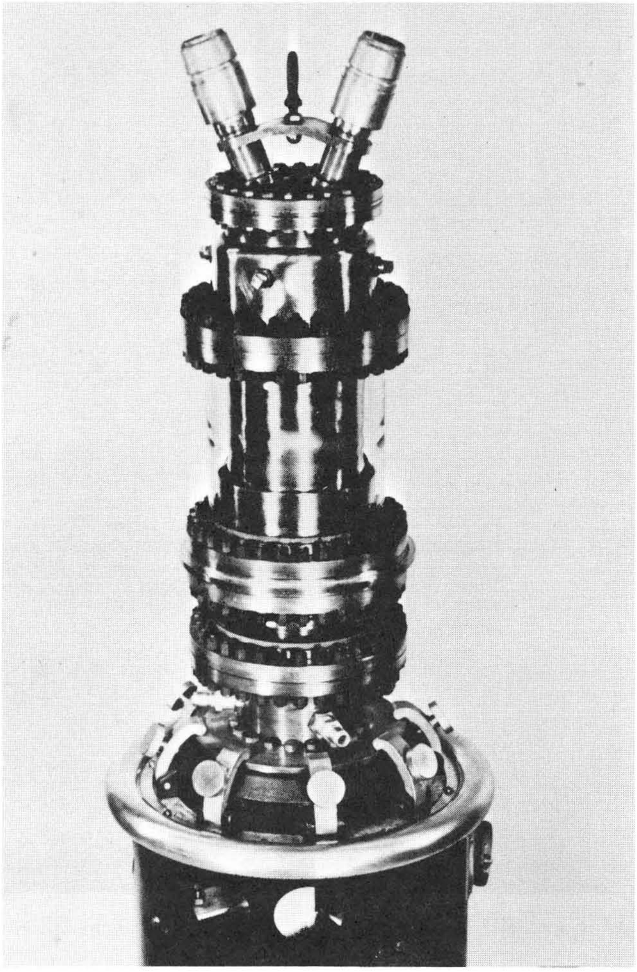

Fig. 2. RCA tube type 5831. (Photo courtesy of RCA.)

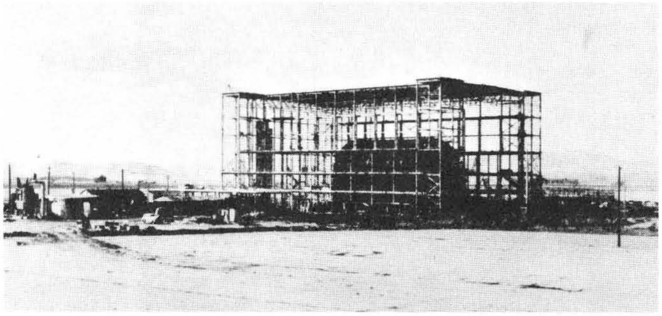

Fig. 3. Mark I vacuum tank with the building being erected around it.

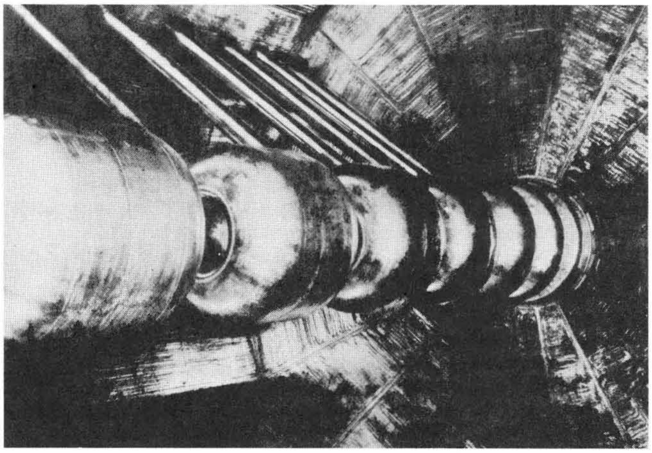

Fig. 4. Mark I drift tubes.

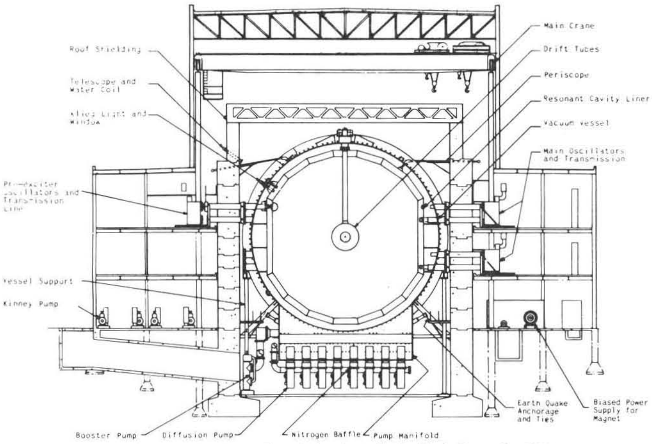

Fig. 5. Cross sectional drawing of the Mark I accelerator.

Table 2

Mark I Accelerator Characteristics

Proton Injection Energy	80 KeV
Proton Exit Energy	15 MeV
Frequency	12 MHz
Cavity Length	60 feet
Cavity Diameter	60 feet
No. of accelerator cells	8-1/2
G/ℓ	0.25
Synch. Phase Angle	-74^{o}
Proton End-to-End Voltage (Peak)	22.5 Mv
Average Gap Gradient (Peak Volts)	1.5 Mv/ft

RF System - 18 oscillators, 0.5 Mw ea
tube type 5831

Vacuum System - Mercury Diffusion Pumps
48 - 32" Diameter
Liquid N_2 Baffles on each

Roughing System - 1500 CFM Kinney Pumps
- 54 each
- with Liquid N_2 Traps

Operation of Mark I was terminated in late 1952 after having accelerated protons to about 15 MeV for short periods of time. Peak currents as high as 225 mA of protons were achieved at a duty cycle of more than 20% and 100 mA were accelerated in a CW operating mode.

Mark I had revealed that the operating gradient required for the acceleration of deuterons, at least a frequency of 12 MHz, was much too high and that sparking in the first accelerating gaps, with such large stored energy in the cavity, so badly damaged the surfaces of the low energy end drift tubes that operation could only be sustained - even for proton acceleration - for short periods of time.

This experience initiated an expanded program of development effort to a) develop rf amplifier tubes with a higher frequency limit; b) develop a research program to understand sparking phenomena and to determine practical limits for operational accelerating gradients; c) develop new vacuum techniques, such as linear jet diffusion pumps, low-temperature refrigeration systems to replace the liquid nitrogen requiremnt for mercury pumps, and investigate electronic ion pumps; and d) develop accelerating geometries to circumvent the low-energy accelerating gap voltage holding problems.

RCA had by this time developed a triode which had a ceramic cylinder vacuum enclosure in which all vacuum seals are welded, or brazed. They had further developed the shielded grid concept for large power amplifier tubes. These factors lead to the successful completion of the 2332D which were capable of delivering 600 kW cw at 50 MHz.[7] Figure 6 is a photograph of this tube. This development ultimately resulted in the 7835 which has commonly been used for U.S. linacs at 200 MHz.

At Berkeley a group started a research program to investigate rf sparking phenomena. Although no complete theory was evolved which explained the influence of all of the parameters such as, gap length, pressure, presence of contaminants, surface condition, surface material, stored energy, frequency, etc., a criterion, thereafter called the Kilpatrick criteron, was identified which quite accurately defined a threshold for sparking with rf or dc voltages.[8] This criterion relates the energy, W, which can be gained by an ion crossing a gap with the cathode gradient E. This empirical relationship can be expressed as:

$$WI_o = WE^2 e^{-\frac{1.7 \times 10^5}{E}} = 1.8 \times 10^{14} \frac{V^3}{CM^2}$$

where I_o, the current in the gap is expressed by $IE^2 e^{-b/E}$. This relationship was plotted relative to the experimental data recorded at that time as shown in Fig. 7.

Beyond this investigation there have been later efforts at MURA[9] and subsequently at CERN[10] to develop a more substantial physics basis for vacuum sparking. These efforts have offered a better understanding of the phenomena but the criterion postulated by Kilpatrick still serves as

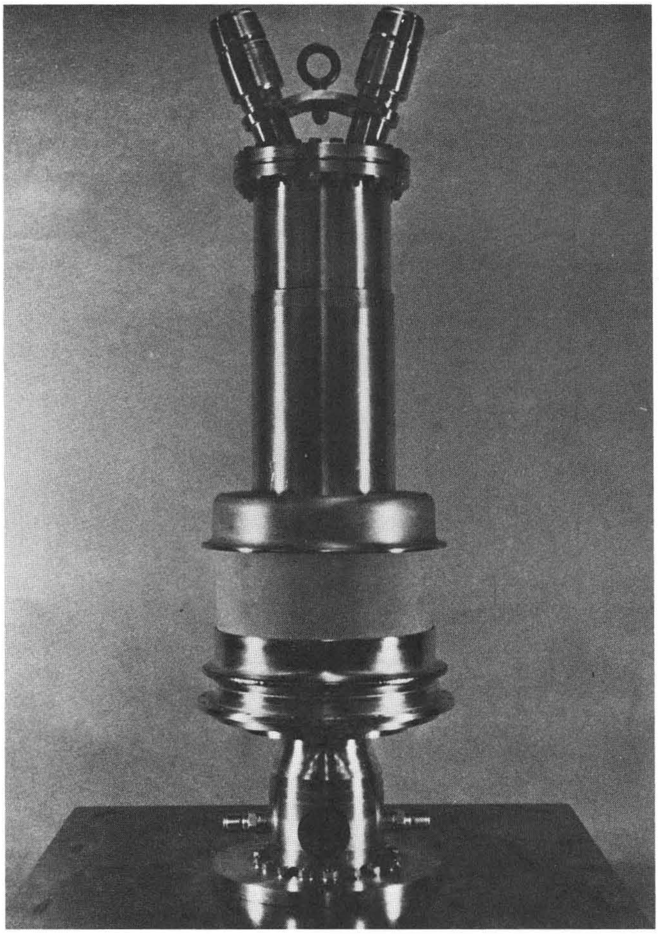

Fig. 6. RCA triode type 2332D (Photo courtesy of RCA.)

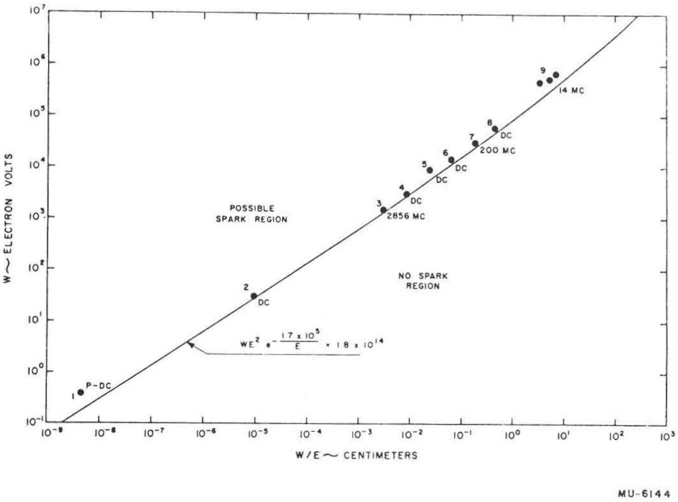

Fig. 7. Kilpatrick criterion as plotted in UCRL Report 2321.

the most reliable guide to be used in designing linac cavities although with modern day vacuum techniques the criterion has proven to be very conservative.

Vacuum technology advanced rapidly, at least in part motivated by the Mark I experience. Linear jet mercury diffusion pumps were built which produced pumping speeds that were limited only by the conductance into the pump and the length which one wished to build them. Experiments with electronic pumping systems, however, were so encouraging that further work on the mercury diffusion pump technique was not continued.

Electronic pumps were built and tested which used hot cathodes and ion source techniques to produce electrical discharges in solenoidal magnet fields. These pumps produce vacuum by ionization of the residual gas with gettering and ion burial in the cathode potential electrodes. Testing of these pumps revealed that the pumping continued after turning off the filament current of the source and the magnetic field current. The pumps consumed large amounts of power, therefore work continued on cold cathode pumps. Concurrent commercial development now makes later generation pumps available as catalogue items.

Low temperature refrigerators (-350°F) were developed to eliminate the need for liquid nitrogen for diffusion pump baffles. These refrigerators were utilized on later prototype linear accelerators of the MTA program.

Theoretical work was initiated to generate more reliable means for calculating rf fields in cavities and to calculate particle trajectories in the accelerating and focusing fields of the cavity. This work was enhanced greatly by the advent of new digital computing systems which were just becoming available.

Since sparking in the low energy gaps of Mark I was the most serious problem, two parallel efforts to circumvent the problem were built to serve as alternative pre-accelerators for the next prototype. One effort was the construction of a low gradient, 2βλ Alverez type accelerating cavity. The other was to develop a 3/2 βλ geometry consisting of two separate 3/4 wave length transmission line cavities.

A-54 Accelerator

The A-54 accelerator, completed and put into operation in 1954, consisted of the ion injector operating at 100 kV and an Alvarez cavity about 12 feet in diameter and 20 feet in length. In order to provide enough room to house solenoidal focusing magnets the drift tube configuration was designed to operate in the 2 βλ mode. The cavity was constructed of copper-clad steel and contained 22 drift tubes with 3-in-diameter bore throughout. The resonant frequency was 48.6 MHz. The cavity was energized by six RCA 2332 amplifier tubes each delivering 400 kW of continuous rf power. The amplifier could be driven either by a master oscillator or by a feed-back signal from the cavity. Proton output energy was about 500 keV, and the operating efficiency over an 8-hour shift was 97% with 220 mA output current. About half the continuously injected beam was accelerated to full energy. The highest rf gradient consistently maintained was 10% above deuteron gradient; however, deuteron acceleration was not possible because the injector power supply could not provide the 200 kV required for injection.

Quarter Wave Accelerators

Concurrently with A-54 operation a quarter-wave stem accelerator as shown in Fig. 8 was built and tested.[11] Each of the two resonators consisted of a drift tube mounted on a stem which was the center conductor of an open-ended 3/4 λ transmission line, adjusted to oscillate at 24.3 MHz. To provide room for solenoidal focusing magnets the accelerating gaps were spaced at 3/2 βλ. The two resonators were excited independently, each by an RCA 2332 amplifier tube. Both amplifiers were driven from a common rf source with a variable delay line to adjust the phase between the cavities. Both cavities were tuned to the driving frequency by servo-controlled, variable capacity tuners mounted directly below the drift tubes. The continuous beam from the injector was bunched at the accelerator frequency and adjusted in phase for maximum acceptance at the first accelerator gap. In addition to the drift-tube magnets, solenoidal magnets were located between the buncher and the first accelerating gap, between the two cavities and at the output end of the second accelerating section. An average axial magnetic field strength up to 10 kG could be maintained along the beam path. This field strength proved to be adequate to prevent significant radial beam losses for both proton and deuteron acceleration. The quarter-wave accelerator was capable of accelerating 300 mA of protons to 500 KeV with the injector operating at 87 kV and 0.5 A. Deuteron acceleration again was limited due to the voltage limitation of the injector power supply.

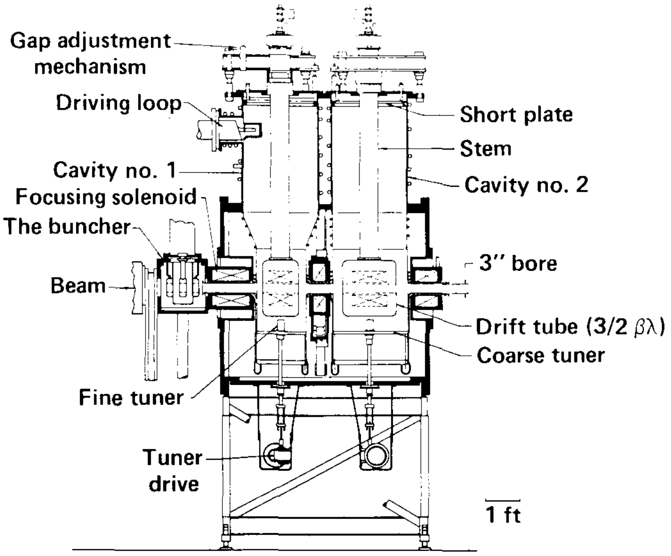

Fig. 8. Quarter-wave stem Pre-accelerator for the A-48 accelerator.

A-48 Accelerator

The A-48 accelerator[12] consisted of the quarter-wave accelerator described above followed by two Alvarez-type cavities each about 12 feet in diameter and 20 feet in length which were resonant at 48.6 MHz (see Fig. 9). The drift tube configuration was designed to operate in the $1\ \beta\lambda$ mode with solenoidal magnets in the drift tubes. The required injection energy was matched to the output of the quarter-wave accelerator. The output energy was 3.75 MeV for protons and 7.5 MeV for deuterons. Since the quarter-wave accelerator operated at half the frequency of the Alvarez cavities, the beam was bunched into every other accelerating gap. The design rf gradient was slightly less than 1 MV/m for deuterons, which was easily maintained. At half this gradient proton beam currents in excess of 100 mA cw were accelerated. Deuteron currents were limited to 30 mA by two factors: the voltage limit on the injector power supply and by activation and damage to the target by 7.5 MeV deuterons. At this time in the program (1955) the funding for MTA accelerator development was eliminated and the program was stopped, the cavities were disassembled and the building space was utilized for fusion research.

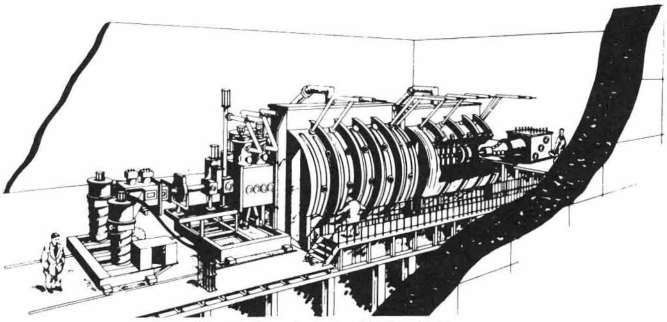

Figure 9 Perspective drawing of A-48 accelerator.

Conclusion

The MTA accelerators played an important role in stimulating research and development work in many important areas of technology. It was a project which has been characterized as being 40 years before its time. In my view it was a remarkable effort which required an extraordinary amount of courage and determination. These qualities were characteristic of Ernest O. Lawrence and his colleagues at that time. Certainly for those persons directly involved in the project it provided a great deal of excitement and experiences which we will never forget.

Perhaps as impressive as all of the technical advances was the speed with which these accelerators were built. Construction of Mark I began in early 1950. Testing started in mid 1951 and continued through 1952. In the next two years the $1/4\ \lambda$ accelerator as well as A54 were built and tested. These machines were then rearranged and modified to become A48 which was tested and used for physics research by mid 1956 when the program was stopped.

To achieve these goals required the courageous and visionary leadership of persons like Lawrence and Van Atta as well as a willingness on the part of the government to pursue projects which are considered to be a gamble. Does this same level of leadership and adventurous spirit continue today?

The project spurred high intensity investigations of ion sources, pre-accelerators, magnet focusing systems, rf power sources, accelerator cavity design, power supplies and vacuum components. All of these have played an important part in bringing technology to the state of development that accelerators enjoy today.

Acknowledgements

After thirty years it is impossible to credit all of those persons who worked on the project but I want to particularly thank Dr. C. M. Van Atta, who is now retired from the Lawrence Livermore National Laboratory, and Dr. John Frazier of Chalk River Laboratory in Canada who were of great help in finding reference material.

References

1. C.M. Van Atta, A Brief History of the MTA Project UCRL-79151, Jan 31, 1977.
2. Alden P. Armagnac, The Most Fantastic Atom-Smasher, Popular Science, Nov. 1958.
3. W.A.S. Lamb and E.M. Logren, A High Current Ion Injector, Rev. of Sci. Inst., 27, 907 (1956).
4. L. Alvarez, et al, Berkeley 40 MeV Proton Linac, UCRL-236
5. E.A. Day, R.P. Featherstone, L.H. Johnson, E.E. Lampi, E.B. Tucker, and J.H. Williams, Rev. Sci. Instr. 29, 457 (1958)
6. M.V. Hoover, Advances in Techniques and Applications of Very-High-Power Grid-Controlled Tubes, Prog. of Convention on Microwave Valves, London, Eng., May 1958.
7. Design and Construction of the Livermore Linear Accelerator - MTA Project LRL-60, Calif. Research & Development Company, Feb. 1954.
8. W.D. Kilpatrick, A Criterion for Vacuum Sparking UCRL-2321, Sept. 4, 1953.
9. C.W. Owen, et al, Preliminary Sparking and X-ray Phenomena 200 MHz Linac Cavity, MURA Report 7 N-535 (1965, unpublished).
10. A.J. Davis, Some Thoughts on Radio Frequency Spark Breakdown in Linear Accelerators, CERN Internal Report MPS/Int LIN 69-13, Sept. 6, 1969.

11. W.A.S. Lamb, et al, A High Current Radio-Frequency Ion Injector, UCRL-4815, Feb. 1975.

12. E.O. Lawrence, High Current Accelerators, Science, 122 127 (1955).

Discussion

One spin-off I didn't mention; they anticipated extending the accelerators to 350 or even 500 MeV, so a program for manufacturing copper-clad steel was started. The warehoused copper-clad steel later built the Hilac, A-48, and the linac tanks for ANL and BNL. It was a resource that we enjoyed for many years.

A comment on the drift-tube stems: they were vertical in the original design, but in the modified design they had to be slanted to get the proper drift-tube spacing. We were very worried about the stem currents, but we never saw any effect in operation.