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One of our operating accelerators at the Lawrence Radiation Laboratory in Berkeley is a linear machine designed to accelerate ions which are heavy compared to protons. The Hilac (heavy-ion linear accelerator) accelerates helium, boron, carbon, nitrogen, oxygen, neon, and argon ions. It was designed jointly by LRL and Yale University and its sister machine is operating in New Haven. The Hilac is really two linear accelerators in tandem. The first is 10 feet in diameter and 15 feet long; the second is 9 feet in diameter and 90 feet long. Each tank is an evacuated radio-frequency cavity (Fig. 1.) Together they make up the load for our radio-frequency amplifiers. Average design gradient in the cavities is 0.5×10^6 volts per foot, at which level there is a transfer of 850 joules back and forth between magnetic and electric fields in the main cavity. The transfer takes place so rapidly that there is a reactive power flow of 3.75×10^{11} volt-amperes with a power loss of 3×10^6 watts. This means that the Q is about 125,000.

This energy (850 joules) is more than enough to cause serious damage if allowed to dissipate in the grid or filament bars of the amplifier tubes. More will be said of this later when the crowbar is discussed. The cavities are operated in the simple or TM_{010} mode in which the magnetic fields at the wall and the electric fields along the axis are in phase along the tank. The resonant frequency of the TM_{010} mode of cavities is 70.1 Mc, and the nearest other mode is at approximately 70.3 Mc. With the high Q of the cavity there is no trouble distinguishing between modes.

For reasons of original cost and economy of operation, the machine is pulsed. The pulses are 3 msec long, and the present repetition rate is 15 per second, resulting in a duty cycle of 4.5 percent (including 0.5×10^6 watts of peak power in the small cavity.) The average rf power required is about 150 kw. Radio-frequency power is supplied by four RCA 6949 superpower beam triodes (Fig. 2.) Each tube is in its own amplifier circuit and each amplifier is loop-coupled to the main cavity. At the present, power is supplied to the small cavity through a coupling line; however, we have a fifth amplifier ready to drive the small cavity. Before the accelerator was put into operation we had some question about the difficulty of making the amplifiers share the load. In practice this has not been a problem, and we can make a particular amplifier take more or less load by changing either drive or plate voltage. When one amplifier is turned off and its loop decoupled, the remaining amplifiers share the load equally well.

The input and output capacitances of the 6949 are 1400 pf and 160 pf respectively. There is also considerable inductance associated with the tube structure. Because we are operating at a frequency at which the input and output circuits are approaching series resonance, we use π networks to couple to both grid and plate. External capacitances equal to the tube capacitances were used to keep input and output voltage at the same levels as at the grid and plate. The schematic in Fig. 3 is the equivalent circuit.

The output circuit is connected to a coupling loop through a half-wave transmission line. Notice on the schematic that there is another small coupling loop and a half-wave transmission line to the input of the amplifier.

These were originally put in to supply drive power to the amplifier so that it could be operated as an oscillator. The tubes are now driven by Eimac 3W5000 triodes in grounded-grid circuits, and the grid lines are used to neutralize the grid-to-plate capacitance of the 6949. The grounded-grid drivers for all four amplifiers are driven from a single amplifier which is in turn driven from a master oscillator. A special circuit compares the phase of the rf in the tank with that of the drive, and the master oscillator is servoed to follow frequency drifts of the main rf cavity. Similarly, the resonant frequency of the small cavity is servoed to follow the frequency of the main tank by means of a motor-driven tuner that extends into the tank. The rf level of the main tank can also be servoed by comparing the voltage from a small monitoring loop with a reference. The difference is used to modulate the screen grid of the amplifier that drives the grounded-grid 3W5000 stages.

A pictorial representation of the amplifier is shown in Fig. 4. This is a figure of revolution, with the transmission lines extending in only one direction. Fig. 5 shows an amplifier with the outer cover removed. The grid circuit is a lumped-constant circuit tunable by a variable air capacitor consisting of intermeshing ribbed plates. The anode circuit is the coaxial transmission-line-like structure with the coupling capacitor connected to the upper part of the inner conductor. This capacitor is visible in the photograph. The output circuit is tuned somewhat higher than 70.1 Mc by extending the upper part of this structure. If we tune the output circuit of the amplifier to 70.1 Mc, we can get a situation in which the energy builds up in the anode circuit instead of the load cavity. This is accompanied by loud arching across high-voltage points in the amplifier circuit. Also if the inner conductor is not concentric with the outer conductor, we sometimes have a parasitic oscillation whose wave length is related to the circumferential distance around the inner conductor. This parasitic oscillator causes an increased rf current flow in the amplifier so that contact fingers are sometimes burned. The parasitic also causes the amplifier to refuse its full share of the load.

The amplifiers are run self-biased with a 167-ohm grid resistor, which develops 600 volts of bias when the grid is being driven about 2000 volts positive. In this condition the angle of plate current flow is approximately 170 degrees. Plate voltage not exceeding 20 kv is supplied from the pulse lines shown in Fig. 6. In general the heavier the ion, the more voltage is required. The line has a pulse length of 3 msec and a characteristic impedance of 133 ohms. The plate current of the 6949 is chopped into 70-Mc pulses by the drive, and requires peak emission of 240 amperes under the most severe loading conditions. The normal peak emission required is about 130 amps. Average plate current during the pulse varies from 40 to 80 amps. depending on the load. The plate circuit of the main amplifiers is so tightly coupled to the rf cavity that the plate-voltage swing is proportional to the level in the cavity. Thus there is no plate swing at the start of the pulse when the rf cavity voltage is zero; as the rf cavity builds up, so does the plate-voltage swing. It takes about 1 msec to get the rf cavity up to its final level, so during this time the rf component of plate voltage is gradually building up. During the remaining part of the pulse (2 msec), the amplifier is operating almost in a class B fashion.

An important factor in an rf system in which there are electric fields in a vacuum is a phenomenon called multipactoring. In a linear accelerator there are many drift tubes, all with different spacings. Corresponding to each spacing there is a critical voltage for which an electron accelerated on one-half cycle of the rf creates secondaries which are accelerated back on the next half-cycle. At the critical voltage levels it does not take long to have amperes flowing between drift tubes, so that the rf cavity is very effectively short-circuited. If the cavity locks at one of these levels, all the power one can furnish goes into moving electrons back and forth. It helps to have the metal surfaces clean and spark-conditioned, but it is also necessary to have the rate of rise of rf level in the cavity rapid enough to pass through these critical resonances before there have been enough cycles of the rf to build up the loading current. This means that the drive must be brought on very rapidly, and be kept as large as possible commensurate with the 6949 grid ratings. When the machine was being put in service there was some question whether three amplifiers operating in parallel could break through the multipactoring levels, but now, with improved drive and subsequent conditioning of the critical surfaces in the rf cavity, the main cavity can be brought up through these levels with two amplifiers. In any case the drift-tube magnets need to be on in order to inhibit the flow of electrons and ions between drift tubes.

In the early days of Hilac, when it was operating with three amplifiers, the maximum plate voltage was required to accelerate neon. The same is now true for accelerating argon with four amplifiers. High voltage causes the tubes to spark internally. If the full energy stored in the pulse line (8000 joules) were allowed to dissipate itself in this spark, cumulative damage to the tube would result. To protect the tube against this possibility, we have an ignitron switch or "crowbar" which short circuits the pulse line and diverts current from the amplifier tube. Excessive current in the pulse-line lead triggers the crowbar within a few microseconds of the fault. As mentioned earlier, there is also 850 joules stored in the rf fields in the tank. At least one tube has been damaged because of this energy, and now we have an rf crowbar in addition to the pulse-line crowbar. This works by causing a spark gap to fire in the vacuum tank. The resulting discharge spews electrons and ions into the rf fields, dissipating the energy in the tank within 10 -15 μsec. Because the discharge is tightly coupled to the fields, most of the stored energy is kept out of the amplifier circuits. The rf crowbar is fired when there is a call for a dc crowbar on any of the tubes; it is also fired when a directional coupler on the transmission line of any amplifier indicates a reversal of energy flow to the cavity.

Both the Hilac and the one at Yale have been operating for several years with the present system. A slow but continuous process of refinement of the drive system and the main amplifiers have been going on in an effort to get trouble-free three-shift operation. At LRL we have had five amplifiers operating on occasion, and hope to have these on continuously in a few months. We plan to eventually have a sixth operating amplifier which will give us an installed spare in case of trouble, and will also serve to reduce the load on the other amplifiers.

A number of people have been responsible for the development of this rf system. The original design of the amplifiers was due to Neil Norris from LRL and George Wheeler of Yale. William Baker contributed much to debugging the system when it was first put in operation. Later work on servoing frequency and rf level was due to Ed Hartwig.

The development and operation of these machines was done under the auspices of the Atomic Energy Commission.

LEGENDS

Fig. 1. Interior of the main cavity.

Fig. 2. The four rf amplifiers connected to the main cavity.

Fig. 3. Equivalent circuit for the final amplifier.

Fig. 4. Final amplifier circuit.

Fig. 5. An amplifier with the outer cover removed.

Fig. 6. Two of the pulse lines used to supply energy to the main cavity.

Fig. 1

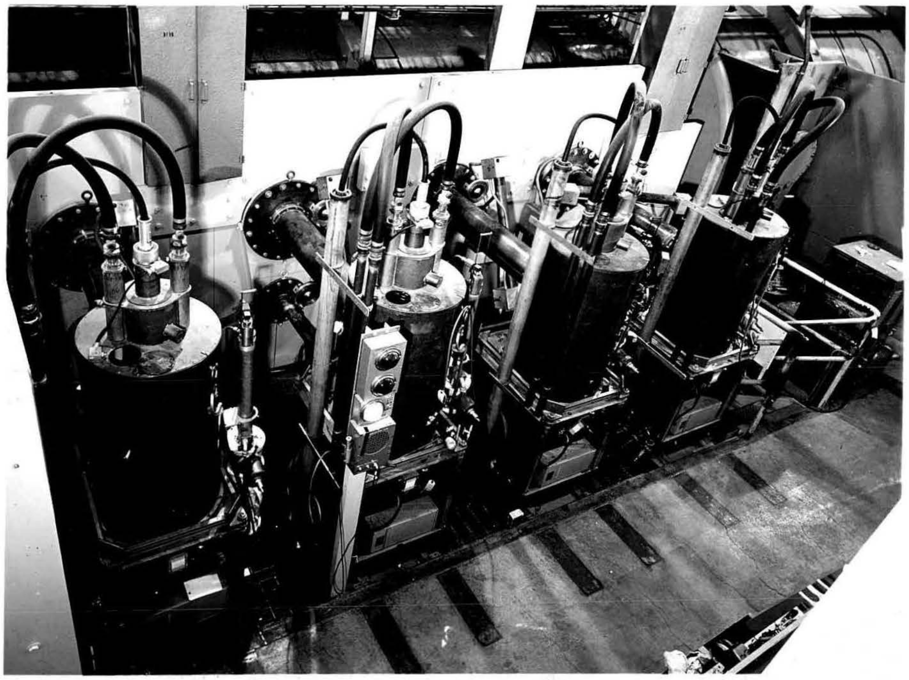

Fig. 2

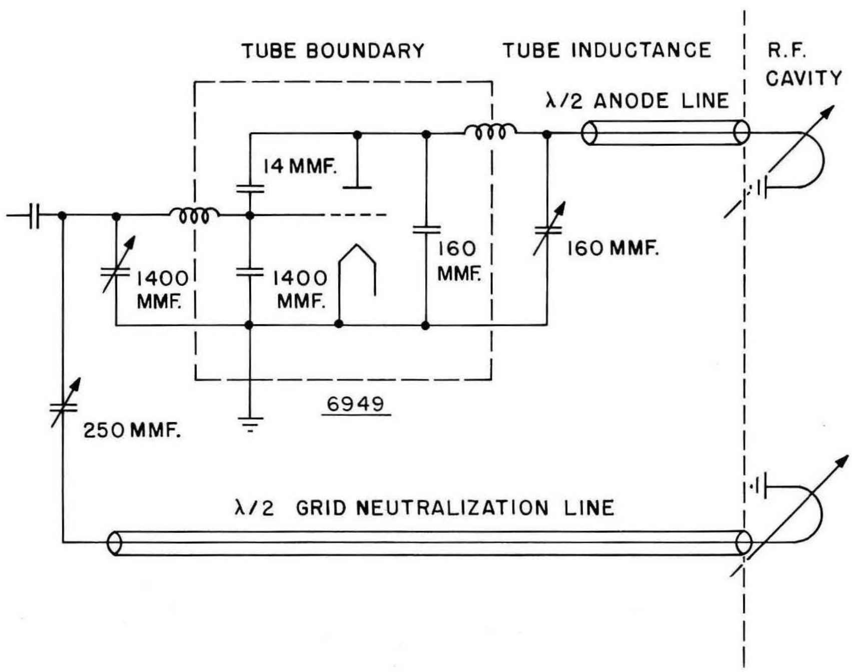
TUBE BOUNDARY
TUBE INDUCTANCE
R.F. CAVITY
λ/2 ANODE LINE
14 MMF.
160 MMF.
160 MMF.
1400 MMF.
1400 MMF.
6949
250 MMF.
λ/2 GRID NEUTRALIZATION LINE

Fig. 3

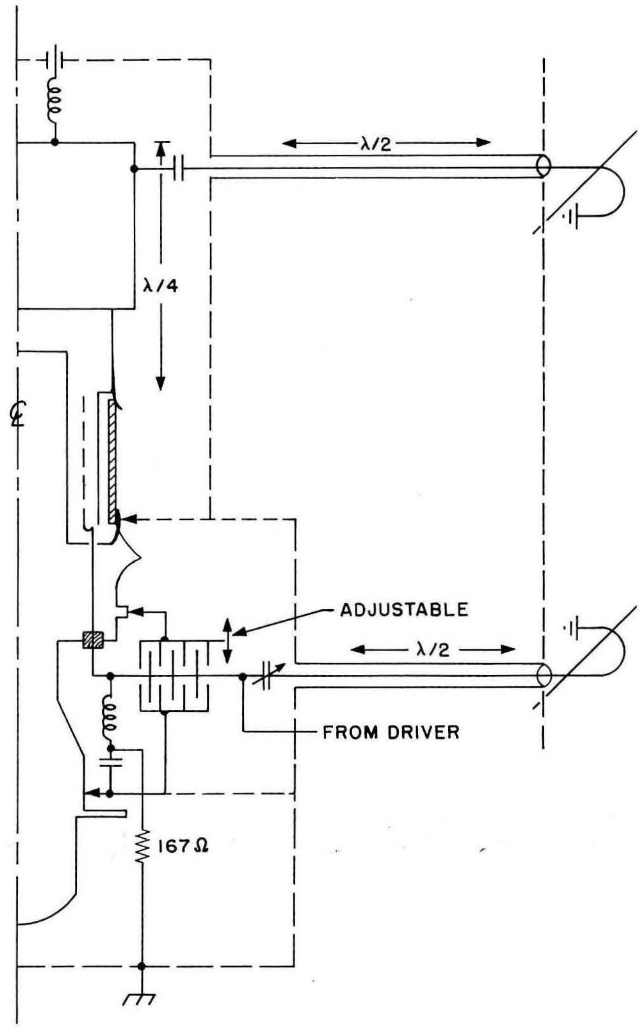

Fig. 4

Fig. 5

Fig. 6