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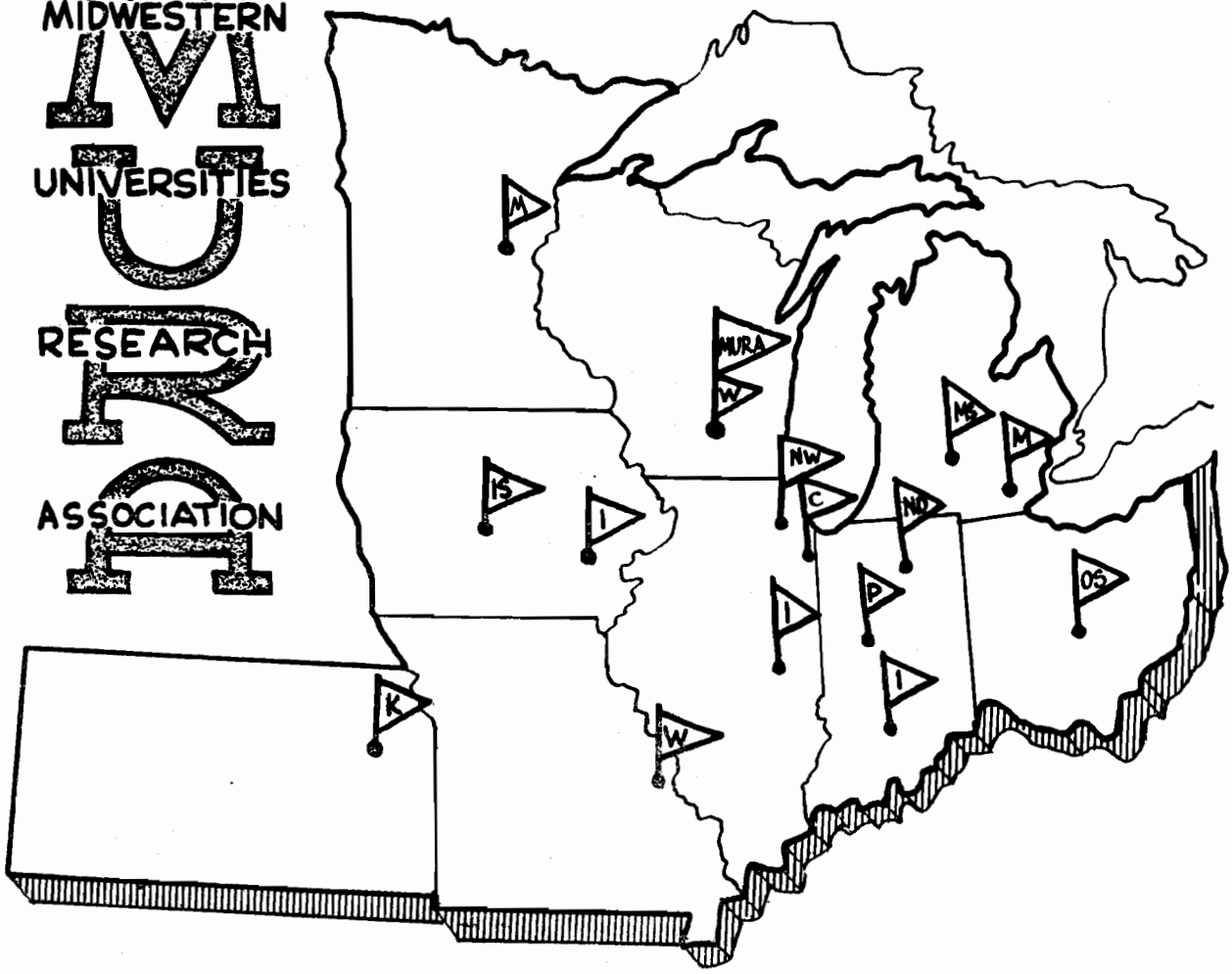

THE LINEAR ACCELERATOR

A Brief Summary

J. P. Blewett

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2203 University Avenue, Madison, Wisconsin

THE LINEAR ACCELERATOR

A Brief Summary

J. P. Blewett**

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**Summer visitor from Brookhaven National Laboratory

INTRODUCTION

Linear accelerators now popular are of two types. For electrons the accelerating field is set up in a disc-loaded waveguide. Protons and other nuclear particles are accelerated by the fields between the ends of drift tubes hung in resonant cavities. In both cases the mode pattern is essentially the transverse magnetic mode (having a paraxial electric field).

In both cases the essential field component is a wave traveling at about the speed of the particles. In electron linacs the electron velocity is so close to the velocity of light that the phase velocity of the accelerating wave is set equal to the velocity of light. This has the advantage of making all parts of the linac identical thereby simplifying the manufacturing procedures. In proton and heavy ion linacs, the pattern set up in the resonant tank is the TM_{010} mode. The drift tubes are cut to lengths corresponding to the distance traveled by the particles in one full period of the accelerating field. The resulting field pattern seen by the particles includes the essential traveling wave component.

Another way of looking at proton linacs is equally valid and perhaps clearer in concept. From one end to the other of a 50 Mev linac the integral of the electric field at its peak is actually somewhat more than 50 Mev. Unlike the cyclotron, the linac does not fool the particles into thinking that the volts available are more than actually exist. But the particles cannot traverse the whole tank while the field is at its peak value so it is necessary to introduce drift tubes to shield the particles from the field while it goes through its reversed phase.

INJECTION

Injection into electron linacs is from electron guns yielding electron beams of energies usually below 100 Kev. A short section of waveguide of increasing phase velocity serves as a "buncher" and the electrons are then released into the final guide.

Injection into proton and heavy ion linacs is usually at energies between 500 and 1000 Kev. The presently favored injector is the Cockcroft-Walton cascade transformer system. Injection at higher energy (such as 4 Mev, using an electrostatic accelerator) has the advantages of eliminating a number of short drift tubes and of simplifying the focusing problem which is worst at low energy. But it has the disadvantage of operation in a pressure tank; minor modifications of ion sources or repairs of component breakdown require about two days for removal of the pressure tank and its reinstallation. Also, continuous currents available in electrostatic machines are of the order of 300 microamps compared with 5 milliamps for cascade transformer sets. High continuous currents are useful in voltage division and in measuring equipment.

CHOICE OF FREQUENCY

For relativistic particles it is convenient to raise the frequency as high as possible. In the disc-loaded guide the aperture available is of the order of a quarter wavelength. Wavelengths of the order of 10 cm (3000 megacycles) give apertures of convenient size and result in accelerating structures that are relatively easily fabricated and handled.

For the slower nuclear particles the disc-loaded guide becomes inefficient. At velocities much lower than the velocity of light

(a 750 Kev proton has a velocity of about 0.03 c) the field pattern at high frequencies begins to vary rapidly with radial displacement from the axis. To provide reasonably uniform gap fields and to make drift tube lengths somewhat greater than the desired apertures it becomes necessary to drop frequency to about 200 megacycles or less. For heavy ion linacs the frequency must fall to less than 100 megacycles.

Since a cavity resonant in the TM mode is of the order of two-thirds of a wavelength, the 200 megacycle tanks used in proton linacs are of the order of one meter in diameter. The proton linac is thus a structure of an entirely different character from the electron linac. It is so bulky and heavy that it must be handled with a crane. In early proton linacs the resonant structure was a light copper structure housed in a heavy steel vacuum tank. It is now customary to combine rf and vacuum tanks in a single copper-clad tank.

POWER REQUIREMENTS

The most useful parameter in describing linac power requirements is the "shunt impedance." This is defined in various ways by various experts. Here we define it by

$$\text{Shunt impedance} = \frac{(\text{Particle energy gain per meter})^2}{\text{Power dissipated per meter}} \text{ ohms per meter}$$

The shunt impedance for conventional proton and electron linacs is of the order of 30 megohms per meter. For two typical machines the power required is as follows:

Stanford linac (660 Mev in 220 ft): power required is 3 megawatts per meter
total power is 200 megawatts

Brookhaven AGS injector (50 Mev in 110 ft): power required is 0.07 megawatts/m
total power is 2.4 megawatts

The Q's of the structures used in linacs are very high, usually in the range between 10,000 and 100,000. Therefore it takes an appreciable time to build up the accelerating field. In proton linacs this time is of the order of 200 microseconds. In electron linacs the build-up time is about 1 microsecond. In experimental proton linacs the total pulse length used is usually about 600 microseconds of which the last 400 microseconds can be used for acceleration. In electron linacs 2 microsecond pulses are usual. These pulse lengths are limited by the available rf power sources.

POWER SOURCES

In electron linacs power is invariably supplied by klystron amplifiers. Power ratings of the order of 10 megawatts per klystron are now standard and such klystrons are built both by the Stanford group and by several manufacturers. These klystrons run with anode-cathode voltages as high as 400 kv. Breakdown in the klystron structure is kept under control by use of short pulses. Although the Stanford group has predicted successful operation with pulses as long as 10 microseconds, this cannot yet by guaranteed.

Various power sources have been used with proton linacs. Some of these are as follows:

Eimac 3W10000A3 triodes which give about 250 kw apiece and are used on the Berkeley proton linacs

Home-built tetrodes ("Resnatrons") used at the University of Minnesota and capable of delivering 3.5 megawatts each

French Thomson-Houston TH-470 triodes rated at 2.3 megawatts each. These are used on the CERN and Brookhaven AGS injectors

RCA 2332 triodes good for 0.5 to 1.0 megawatts continuous. These are good only to about 70 megacycles. They were used on the Livermore linacs and are used now on the heavy ion machines at Berkeley and Yale.

RCA 2346 triodes good for 5 to 10 megawatts up to 400 megacycles. This tube is just now emerging from the developmental stage and will be used on the Argonne linac injector. It is promising but quite expensive. We have had estimates of $55,000 per tube plus $230,000 for the associated resonant structure.

PARTICLE ORBITS

a) Radial Forces

Because of the action of the accelerating field the particles continually experience a radial force given approximately by

$$E_r = \omega Er/v \ (1 - v^2/c^2)$$

where E is the effective axial accelerating field strength, r is distance from the axis and v is the particle velocity. For relativistic electrons in the electron linac this force is important only at the injection end of the machine. In proton linacs this defocusing force is very strong over the whole length of the machine. It can be compensated by grid focusing or by electrostatic or magnetic quadrupole focusing[1].

b) Phase Oscillations

Phase oscillations in the non-relativistic or in the relativistic regions can be described by the equation

$$\frac{d^2(P\Delta\phi)}{du^2} + (A/P - 1)(P\Delta\phi) = 0$$

where $\Delta\phi$ is the phase error

P is the dimensionless ratio $\frac{\text{(particle momentum)}}{m_o c}$

$$A = \frac{\omega\, m_o c \cos \phi_o}{eE \sin^2 \phi_o}$$

(ϕ_o is the stable phase angle measured from the preceding value where sin ϕ is zero)

$$u = \sinh^{-1} P$$

The above relation is valid if E, the accelerating field is constant along the machine.

Momentum errors are given approximately by

$$\Delta p = (eE \sin \phi_o \cosh u/\omega) \frac{d}{du} (P \Delta \phi)$$

In the non-relativistic range the above relations can be solved analytically to give the fractional energy error. If T represents kinetic energy, the energy error in the Brookhaven linac injector is given by

$$\frac{\Delta T}{T} = 0.065\ \Delta \phi_i\ (T/T_i)^{-5/8}$$

where the subscript i indicates injection values. For the Brookhaven injector the energy error at 50 Mev is about 0.005 per radian of injected phase error. If this machine were extended to 200 Mev, the energy error would be about 0.002 per radian of injected phase error.

c) Space Charge Limitations

Space charge effects become detectable at about the same current value at both ends of the proton linear accelerator. At the injection end they are effective in the radial direction. At the high energy end they act in the axial direction in a fashion such as to debunch the rather tightly bunched beam. A rough computation performed for the Brookhaven accelerator by Lloyd Smith indicated that these effects become perceptible when the beam current reaches a value of about 15 ma. More detailed analyses involving orbit tracing

for numerous particles have been performed at Argonne with the result that space charge effects should not be destructive until the beam current reaches at least 50 ma.

Because of the relativistic magnetic cancellation of electrostatic space charge effects at high particle velocities, the space charge limit in electron linacs is much higher. It will not be discussed further here beyond the comment that the important point for space charge limitation in the electron linac is the injection gun.

COSTS

A rough figure for the overall cost of a large electron linac can be derived from the Stanford estimate of about $90 million (0.9 pittance) for a 45 Bev machine. It is legitimate to conclude that smaller machines can be built for about $2,000 per Mev.

The Brookhaven proton linac could be duplicated for about $1.5 million. 50 Mev additions could be added for about $1.2 million each. Hence we can write approximately for the cost of a proton linac

Cost = $0.3 million + $24,000 per Mev.

From these figures it would appear that, if one wishes to build a proton linac in the Bev range, it will pay to convert the structure to the microwave system as soon as the protons become sufficiently relativistic. This can probably be done around the 200 Mev point ($v = 0.5c$).

REFERENCES

1) Review of Scientific Instruments, Linear Accelerator Issue, Feb., 1955.

2) Day et al (Minnesota Linac) R. S. I. 29, 457, (1958)

3) CERN Symposium 1956, pp 159 and 530

PARAMETERS OF 50 MEV PROTON LINEAR ACCELERATOR AT BROOKHAVEN

General

Length of preaccelerator column....6'
Distance from preaccelerator output to linac input....10'
Length of linac....110'

Distance from buncher to linac....5'
Distance from linac to debuncher....50'

Proton energy at output of linac....50 Mev

Expected diameter of proton beam at linac output....1 cm approx.
Expected angular deviation of protons from beam axis at linac output....
0.1° approx.
Expected energy spread of protons at linac output....±0.5 percent
Expected energy spread after debuncher....less than ±0.2 percent

Frequency of rf power for linac....200 Mc

Sequence of focusing gradients in linac.... ++ -- ++ -- etc

Size of buildings....Head house....60' x 60'
Width of linac tunnel....32'
(N. B. these buildings are not quite large enough)

Preaccelerator (5 stage Philips cascade transformer and filter stack)

Voltage....750 kv
Maximum continuous current....8 ma.
Ripple....70 volts per milliamp
Filter stack circuit....Series resistance....5 megohms
Stack capacity....8000 micromicrofarads
Power available in filter stack terminal for ion source etc....10 kw
3 phase 400 cycles

Aperture in accelerating column....5.5"

Linear Accelerator

Inside diameter....95 cm
Wall thickness....1.00" = 0.85" steel + 0.15" copper
Number of tank sections....11
Number of drift tubes....124
Drift tube internal aperture....No. 1 through No. 8....0.5"
No. 9 through No.18....0.75"
No.19 through No.33....1.0"
No.34 through No.124...1.25"
Tolerance on drift tube alignment....0.005"

Estimated Q of linac....90,000
Estimated rf power dissipation....2.5 megawatts
Estimated stored energy....120 joules

Proton Orbits

Peak value of accelerating field....1.9 Mev/m
Equilibrium phase....64° ($\sin \phi = 0.9$)

Phase error damps like $(\text{energy})^{-3/8}$

Ratio $\frac{\text{energy error}}{\text{energy}}$ damps like $(\text{energy})^{-5/8}$

Radial oscillation amplitude is approximately constant along the linac

For further orbit data see ADD Internal Report LS-3 (by Lloyd Smith)

Drift Tube Parameters

Drift Tube No.	Length cm	Diameter cm	Gap Length cm	Proton Energy Mev	Quadrupole Strength gauss/cm
2	4.9	21	1.4	0.84	4460
10	7.0	23	2.0	1.72	2500
20	9.6	24	2.8	3.27	1600
40	29	25	4.5	7.85	950
80	50	22	7.9	23.4	840
124	35	15	11.8	50.5	790

Proton Current From Linac

Expected current during initial operation....1.0 ma
Expected current after a year or so....10 ma
Maximum possible current with 4.5 megawatt input....40 ma
Space charge limited current (according to Argonne analysis)....50 ma

(N. B. in a redesigned linac with twice the aperture it should be quite possible to raise these limits by a factor of four.)