ELECTRON ANALOG TESTS OF PROTON LINEAR ACCELERATOR STRUCTURE*

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Summary

Electron analog tests of the 805-Mc cloverleaf accelerating structure being considered for the proposed Los Alamos linac have been made and are being extended. In the test which has been completed, 187-kev electrons, which are relatively easy to handle, are substituted for 343-Mev protons in the full-scale structure, which represents half of a prototype tank. The energy gain has been measured using a lens filter system, which acts as a decelerating device that returns the electrons to zero energy. The additional voltage needed on the lens filter to stop electrons which have been further accelerated by the cloverleaf model is a direct measure of the energy gain. The gain observed in the analog experiment corresponds to that expected from independent shunt resistance measurements.

Introduction

Important and interesting properties of proton linear accelerator structures may be investigated by using an electron beam to simulate the proton beam. The requirements used for the electron analog are that the beam current, the electromagnetic fields, and kinetic energies for the proton prototype be reduced by the ratio of the proton mass to the electron mass (1836). Space and time parameters, beam ballistics, applied frequencies, and beam pulse width remain full-scale. A practical advantage of the analog system is that the conditions impose only a modest demand on high voltage supplies and radio frequency power equipment.

The requirements for the dynamical similitude are assured from the following considerations. First, the equation of motion for a particle can be written

$$\vec{F} = e(\vec{\mathcal{E}} + \vec{v} \times \vec{H}) = m_o \frac{d}{dt}\left[(1 - \frac{v^2}{c^2})^{-1/2} \vec{v}\right]. \quad (1)$$

If we require that the beam particle ballistics for the electron analog be identical to the proton prototype, that is $\vec{v}_e(r,\theta,z,t) \equiv \vec{v}_p(r,\theta,z,t)$, then Eq. (1) implies that

$$\vec{\mathcal{E}}_e(r,\theta,z,t) = -\frac{m_o}{M_o}\vec{\mathcal{E}}_p(r,\theta,z,t)$$

and

$$\vec{H}_e(r,\theta,z,t) = -\frac{m_o}{M_o}\vec{H}_p(r,\theta,z,t) \quad (2)$$

will suffice. Equation (1) also implies that any electromagnetic field forces generated by the charge density distribution of the beam current (space charge and induced charged effects) must be reduced by the mass ratio, thus it follows that

$$\vec{I}_e(r,\theta,z,t) = -\frac{m_o}{M_o}\vec{I}_p(r,\theta,z,t). \quad (3)$$

Second, Einstein's energy relationship

$$E = m_o(1 - \frac{v^2}{c^2})^{-1/2} c^2 \quad (4)$$

similarly implies for identical beam dynamics, $\vec{v}_p(r,\theta,z,t) \equiv \vec{v}_e(r,\theta,z,t)$, that

$$E_e(r,\theta,z,t) = \frac{m_o}{M_o}E_p(r,\theta,z,t). \quad (5)$$

Since all field strengths and the current density distribution are everywhere reduced by the ratio of the proton mass to the electron mass, all power levels must be reduced by the square of this ratio.

Experimental Apparatus

The basic components of the electron analog accelerator are shown in Fig. 1. A continuous electron beam is pulse-modulated by a radio frequency chopper. The one source frequency is multiplied to 100 Mc for the chopper and to 800 Mc for the accelerator. The relative phase between the chopper and the accelerator is adjusted in the 800-Mc branch. The power level delivered to both the chopper and the accelerator structure can be controlled and measured. Acceleration occurs in the structure to be tested and the energy gain is measured in a lens filter system. An important feature of the system is that the same 200-kv power supply is used for the electron gun acceleration and the lens filter.

The electron gun was originally designed for use in a high-intensity, high-energy pulsed x-ray machine.[1] The gun was modified to accommodate a smaller L-type of cathode.[2,3] The gun and power supply are capable of supplying 10 ma of current at 200 kv.

The electron beam is focused and guided through the chopper and accelerator structure by magnetic solonoidal lenses and steering magnets. Information for the control of these elements comes from beam position sensing quadrants which locate the beam if it drifts off axis. All sections of the apparatus through which the beam is guided are maintained at less than 10^{-7} mm Hg pressure by ion pumps.

The beam of desired pulse width and frequency corresponding to that of the 200-Mc section of the proposed linear accelerator are generated by chopping the dc beam from the electron gun.[4] A quarter-wave stub line is used to generate an electric field to sweep the dc beam across a downstream aperture. The stub line is driven at a frequency, one-eighth of the resonant frequency of the accelerating structure. Thus the chopper produces one pulse for every four cycles in the accelerator. The characteristics of the chopper are determined by measuring the current in the chopped beam as a function of the power applied to the chopper. The average current of the chopped beam should be inversely proportional to the square root of the radio frequency power applied to the chopper. This simple relation holds provided that the maximum deflection at the chopping aperture is large compared to the aperture diameter so that the current passes only during the approximately straight line portion of the sine wave at field reversal time. Figure 2 shows the experimental verification of the chopper performance.

After modulation the pulsed beam traverses the accelerator structure which is driven by 800-Mc power at a known level. The accelerated beam then enters the last component of the system, the energy monitor. Rather stringent requirements impose on the monitor. It should be capable of measuring the energy gain to a few percent even though the gain itself is usually less than one percent of the incoming energy. A satisfactory measuring device is the retarding field energy analyzer,[5] more often referred to as a lens filter.

The lens filter is a decelerating device that returns the high-energy electrons from the electron gun to zero energy by a retarding voltage equal to the gun voltage. As both the electron gun and the lens filter are operated from the same high-voltage supply, all electrons are returned to zero energy in the retarding plane regardless of the high voltage potential. If the electrons are now further accelerated in a structure imposed between the gun and the lens filter, the electrons at the retarding plane of the lens filter will have a residual energy equal to the energy gained in the accelerator section. An additional stopping voltage equal to the energy gain of the electrons in the accelerator section must be added to the lens filter system to cut off the lens output current. Thus, the additional voltage is a direct measure of the energy gained in the accelerator. Poor regulation and noise of the high-voltage power supply are to a large extent cancelled.

The lens filter used in this experiment consists of five circular parallel plates as shown in Fig. 3. The inner three plates generate the retarding field, and only electrons whose energy is greater than zero at the central plane can pass through. These electrons are then reaccelerated and detected. The electron current is cut off when the retarding voltage reaches the lens filter input energy of these electrons. The bias plates which help to make up the retarding field are kept at almost the same potential as the retarding plate: this bias is adjusted for proper focal properties of the lens and sharp cut-off characteristics. The reacceleration lens permits easier detection of electrons at a high energy, use of a Faraday cup at ground potential, and an uncluttered region for the retarding field electrodes.

The power supply for the lens filter and the electron gun is a 300-kv, 10-ma unit. Although the supply is not closely regulated, it possesses adequate short term stability; excursions are confined manually to less than ± 200 volts. The lens filter bias and additional decelerating voltages are supplied by two variable precision 1-2000-v sources housed in a corona box which is kept above ground by the accelerating voltage; 200-kv transmission lines run from the corona box to the lens filter.

The apparatus downstream from the electron gun is shown in Fig. 4. The water-cooled quarter-wave stub can be seen at the left. The large diameter vacuum tank houses the accelerator structure and at its far end is the termination of the high-voltage transmission line at the lens filter.

Experimental Results

Electron analog experiments have been performed using an 805-Mc cloverleaf structure operating in the π mode and consisting of 19 full cells and two half cells, one on either end. This arrangement mocks up half of a prototype tank proposed for the Los Alamos linac. The primary concern was to measure the energy gain in the accelerating structure. The results are shown in Fig. 5. The current through the lens filter is plotted as a function of the supplemental retarding voltage on the lens filter for four radio frequency power levels delivered to the accelerating structure: 0, 7.9, 22.6, and 39.0 milliwatts. The power levels have been corrected for the power lost to the beam current. A background current, believed to be mainly from field emission of the lens filter, was subtracted from the total currents and the residual currents have been normalized to the saturation current for each power level. In each case the average value of the pulsed current through the accelerator structure was held to about one microampere and the pulse width was adjusted to approximately 40° with reference to the 805 Mc on the accelerator structure.

The beam current pulses were made synchronous by maximizing the lens filter output current as a function of both the input voltage and the relative phase of the pulse with respect to the acceleration fields in the cloverleaf section. These adjustments are made by setting the retarding potential near the midpoint of the cut-off curve and varying the energy or phase for a maximum output. In both cases a well defined maximum in lens current output is observed as the adjustment is made through its optimum value.

The results indicated in Fig. 5 can be compared with that predicted by independent field distribution measurements using a perturbation technique made previously on a test bench and a recent cavity Q measurement. These measurements indicate energy gains of 710, 1200, and 1570 should be expected for these respective power levels. The results of the test can be extrapolated to the proton prototype by the scaling factors. For example, the 39.0-milliwatts excitation and resulting 1440-volts gain corresponds to an excitation level of 132 kilowatts and an energy gain of 2.64 Mev. The results of the test can also be expressed in terms of the effective shunt impedance or shunt resistance:

$$ZT^2 = R = \frac{(\text{Energy Gain Per Meter})^2}{\text{Power Dissipated Per Meter}} \qquad (6)$$

This electron analog experiment implies a shunt resistance of approximately 23 MΩ/meter while the independent bench test indicates a value of about 25 MΩ/meter. Both these values are based on recent Q measurements.

An interesting by-product of the experiment develops from analyzing the reason the 0-level RF excitation requires some -460 volts of lens filter retardation voltage for cut off. This cut off was reduced to near zero when the chopper was turned off, indicating that the chopper, when operated at 500 watts, was supplying some 460 volts of gain to the beam. As one of the chopper electrodes is grounded to the beam tube, the perturbation is attributed to this nonsymmetrical arrangement of the quarter-wave stub and to the transit time of the beam through the effective region of the chopper.

As the chopper sweeps across the aperture in both directions during its cycle, one expects the alternate pulses to be decelerated. This was looked for and found at approximately 450-volts loss.

It is intended to pursue further tests on the cloverleaf as well as other structures, including such tests as beam loading and spurious mode excitations.

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References

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1. LASL PHERMEX Project internal reports (unpublished).

2. H. J. Lemmens, M. J. Jansen, and R. Loosjes, Philips Tech. Rev., Vol. 11 (1950).

3. G. A. Espersen, Proc. IRE, Vol. 40, 284 (1952).

4. C. M. Turner and S. D. Bloom, Rev. Sci. Instr. Vol. 29, 480 (1958).

5. J. A. Simpson, Rev. Sci. Instr. Vol. 32, 1283 (1961).

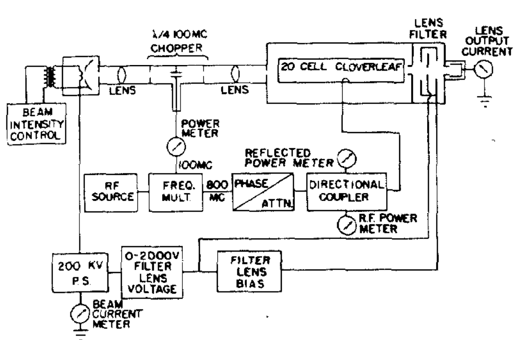

Fig. 1. Schematic outline of the experiment.

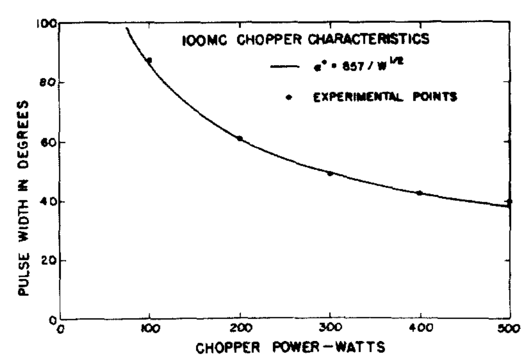

Fig. 2. The pulse width in degrees, which is proportional to the ratio of the average current in the chopped beam to the current in the unchopped beam, is given as a function of power to the chopper.

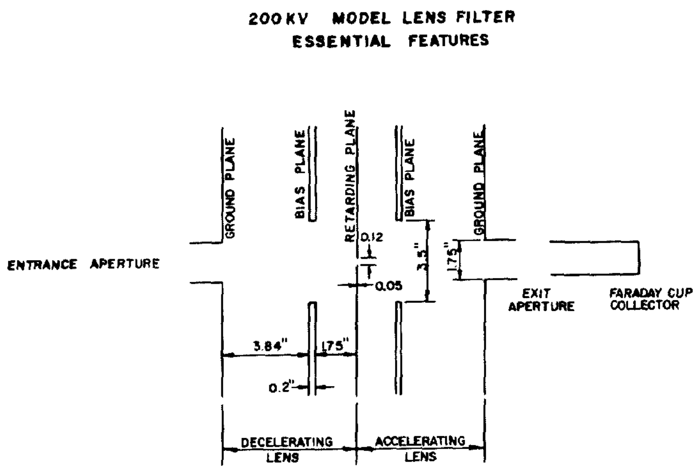

Fig. 3. The lens-filter components are shown to scale.

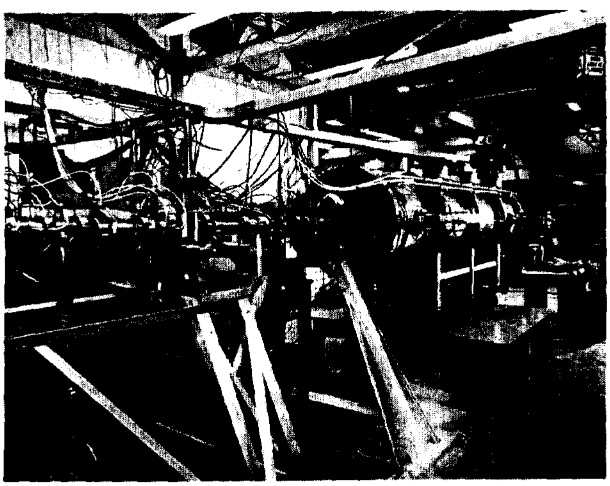

Fig. 4. This is a view of the apparatus looking downstream. Beam guidance and chopping components are in the foreground. The large tank contains the accelerating structure. The electron gun and its power supply are out of the field to the left and the lens-filter system is mounted on the far end of the large tank.

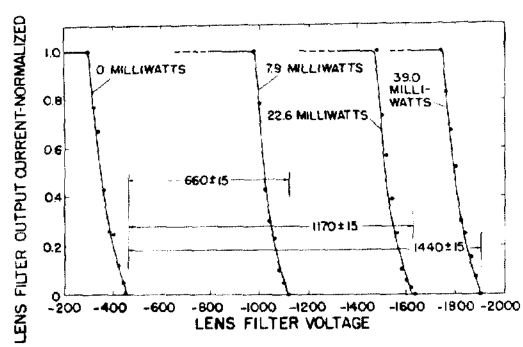

Fig. 5. Four lens-filter cut-off curves are shown. The first is with no excitation power into the accelerating structure. Cut-off curves for 7.9, 22.6, and 39.0 milliwatts net power to the accelerating structure are also shown. The displacements 660, 1170, and 1440 volts are a measure of the corresponding energy gains.