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THE ELECTRICAL DESIGN OF A HEAVY-ION ACCELERATOR

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Abstract

A linear accelerator designed to accelerate particles of atomic weight 12 through 20 (carbon through neon) is now in operation in Berkeley. This machine has four parts: an injector, a short section of linear accelerator, a stripper, and a main section of linear accelerator. The injector consists of an ion source, the electronic equipment to pulse-power it, and a 500-kv Cockcroft-Walton power supply using dry-disc rectifiers.

The first linear accelerator section is an rf cavity 10 ft in diameter and 15 ft in length. When it is at design gradient (500 kv/ft), 385 kw are dissipated in the cavity walls and drift tubes. There are 37 drift tubes, with grid focusing, which are spaced for an exit energy of 0.97 Mev/nucleon; i.e., N_{14} would have an exit energy of 13.6 Mev. The main linear accelerator section is 9 ft in diameter and 90 ft in length. At design gradient (500 kv/ft), 2.6 Mw are dissipated in the cavity walls and drift tubes. In this section there are 67 drift tubes, with strong-focusing magnets in each. The magnets are powered by individual water-cooled germanium rectifiers capable of delivering 750 amp at 21 v. These together with the power-supply transformers, are mounted at the drift-tube stems. The exit energy from this section is 10 Mev/nucleon, or 140 Mev for N_{14}.

A pulsed radio-frequency system capable of supplying 3 Mw of 70-Mc energy for 3 msec furnishes the power for the two linear accelerator tanks. Power is supplied to the main tank by three amplifiers, and to the smaller tank by a coupling line from the larger one. The amplifiers are powered by individual pulse lines, each with a capacity of 2.25 Mw.

The number of charges that the ion source can remove from a given atom, say Ne_{20}, is limited to about 3. For this reason the first linear accelerator section (prestripper) is designed to accept particles with a charge-to-mass ratio of $e/m = 3/20 = 0.15$. Particles with a higher ratio are accelerated; those with a lower ratio are not. Since it is more efficient to operate the linear accelerator when designed for a high e/m ratio, the first section is only long enough to give the particles enough energy to remove more charge when passed through a foil. In this case there is a continuously replenished foil, consisting of a jet of mercury through which the particles pass, and here they are stripped of some of the remaining charge. After passing through the stripper, particles have charges of +4, +5, and +6. The main section of the linear accelerator, or poststripper, is designed to accelerate particles with $e/m = 0.3$ or greater.

Introduction

Most of the early particle accelerators were built to accelerate electrons, protons, deuterons, and alpha particles. This was primarily because these particles are fundamental building blocks of matter. It is also simpler to design for light particles. There has been an increasing interest, particularly among nuclear chemists, in accelerating ions of much greater atomic weight, and we now have in Berkeley a linear accelerator capable of accelerating ions of atomic weight 12 through 20. These are atoms of carbon through neon, and they are not, strictly speaking, heavy ions except in comparison with hydrogen and helium. The accelerator was designed in collaboration with Yale University, and Yale is now completing construction of a machine that is very similar to the Berkeley accelerator.[1]

A linear accelerator is usually operated at an rf gradient a little less than required for breakdown between drift tubes because this results in a minimum-length machine. For any given particle accelerated to a given energy, the length is inversely proportional to the number of charges on the ion. The rf losses, the cost of rf generating equipment, and the cost of the tank itself are roughly proportional to the length of the machine. The degree of ionization of the charged particle has a great influence on the design. The ratio of net charge to mass, here called e/m, determines the grip that the electric and magnetic fields have on the particle. For example, accelerating and focusing fields must be 20 times as large for singly charged neon atoms as for protons.

Under the best operating conditions, our ion source[2] will deliver about a milliampere of $(N^{14})^{+3}$ or $(Ne^{20})^{+3}$. One of the design problems on this machine was to maintain a large value of e/m for elements as heavy as neon. For example, $(N^{14})^{+3}$ has an $e/m = 0.214$ and $(Ne^{20})^{+3}$ has an $e/m = 0.15$. For best over-all performance, the linear accelerator was divided into two parts. The first part was designed for an $e/m = 0.15$, and the second part was designed for an $e/m = 0.3$. The first section of the linear accelerator is 15-ft long and has an energy gain of 1 mev/nucleon, that is, 14 mev for N^{14} or 20 mev for Ne^{20}. This is sufficient energy to strip off additional charge from the atom when it passes through matter. Between the sections of the linear accelerator, there is a device that projects a jet of mercury vapor through the path of the beam. After passing through the stripper as this device is called, some of the ions have four,

five, and six electrons removed. Ions $(C^{12})^{+4}$, $(N^{14})^{+5}$, and $(Ne^{20})^{+6}$ all have an e/m ratio greater than 0.3, which is the design minimum for the second linear-accelerator section. Any $(N^{14})^{+6}$ ions that exist, for example, have an e/m = 0.428, and the rf gradient necessary to accelerate these ions is 0.3/0.428, or 70% of the maximum design gradient. The second section is 9 ft in diameter and 90-ft long and has an exit energy of 10 mev/nucleon. A block diagram of the heavy-ion accelerator is shown in Fig. 1.

Injector

The injector consists of a high-voltage cubicle in which the ions are created, an evacuated tube through which the ions are accelerated, and a Cockcroft-Walton power supply to accelerate the ions to an energy acceptable to the prestripper. In a linear accelerator, the drift-tube spacing is equal to the distance a particle travels during an rf cycle. The cost per foot of machine is high with low injection energies, because many additional drifttubes must be packed into the first few feet of machine. On the other hand, the cost of injector power-supply increases rapidly with higher voltage. In the case of the heavy ion accelerator, 500 kv was the most economical choice for an injection voltage.

The Cockcroft-Walton power supply has 14 cascaded decks, each a voltage doubler containing four 20-kv, 0.5-μf capacitors, and 2000 1/4-in.-diam. selenium cells. The rectifiers are protected from severe overvoltage by spark gaps, and the capacitors are protected from overcurrent by series resistors in each deck. The stack is driven by an 800-cycle, 20-kv-peak voltage from a transformer, which in turn is supplied by an alternator. A 2700-megohm divider is used to monitor the high voltage, and to provide a feedback signal to control the alternator field current. The loop gain of the regulator is sufficient to provide 0.1% regulation if there is no divider instability. Operating experience has shown no difficulty with stability of injector voltage to date. The Cockcroft-Walton was designed to supply 1.5 ma at 500 kv with about 1500-v-peak ripple. Figure 2 is a picture of the Cockcroft-Walton.

The high-voltage cubicle contains a vacuum system, a magnet, and an ion source with its associated electronic equipment. The ion source is of the Philips Ion Gauge type in which an electrical discharge is maintained between electrodes in the presence of a magnetic field. The wall of a graphite cylinder acts as an anode, and the insulated ends act as a cathode. The cylinder is so oriented between the poles of a magnet that its axis is in line with the magnetic field. The threshold for removing three electrons from an atom is less than 100 v, but because of the small cross section at this voltage and the high probability of recombination of ions, the ion source is operated with considerably more voltage. The discharge normally has been 3 kv potential drop with 1.5 amp of arc current. Energy for the arc is supplied from a pulse line and a hard-tube modulator. It is possible to vary the pulse length from a few hundred μsec to a maximum of 2 msec with this modulator. Once the arc is established, the ion source including its electronic chassis is raised in potential with respect to an electrode at the potential of the high-voltage cubicle. This electrode is arranged to extract ions through a slit in the wall of the cylinder. The current necessary for extraction is supplied through another hard-tube modulator from a 7.5 μf capacitor charged to 20 kv. The modulator has an adjustable delay, as well as a variable pulse length. For best operation of the source, the arc is allowed to build up and become stable before extracting ions from it.

The field of the magnet extends not only through the ion-source cylinder, but also over all the region through which the extracted ions pass. The energy gained from the extractor and the e/m of the ions determine their path in the magnetic field. The magnetic field is adjusted to allow only desired particles to pass through a slit into the accelerating column. This requires that the electric and magnetic field be constant to 0.1%. A beam of triply charged ions falls through the 500-kv potential created by the Cockcroft-Walton where it gains 1.5 mev per particle.

500-kv isolation of the electrical equipment in the cubicle, was provided by bringing mechanical power in to the high-voltage unit by insulated vee belts. The vee belts drive a 5-kw dc generator for magnet power, and a 35-kva 60-cps alternator to supply power to the electronic chassis, the vacuum pumps, and the refrigeration equipment. Light-beam telemeters transfer trigger-time information to the modulators, and also supply arc-current waveforms to the operator.

Linear-accelerator section

The particular type of linear accelerator in this machine consists of a large tank which is both a vacuum vessel and an rf cavity. The cavity is excited in the TM_{010} mode, in which the axial electric field is uniform from end to end except for perturbations caused by the drifttubes. The length of the cavity is governed by the maximum gradient that can be held between drifttubes in vacuum and by the desired exit energy of the particles. The design gradient in this machine is 0.5 mv/ft average, or 2 mv/ft in the gaps. It has already been decided for beam-dynamics reasons to use alternating-gradient focusing, and this sets the minimum drift-tube magnet size. The diameter of the cavity is determined by the operating frequency, and to make the diameter small, the frequency should be as high as possible. A frequency of 70 mc was chosen because it is compatible with both the drift-tube size, and with the RCA-2332 tube to be used in the final amplifier stages.

The first studies on the rf-cavity problem were done on an electrical analogue network which simulated rf fields in a cylindrical geometry. The network was used to plot values of field for

sections of the linear accelerator with various ratios of drift-tube diameter to cavity diameter, and with various drift-tube gap-to-length ratios. On the assumption that the conductivity of the cavity walls does not appreciably affect the field distribution, it was possible to integrate numerically to find the losses along the conducting surface. By integrating over the volume, the voltage across the gap was determined. This enabled us to calculate the shunt impedance of the cavity and thus determine the losses to be expected in the linear accelerator at a given gradient. Frequency data determined from the network was too crude to be of value, and frequency measurements were taken on a precision-cavity model to determine how diameter ratios and gap lengths determine the frequency of the region from one drift-tube stem to the next.

As the particles gain energy, the drift-tube spacing must be increased to allow for the increased velocity. A table relating velocity gain to drift-tube spacing was prepared by the theoretical group. Using data from this table together with the precision modeling cavity, we found the cell dimensions for the whole machine. Even though the cell lengths vary continually, if each cell, as the region from one drift-tube to the next is called, has the same resonant frequency, the cavity as a whole will also have this resonant frequency. Any variations in the resonant frequency of the cells will cause perturbations in the fields of the total cavity. From the precision cavity data, we were able to find the mechanical tolerances necessary to keep the axial electric field essentially flat along the length of the cavity. For example, the mechanical tolerance is 0.0025" on the drift-tube gap spacing. Figure 3 shows a photograph of the interior of the main tank.

The strong-focusing magnets in the drift-tubes require an additional, axial tolerance of 0.005", and it was necessary to servo the temperature of the top, bottom, and sides of the 90-ft tank in order to keep room temperature from excessively warping the tank during mechanical alignment. Without this precaution the projected end-to-end displacement was as much as 1/4 in. during the day. The difficult mechanical task of building the linear accelerator to these close tolerances, which was accomplished by the mechanical group, saved the electrical group the very complex job of finding what perturbations existed in the axial field, and calculating where to introduce additional perturbations to correct the field.

The shunt impedance data found from the analogue analysis enabled us to predict the amount of rf power necessary to operate the machine at the design gradient. This power was calculated to be nearly 3 Mw. Of this, 385 kw is lost in the first section, and 2.6 Mw is lost in the main accelerator section. About 67% of the losses are in the walls, and about 33% in the drift tubes and stems. We hoped to get 1 Mw of power from each 2332 final-amplifier stage at 70 mc. Then, three final amplifier stages would supply the required 3 Mw with no allowance for contingency. Because some particles can be accelerated at considerably less than the maximum rf gradient, only three amplifiers were built for the first stages of operation. Allowance was made for a fourth stage to be added later. The final stages are tuned-grid, tuned-plate amplifiers, having a pi-input and pi-output circuit as shown in Fig. 4. In order to avoid loading the drive circuit, and especially to keep from feeding power through the amplifier to the cavity prematurely, we have provided neutralization by a grid line coupled to the cavity. The cavity acts as a high-Q filter in the feedback path. At very low voltages in the cavity (several hundred volts across the drift-tube gaps), electrons take about one rf cycle to go across the gap and back. If the secondary emission ratio of the surface material is greater than one, an avalanche of electrons will build up after a number of cycles, and all the output of the amplifiers will be absorbed in this multipactoring phenomena. At full gradient 200 v out of 2 Mv is a ratio of 10^{-4} in voltage or 10^{-8} in power. So, to avoid multipactoring, the power fed through from the driver to the cavity must be less than 30 mw. When the pulse begins, it is necessary to have the rf level rise sufficiently fast through the various multipactoring levels to prevent an avalanche from building up. To accomplish this, the grid-tuned circuit of the RCA 2332 has to be driven approximately 2000 v peak in 1 μsec.

Each of the final amplifiers has a grounded-grid driver stage using an Eimac 3W5000 tube. The driver amplifiers are driven from a common intermediate amplifier using an RCA 2519 tetrode. This in turn is driven by a master oscillator and frequency multiplier. At present the master oscillator is adjusted manually to the frequency of the correct mode, but it is planned to servo the master oscillator to the cavity frequency at a later date.

There are a number of modes in the main tank that are quite near the operating frequency. The nearest is about 30 kc above the operating frequency. When the cavity was first excited a mode was found in which the axial field went through zero about 15 times down the length of the tank. The next few modes expected were TM_{01n} modes, where n = 1, 2, 3. In this case there should have been only 1, 2, or 3 zeros in the axial field. At first this mode was very confusing to us until we realized that it was a higher-order TE mode which had been overlooked. Figure 5 is a chart showing the various modes, and it gives an indication of how the TE modes fit into the picture. Fortunately, with a Q of 100,000 there is no trouble with other modes if the master oscillator is set to approximately the correct frequency.

All the final amplifiers are connected directly to the main tank because it is easy to lock them in phase this way. The pre-stripper requires only a fraction of the total output of one RCA 2332, and it is powered by a coupling line from the main cavity rather than from a separate tube.

There is a rather critical manual adjustment of the coupling loops and tuning loops for proper operation of the pre-stripper, and it is hoped to eventually servo these adjustments. The final amplifiers are powered from individual pulse lines, each capable of delivering 2.25 Mw at 40 kv, with a pulse length of 3 msec. One of these lines is shown in Fig. 6. The pulse lines are charged from seperate 40-kv, 4-a power supplies which are shown in Fig. 7. The charging current is limited by emission limiting the 562 hard-tube rectifiers. Switching of each pulse line to it final amplifier is accomplished by three 5550 ignitrons in series. All three ignitrons are triggered simultaneously from separate trigger transformers. There is also a "crobar" system which uses a triggered air-gap to short-circuit the energy from the pulse lines in case of a fault in the final amplifier. The driver amplifiers and the intermediate amplifier are all supplied with plate power from a separate 20 kv 3 millisecond pulse line.

The prestripper has 37 grid-focusing drift tubes. These drift tubes are small in diameter (about 10 in.) because they do not require drift-tube magnets. Grid focusing was not carried on through all the machine because loss of beam is a steep function of the number of grids. There are 67 drift-tubes, each with an individual quadrupole magnet, in the main accelerator section. The magnets are water-cooled and are powered by individual water-cooled germanium rectifiers. The power-supply transformers together with the rectifiers, which are capable of supplying 750 amp at 21 v from a 6-phase circuit, are mounted at the top of the tank next to the drift-tube stems. Figure 8 shows the machine before the shielding was installed.

Controls and Instrumentation

The individual magnet power supplies are monitored by 24-v lamps in the control room. The brightness of the lights gives visual indication of power-supply voltage. Current indication from each drift-tube magnet shunt is connected to a Speedomax dial indicator through a 67-position switch. The indicator has a suppressed zero with five positions, enabling the operator to read individual magnet current to 600 a with 0.5 amp accuracy. A separate push-button control allows raising or lowering current through the monitored magnet, and all the magnets can be turned off and on without changing previous current settings. Fortunately, it has proved possible to get beam through the machine by setting up the magnet current according to theoretical calculated values, rather than to have to adjust 67 variables while searching for beam.

The control room is adjacent to the injector, and it has a large window allowing the operator to view the meters and lights across the intervening 500 kv. Lucite shafts are used to manually adjust the ion-source components. The critical signals are carried on light-beam telemeters, and there is a photoelectric alarm circuit to warn of vacuum or refrigeration failure. Each vacuum vessel is monitored by dual Hasting gauge interlocks, and there is ion-gauge indication of pressure.

Directional couplers are provided on each amplifier coupling line, and on the line between the prestripper and the main tank. These enable the operator to monitor rf power from each amplifier and rf power to the prestripper. Two Tektronix oscilloscopes are used to view 100 assorted voltage and current waveforms available at a plug board. There is also a monitor chassis with three 3-in. oscilloscopes for waveforms that the operator needs to observe continuously.

Conclusion

At present the heavy ion accelerator has provided at least 10 μamp of C^{12} and N^{14} at exit energies of 10 Mev/nucleon. This is 120 Mev for carbon and 140 Mev for nitrogen. Ne^{20} has been accelerated on occasion, but operation at this gradient will be more reliable when the fourth amplifier is completed. With the fourth amplifier, it will also be possible to accelerate Ne^{22} and possibly some heavier elements.

The strong-focusing quadrupoles have been unusually successful in controlling the beam through the main accelerator. The exit diameter of the beam has been as small as 2 mm with almost no loss of beam, even though the diameter at the entrance is almost a centimeter. At the present time a buncher is being built to increase the amount of beam accepted by the linear accelerator. The pulse-line power supplies are being oil-cooled to increase their power output which will allow a higher repetition rate for the machine.

Acknowledgment

A great many people were responsible for bringing the machine from an idea to an operating accelerator. Special recognition is due Warren Dexter, William Baker, Niel Norris, Larry Brown, and Karl Sterne from the electrical group.

This work was done under the auspices of the Atomic Energy Commission.

References

1. Beringer, Gluckstern, Malkin, Hubbard, Smith and Van Atta, "Linear Accelerator for Heavy Ions", UCRL-2796, Nov. 1954.
2. C.E. Anderson and K.W. Ehlers, "Ion Source for the Production of Multiply Charged Heavy Ions", UCRL-3218, Dec. 1955.

Figure Captions

Fig. 1. Block diagram.

Fig. 2. Cockcroft-Walton power supply.

Fig. 3. Interior of main tank.

Fig. 4. Equivalent circuit for final amplifier.

Fig. 5. Modes in main accelerator cavity.

Fig. 6. 2.25 Mw pulse line.

Fig. 7. 45 kv 4 a power supply for charging pulse lines.

Fig. 8. Heavy ion accelerator before installation of shielding.

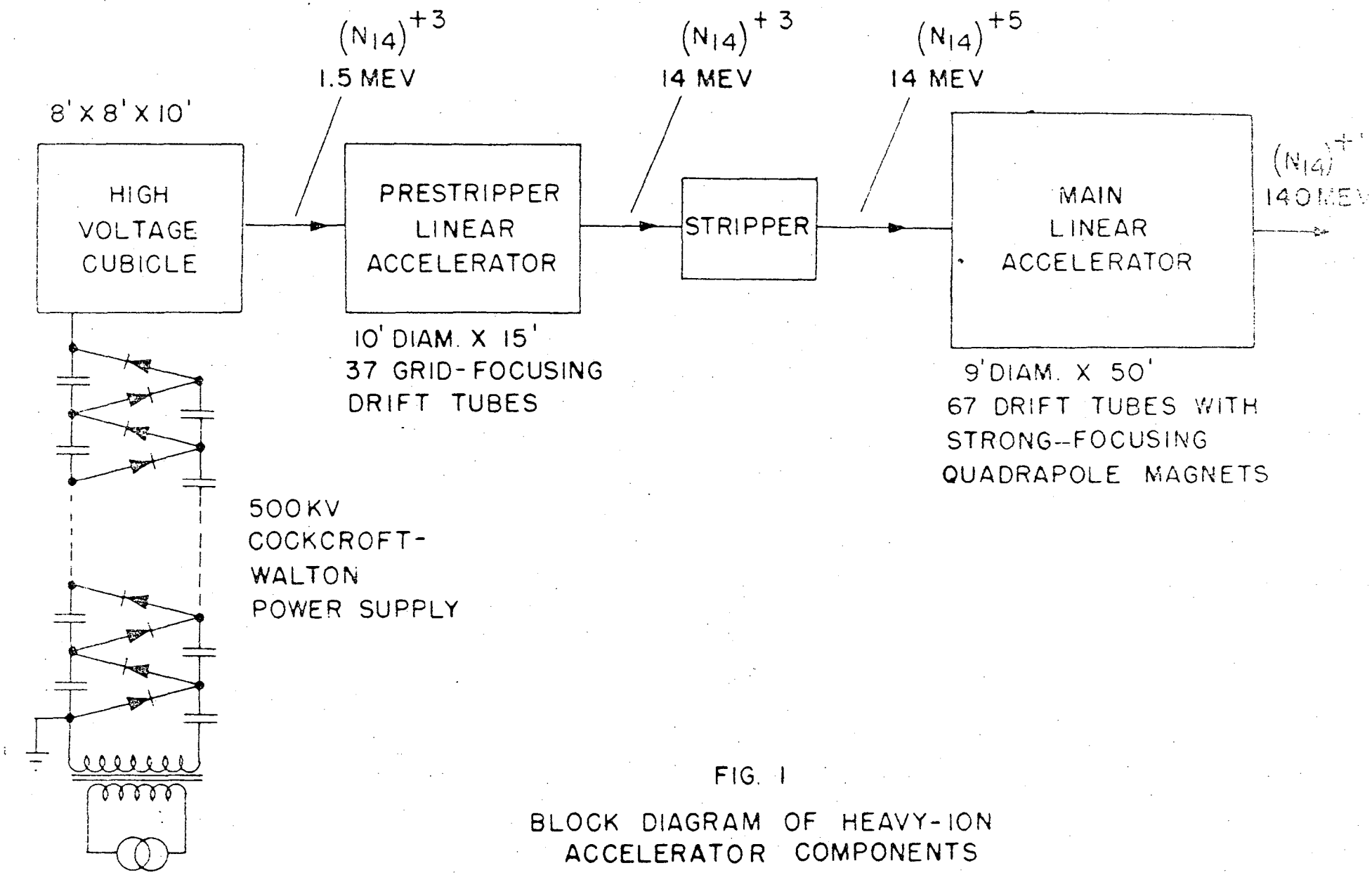

FIG. 1

BLOCK DIAGRAM OF HEAVY-ION ACCELERATOR COMPONENTS

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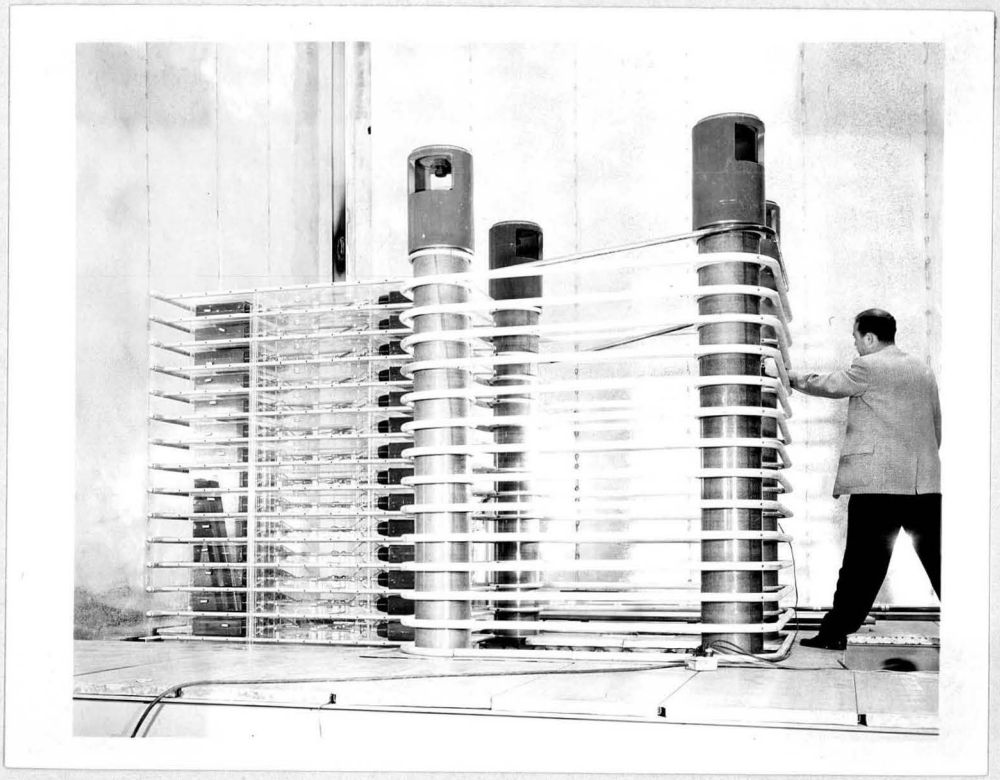

Fig. 2

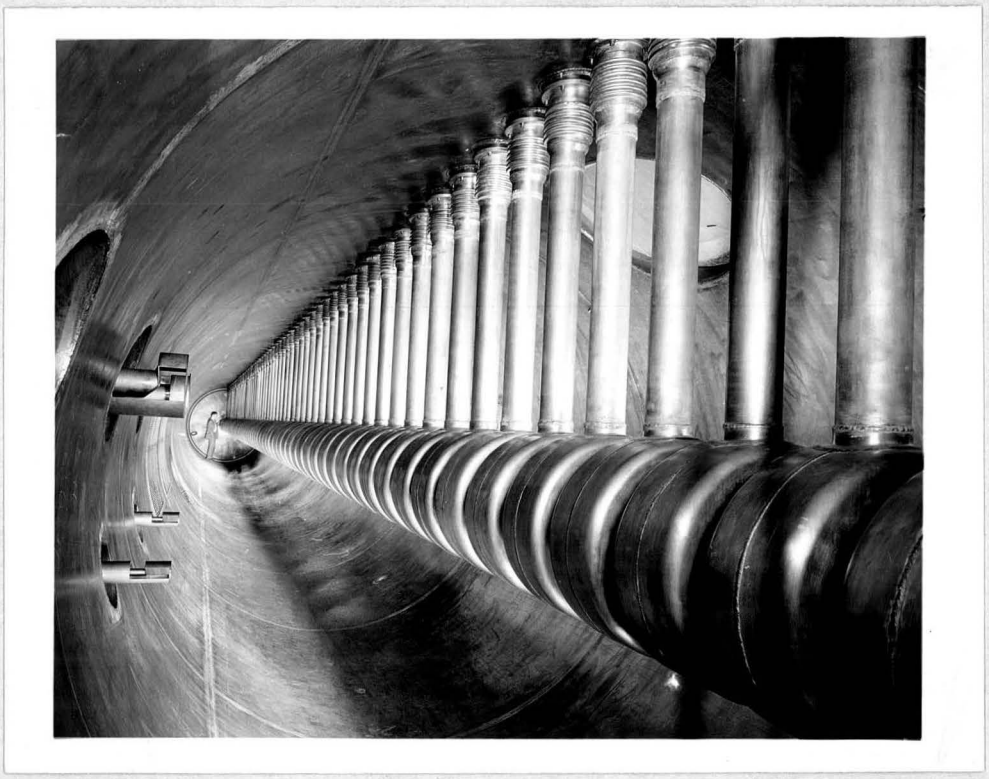

Fig. 3.

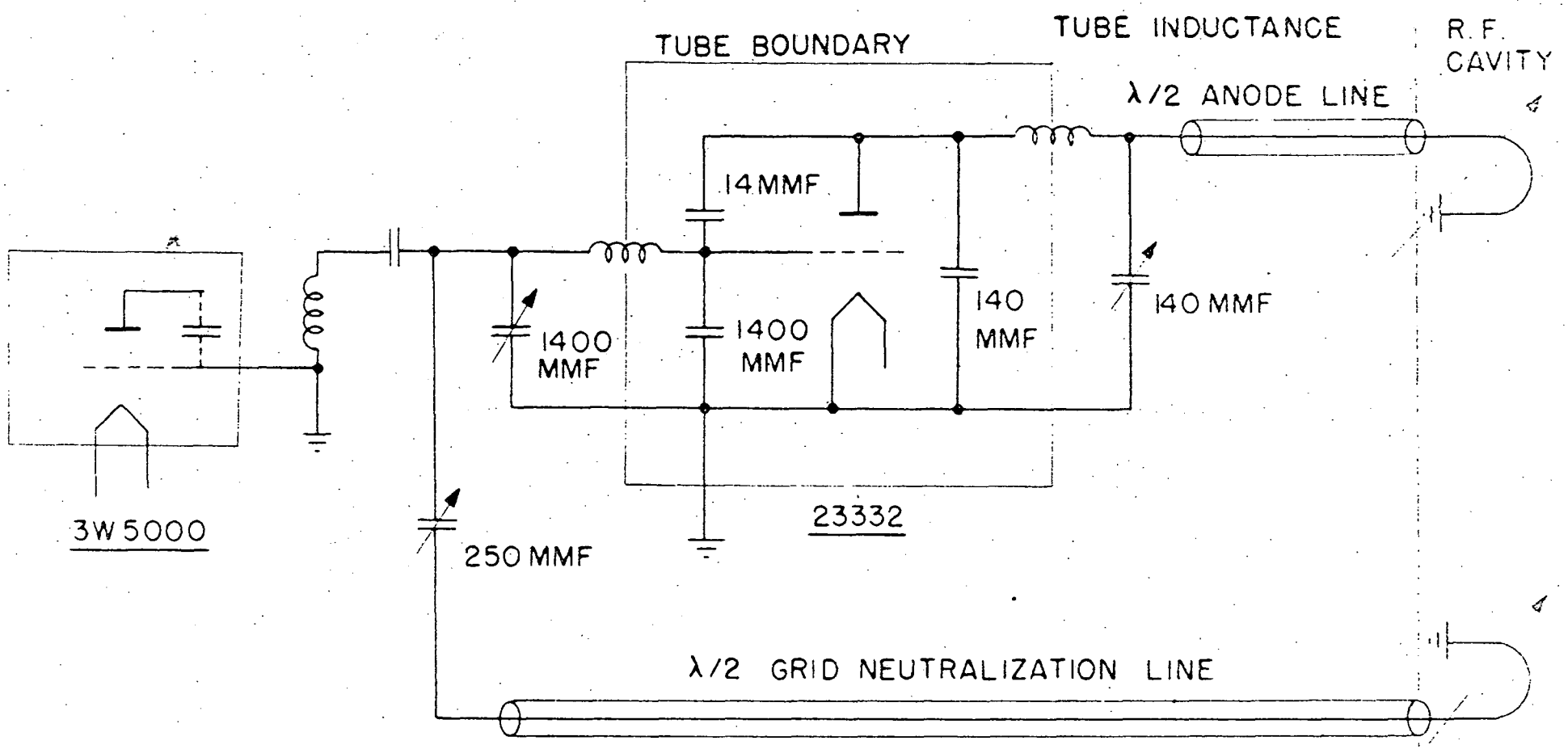

FIG. 4

EQUIVALENT CIRCUIT FOR FINAL AMPLIFIER

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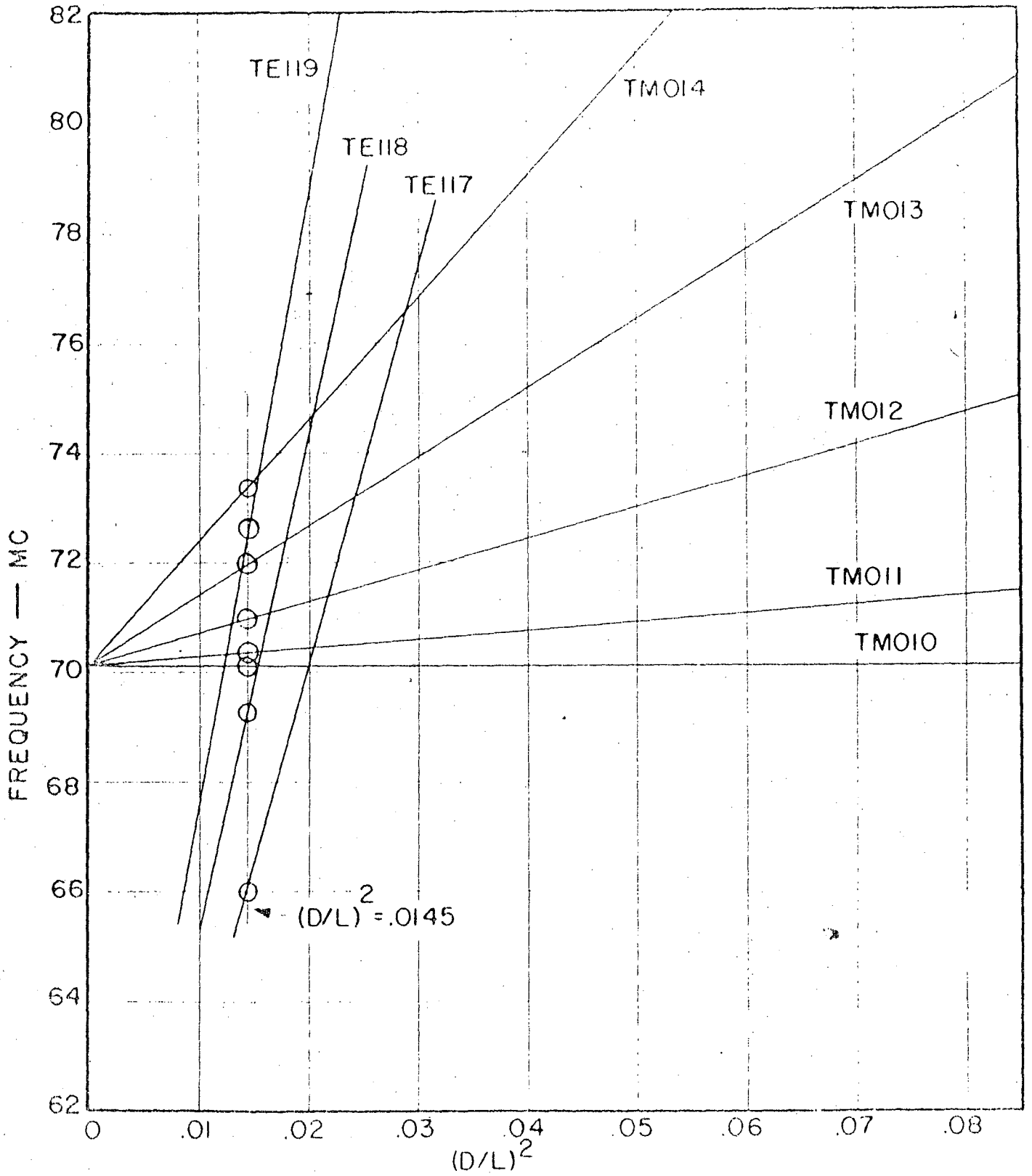

FIG. 5 MODES IN MAIN ACCELERATOR CAVITY

Fig. 6.

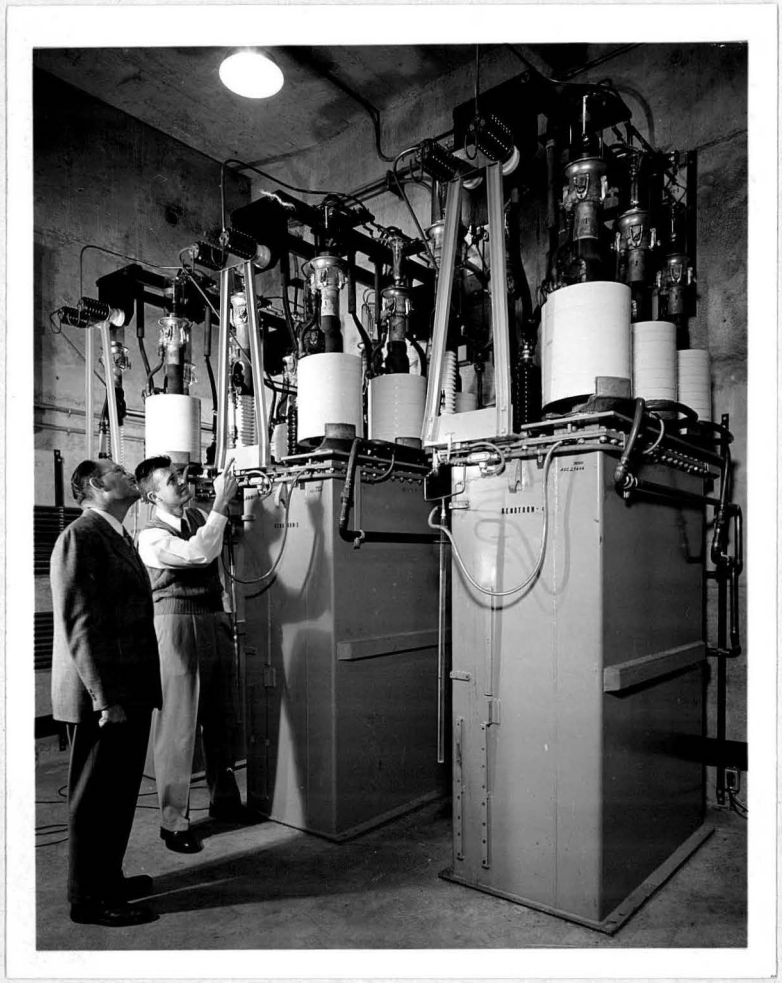

Fig. 7

Fig. 8