DYNAMITRONS OF THE FUTURE

Marshall R. Cleland and Paul Farrell
Radiation Dynamics, Inc.
Westbury, New York

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I. ABSTRACT

A description of the Dynamitron high-current accelerator is given, illustrated with a photograph of a 3.0 Mv unit. Simplified circuit diagrams of the rectifier cascade are presented and performance data are compared with formulas for internal impedance and power consumption. Brief descriptions of the ion source and the beam tube are also given. Possibilities for future development of the accelerator and accessories are discussed. These include higher voltage, higher beam current, terminal pumping, terminal mass analysis, nanosecond beam pulsing, high intensity pulsing, high energy negative ion production and dual purpose tandem accelerators.

II. GENERAL DESCRIPTION

A photograph of the 3.0 Mv Dynamitron recently installed at the University of Mexico is shown in Fig. 1. In this view the essential features of the system are evident; the long acceleration column, the corona rings, the high voltage terminal, the pressure vessel and the rf electrode system mounted within the vessel.

The corona rings are semicircular and, in addition to the usual function of suppressing sparks and corona discharges, provide the coupling capacitance through which rf power is transmitted to the rectifiers within the column. When the vessel is closed, the large, semicylindrical electrodes completely surround the high voltage column and energize all the rectifier stages equally through the mutual capacitance between these electrodes and the split corona rings.

A combined pictorial and circuit diagram of the high voltage generator is shown in Fig. 2. The rf electrodes are shown connected to the center-tapped inductor which serves as an rf voltage transformer. This is shunt-fed at a tap point near ground by a power triode which receives its grid excitation by direct feedback from the opposite side of the inductor. This rf circuit is self-tuning, so that the frequency can change with minor variation in capacitance which is caused by flexing of the electrodes under the stress of the strong electrostatic field from the high voltage column.

The inductor is torroidal in shape and is located within the pressure vessel at the rear to take advantage of the compressed gas insulation and to simplify the connections to the electrodes. The power tube and its auxiliary components are located in a cabinet external to the vessel. The grid and plate connections, which are unterminated coaxial cables, can be up to 50 feet in length without adverse effect on the performance of the circuit. All of the capacitors shown in this diagram are of gaseous dielectric construction. The resonant capacitance (CEG) is mainly the external capacitance from the electrodes to the surrounding pressure vessel. The grid capacitor is formed by a large aluminum plate located between the electrode and the vessel while the coupling capacitors (CSE) are formed as explained before by the surfaces of the corona rings. The rf chokes at each end of the column isolate the first and last corona rings from ground so that the full increment of voltage will be induced across the end rectifiers. The choke at the high voltage end serves also to filter the current pulses from the last rectifier and thus to reduce the high frequency ripple to a very low value estimated at a few hundred volts.

III. ANALYSIS AND PERFORMANCE

A simplified circuit diagram of the cascade is shown in Fig. 3. The output voltage, E, under load for N stages is given by

$$E = NV/k - NI/kfC \pm I/2fC,$$

where I is the load current, V is the peak rf electrode voltage, f is the frequency, C is the coupling capacitance (CSE), and k, the coupling coefficient is the ratio of the applied input to the induced rf voltage per stage. This parameter is given by

$$k = 1 + 4(CAC)/C,$$

where (CAC) is the shunt capacitance of each stage.

The coupling coefficient appears in the impedance term showing that the shunt capacitance of the stages is not entirely detrimental to the performance of the circuit. Of course, a low internal impedance is the primary requisite for a high current generator and this is achieved in spite of the small size of the coupling capacitance, by the use of high frequency power. Typical values are N = 64, V = 300 Kv peak-to-peak, k = 6, (CSE) = 3.5 pf and f = 120 Kc yielding an impedance value of about 24 megohms. This is to be compared with the equivalent load resistance of a 10 milliampere beam at 3.0 Mv which is 300 megohms. Therefore, the inherent full-load droop is about 8 percent. In practice this droop is corrected by a feed-back system which increases the rf input to maintain a constant dc output.

The fact that the impedance term is proportional to the first power of N gives this circuit a very valuable property, namely, that the load regulation, which is the ratio of the first two terms, is independent of the number of stages. This is why it is possible to use so many stages and to achieve such high voltages with this circuit. This is a property which is unique to the Dynamitron, for the impedance of series-coupled cascades such as the Cockcroft-Walton machine increases as the third power of N, in which case the load regulation worsens as the square of the number of stages. It is also interesting to note that the ripple is independent of the number of stages.

Load regulation data are presented in Fig. 4. The rf electrode voltage was held constant by manual adjustment of the controls while the electron beam load was increased so that the fall-off in output voltage is due solely to the internal impedance of the rectifier cascade. The measured impedance of 18 megohms is in approximate agreement with the calculated value. The discrepancy can easily be due to errors in estimating either the coupling capacitance (CSE) or the shunt capacitance (CAC) of the column, both of which depend on the odd shapes and spacings of the electrodes and the corona rings. The higher impedance obtained at the lower voltage was due to reduced emission of the rectifier tube filaments which were not regulated during this test. In production units the filaments are regulated from 0.75 Mv on up and the column impedance is independent of voltage over this range.

Data on input power versus electron beam power are given in Fig. 5. The oscillator plate input power is given by

$$P = 1.25(AE^2 + BEI),$$

where $A = R_e/X^2$,

$$B = 1 + 2R_eZ/X^2,$$

$$Z = N/fr(CSE),$$

and $X = Z(CSE)/\pi(CEG)$.

Here, E is the output voltage of the column, I is the load current, R_e is the effective resistance of the resonant circuit and Z is the column impedance.

The first term represents power to generate voltage without beam load. This goes into heat losses in the coil, the electrode system, the vessel and the oscillator anode. The second term accounts not only for beam power but also for the additional losses associated with the increased rf level required to maintain constant output voltage. Again the discrepancy between the data and the calculated values can be attributed to difficulties in the computation of the system capacitances and the effective coil resistance. The general shape and magnitude of the formula is essentially correct. A beam of 20 milliamperes at 2.0 Mv or 40 kilowatts of beam power has already been demonstrated. The data at 3.0 Mv is still incomplete but 11 ma have been achieved and the extrapolation of the line suggests that 20 ma will be possible within the 150 KW rating of the standard oscillator. At this point the beam power would be 60 kilowatts and the power conversion efficiency would be 40 percent. These are very high figures for any particle accelerator.

IV. BEAM COMPONENTS

a. Ion Source

The duoplasmatron type of ion source has been chosen primarily because of its high output which matches the current rating of the Dynamitron. An experimental model of the source in which the arc is visible is shown in Fig. 6. The concentration of the plasma by the magnetic grid is easily seen and visual observation of the color of the plasma and the cathode are very useful features. Compared to the more conventional rf ion source, the duoplasmatron is more expensive, requires more power to operate and also requires a special cooling system, but it does have several attractive features other than high current. These are low energy spread, low gas flow, small beam emittance and long life at high current. In each of these aspects it is superior to the rf source.

b. Beam Tube

It has been necessary to make some improvements in beam tube design in order to produce stable high-intensity beams. It is necessary to have high pumping speed and good wall shielding, and these design requirements are somewhat contradictory. Two successful designs are shown in a composite drawing in Fig. 7. The lower dynode design which gives partial shielding of the insulators is only satisfactory if the resistivity of the insulators is rather low. The upper dynode design is superior in that it gives complete shielding against both scattered ions and backstreaming electrons and permits a free choice of insulator material. This design was first used by Dr. Turner of Brookhaven on a tube for the G.E. electrostatic machine. A similar version has been built by RDI for the new Dynamitron at Brookhaven. Its voltage conditioning properties are excellent and the stability of the beam is remarkable.

V. FUTURE PROSPECTS

a. Higher Voltage

Perhaps the most important avenue for future development of the Dynamitron line will be the extension to higher voltages up to 6.0 Mv and beyond. This can be done because the load regulation is independent of the number of stages of rectification. It will only be necessary to increase the column length and the number of stages in proportion to the voltage and to increase the radial dimensions to provide adequate insulation and mechanical strength. The column length is 8 feet on the present 3.0 Mv models and will be 16 feet at 6.0 Mv giving a column gradient of 375 Kv/ft. This is less than the 500 Kv/ft gradient of most Van de Graaffs and has been chosen for safety and to provide room for growth in performance.

The radial dimensions are chosen from considerations of coupling capacitance and electric field strength. These parameters are shown in Fig. 8. It can be seen that the ratio of inner to outer diameters should be kept to between 0.3 and 0.7 to minimize the electric field while the coupling capacitance is better for the larger ratios. The ratio for the various Dynamitron models lies between 0.5 and 0.7. Radial dimensions are given in Fig. 9 for four basic models. Ideally the r/R ratio and the V/R ratio should be held constant, but this is not practicable because of lack of space within the column for rectifier tubes and other components on the smaller units.

A comparison of several important design parameters is shown in Fig. 10 for these dimensions. The coupling capacitance (CSE) diminishes for the larger models causing an increase in the coupling coefficient, k. This means a slightly higher rf voltage will be required for the same stage voltage, which, however, will not be a serious problem. The load regulation, Δ, is almost constant because of the dominant effect of the shunt capacitance of the rectifier stages which is the same for all models. The most critical parameter is the electric field strength, E, at the high voltage terminal which is nearly constant. The slight increase indicated can be handled by an increase in gas pressure. These parameters demonstrate the feasibility of extending the rating of the high voltage generator without sacrificing the low impedance characteristic.

b. Higher Current

Electron beams of 20 ma have already been achieved. There are no serious limitations to higher currents in the gun or in the acceleration tube if it is ever needed for some special purpose. The impedance of the power supply would have to be reduced either by operation at a higher frequency or by using a smaller number of stages with a higher voltage per stage. The power rating of the oscillator would, or course, also have to be increased.

The positive ion beam current is limited to a few milliamperes at present, not by the generator nor by the source itself, but by secondary effects associated with gas scattering in the accelerator tube. This problem will be discussed by Mr. Kellogg in a later paper. Extensions to higher currents and higher voltages will require improvements in the gas efficiency of the source, better vacuum pumping at the entrance to the column or mass analysis of the beam before acceleration. With all three of these features it might be possible to achieve proton beams of at least 5.0 ma at maximum voltage. Such beams would certainly challenge the ingenuity of the user for target designs which can withstand this power.

c. Terminal Pumping

The need for terminal pumping in dc accelerators arises because the ion source is isolated from the main vacuum pump by the acceleration column whose pumping speed is typically about

50 liters per second. The addition of a pump at the entrance to the column with a speed of a few hundred liters/second would dramatically improve the situation. This may be achieved for hydrogen by the use of large barium getters or commercial getter-ion pumps. The new Orbitron pump under development at the University of Wisconsin which works without a magnet may be a good solution to this problem.

d. Terminal Mass Analysis

Mass analysis before acceleration will be desirable for the high intensity beams from the duoplasmatron source because as much as 50 percent of the beam may be molecular ions. These molecular ions load down the generator and also contribute to the side effects of gas scattering in the column. The molecular beam is also undesirable in the external beam transport system. Several different approaches can be taken in the design of the analyzer, the choice depending on considerations of size, weight and beam optics. A three-element in-line analyzer has been suggested by Dr. Langsdorf of Argonne, which would permit a controlled admixture of molecular ions along with the atomic beam. The weak molecular beam could then be used for voltage stabilization so as to circumvent the serious problem of slit cooling on the high power proton beam.

e. Nanosecond Beam Pulsing

The nanosecond beam pulsing system developed at Oak Ridge and now manufactured by ORTEC will be installed in a new 3.0 Mv Dynamitron now under construction for the joint facility of the University of Ottawa and Carleton University in Canada. The pulsing system can produce proton pulses of 10 ma peak at 1.0 nanosecond by a combination of beam scanning and velocity bunching. The energy spread introduced by bunching is only a few kilovolts and the time focus can be adjusted over a considerable range of target locations in the laboratory. This Dynamitron is being made slightly larger than previous models to accommodate the components of the pulser without crowding. The terminal will be 3 feet in diameter by 5 feet in length and will have 18 control rod positions available, 14 of which will be used to give operator control of all the important parameters of the ion source, pulser and optical system. The generator is very conservatively rated at 3.0 Mv and somewhat higher voltages are anticipated.

f. High Intensity Pulsing

For some applications very high intensity beam pulses are required. If the pulse length is limited to a few microseconds, the charge stored on the high voltage terminal capacitance will be sufficient to deliver the current and the peak intensity will be limited only by the particle source or the effects of space charge at the entrance to the column. For example, at Brookhaven the 0.75 Mv Cockcroft-Walton injector for the AGS has achieved proton pulses up to 100 ma and the 4.0 Mv Van de Graaff injector for the Cosmotron has delivered about 50 ma. In the 3.0 Mv Dynamitron the column gradient and the entrance apérture impose a theoretical space charge limit somewhere between 100 and 200 ma for proton beams and between 5 and 10 amperes for electron beams. These figures are for an injection energy of about 50 kilovolts. High power electron guns and ion sources already exist with these capabilities so that it would seem reasonable to attempt such ratings provided sufficient space and power were available within the high voltage terminal. The new Ottawa-style machine should be more than adequate with a 4.0 KW shaft-driven alternator in the terminal and room for a duplicate system if required.

g. High Energy Negative Ions

Recent developments in ion source technology at Los Alamos, Oak Ridge and other places have produced negative hydrogen ion beams of more than 50 microamperes by direct extraction from duoplasmatrons. These sources are compact enough to be mounted within the terminal of an accelerator and will provide a practical means of obtaining high energy beams of negative ions of unusually high intensity. Single-ended machines equipped with such sources will be used as injectors to extend the energy range and increase the beam intensity of existing tandem facilities. A Dynamitron injector could be made convertible to high intensity positive ion operation to support a separate research program.

Fig. 11 shows a layout of a 4.5 Mv Dynamitron designed for this purpose. It can be equipped with an Orbitron pump and a crossed-field analyzer in the terminal to maximize the proton yield. These accessories would also be beneficial with the negative ion source to deflect the source electrons and to reduce beam loss from charge-exchange collisions. An additional feature is the provision for future extension to a tandem configuration by inclusion of another main flange and beam port on the rear of the vessel. The rf transformer and its heat exchanger can be housed in a side pod instead of the usual location at the rear of the vessel in order to leave the axis clear for a second column structure. The vessel can be easily extended by inserting a flanged cylindrical section. The rectifier cascade and the rf system would be unchanged by this modification.

h. Dual Purpose Tandems

Since the beam current of tandem accelerators is severely limited by the negative ion injection system, the question naturally arises whether or not there is any justification for the use of the Dynamitron principle for tandems. If injectors can be developed which will produce a milliampere of negative ions then the need will be clear. In the meantime there might be some advantages to using a "brute-force" power supply in order to achieve greater tolerance to electron loading and corona loading effects. This would permit the use of simple uniform-field acceleration tubes instead of inclined-field tubes up to at least 6.0 Mv. Such tubes are still attractive because of the great stability of the beam position on target. A better jusitification can be made for a dual-purpose tandem which would come equipped with a high intensity positive ion source in the terminal. This source could be mounted at an angle to the tandem beam axis with an analyzing magnet to inflect the beam or it could be mounted on a separate beam tube off to one side. The latter configuration would be more expensive and would require a separate analyzing magnet on the output end, but could be used without disturbing the tandem setup.

V. CONCLUSION

The high power capability of the Dynamitron accelerator has been amply demonstrated and the machine is now firmly established as a useful tool in radiation research programs. Twenty-two machines have been delivered to date of which 12 are 3.0 Mv models and three more 3's are in production at Westbury. This accelerator preserves the main advantages of the Van de Graaff in compactness and stability of voltage and of the Cockcroft-Walton machine in its high power rating while avoiding the limitations of low current in the former and low voltage and high energy storage in the latter. It is the first dc accelerator other than the Van de Graaff to operate successfully above 2.0 Mv. It can be anticipated that the future possibilities for the Dynamitron which have been suggested here will soon be required to satisfy the ever-growing needs of research, not only in low-energy nuclear physics but in the other sciences as well.

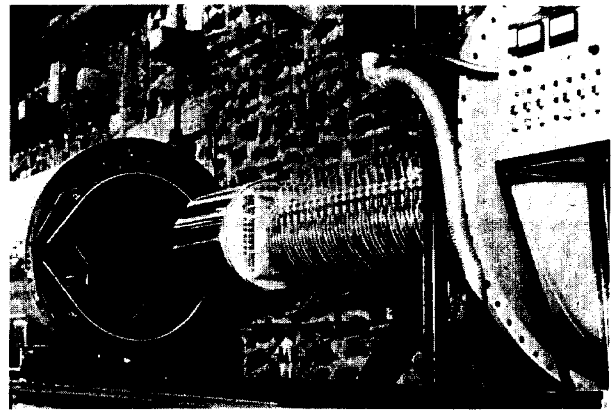
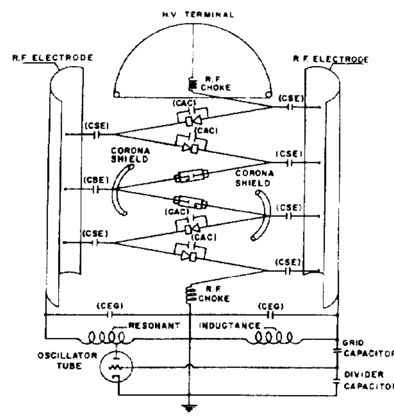


Fig. 1. The 3.0 Mv Dynamitron at the University of Mexico.

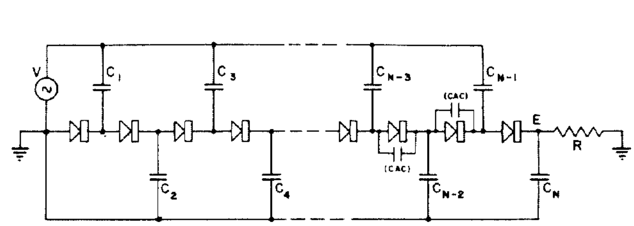


SYM.	CAPACITANCE
(CSE)	SHIELD TO ELECTRODE
(CAC)	ANODE TO CATHODE
(CEG)	ELECTRODE TO GRD

DYNAMITRON ACCELERATOR

Fig.2. Pictorial circuit diagram of the parallel coupled cascade generator.

PARALLEL COUPLED VOLTAGE MULTIPLIER CIRCUIT



$$E = \frac{NV}{k} - \overbrace{\frac{I(N-1)}{fCk}}^{\text{DROOP}} \pm \overbrace{\frac{I}{2fC}}^{\text{RIPPLE}}$$

$$k = 1 + \frac{4(CAC)}{C} \qquad N_{OPTIMUM} = \infty$$

Fig. 3. Simplified diagram of the cascade circuit.

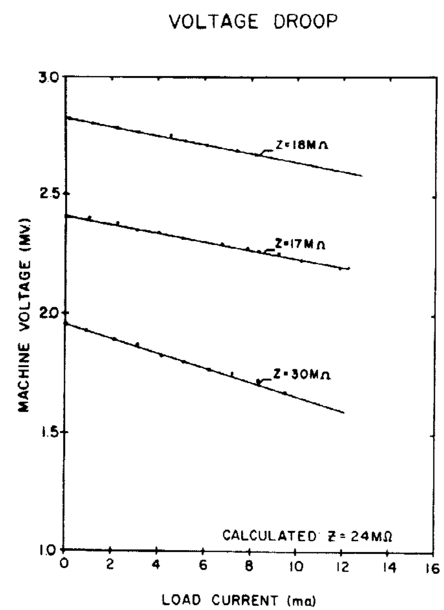


Fig. 4. Load regulation characteristic without feed-back.

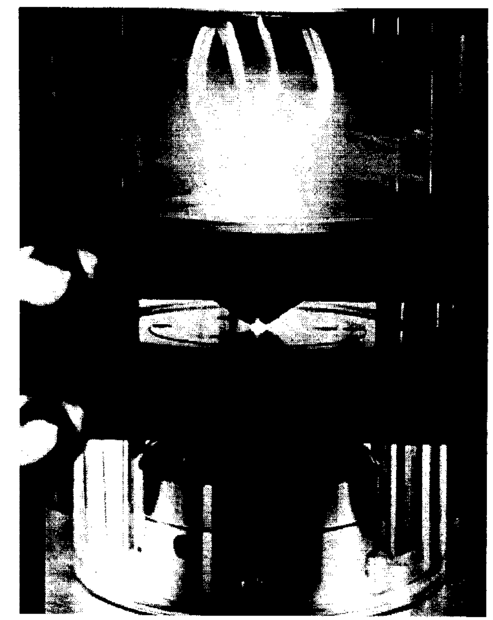


Fig. 6. Duoplasmatron ion source with visible arc chambers.

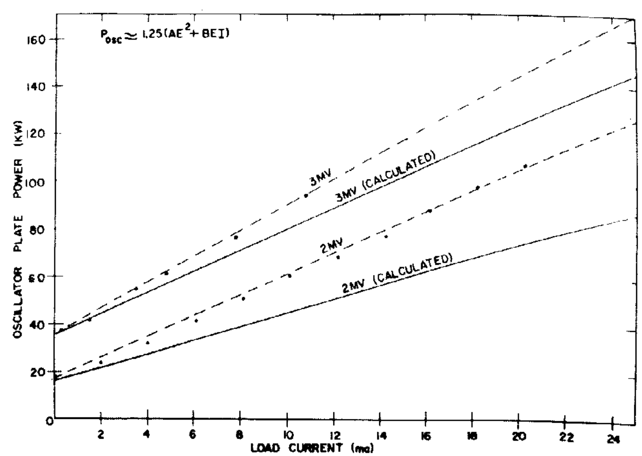


Fig. 5. Input power requirement as a function of output voltage and current.

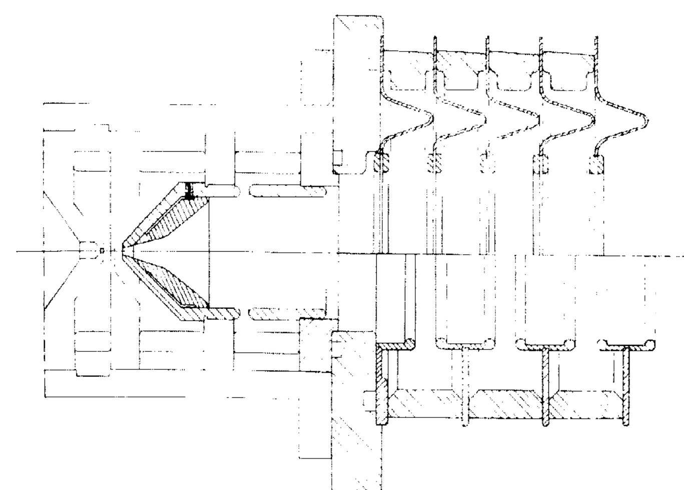


Fig. 7. Composite layout of the acceleration tube showing two dynode designs.

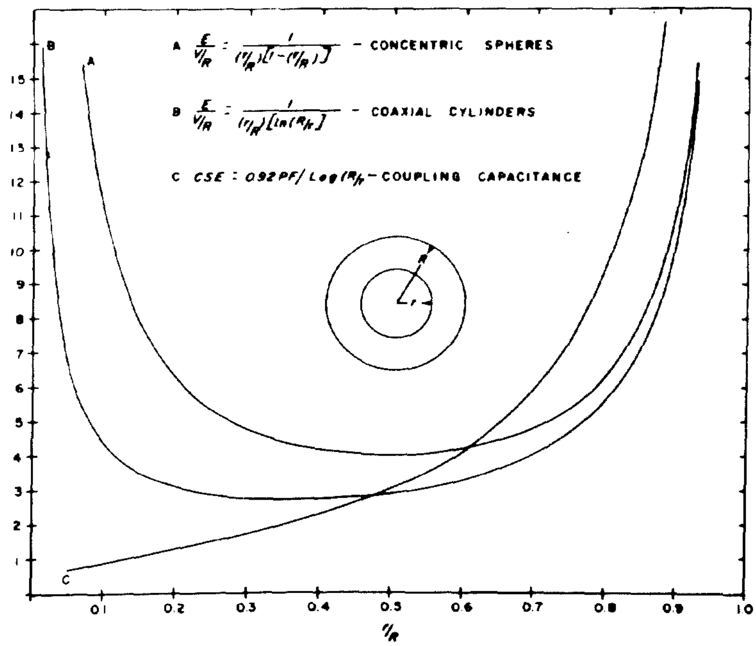


Fig. 8. Electric field strength and coupling capacitance as a function of column radius.

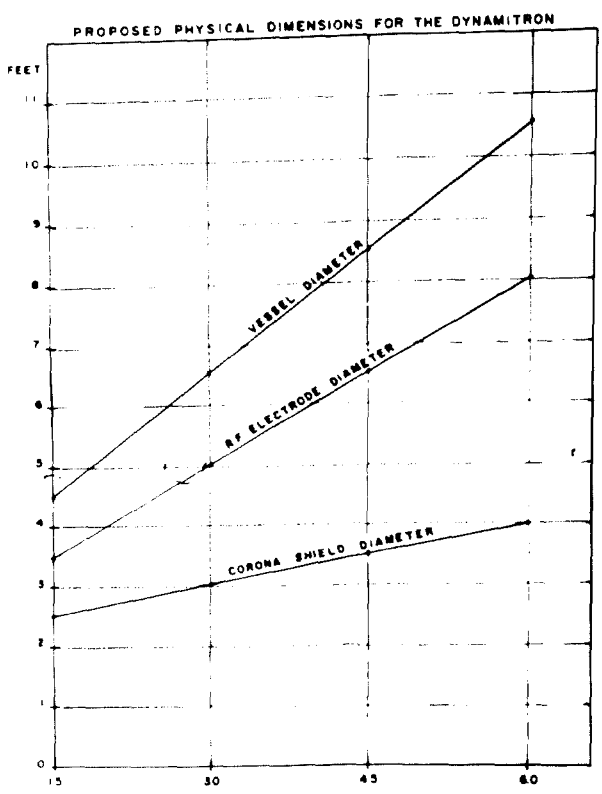


Fig. 9. Radial dimensions of four basic models.

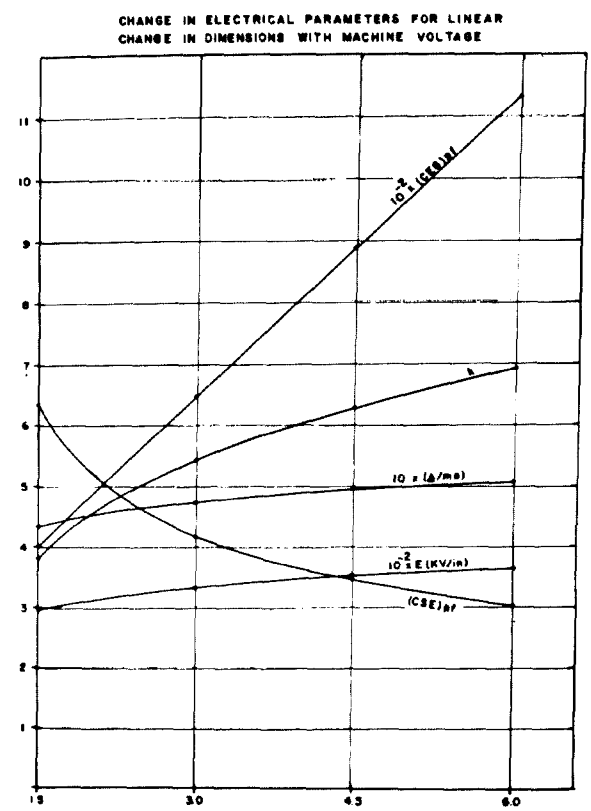


Fig. 10. Electrical design parameters of four basic models.

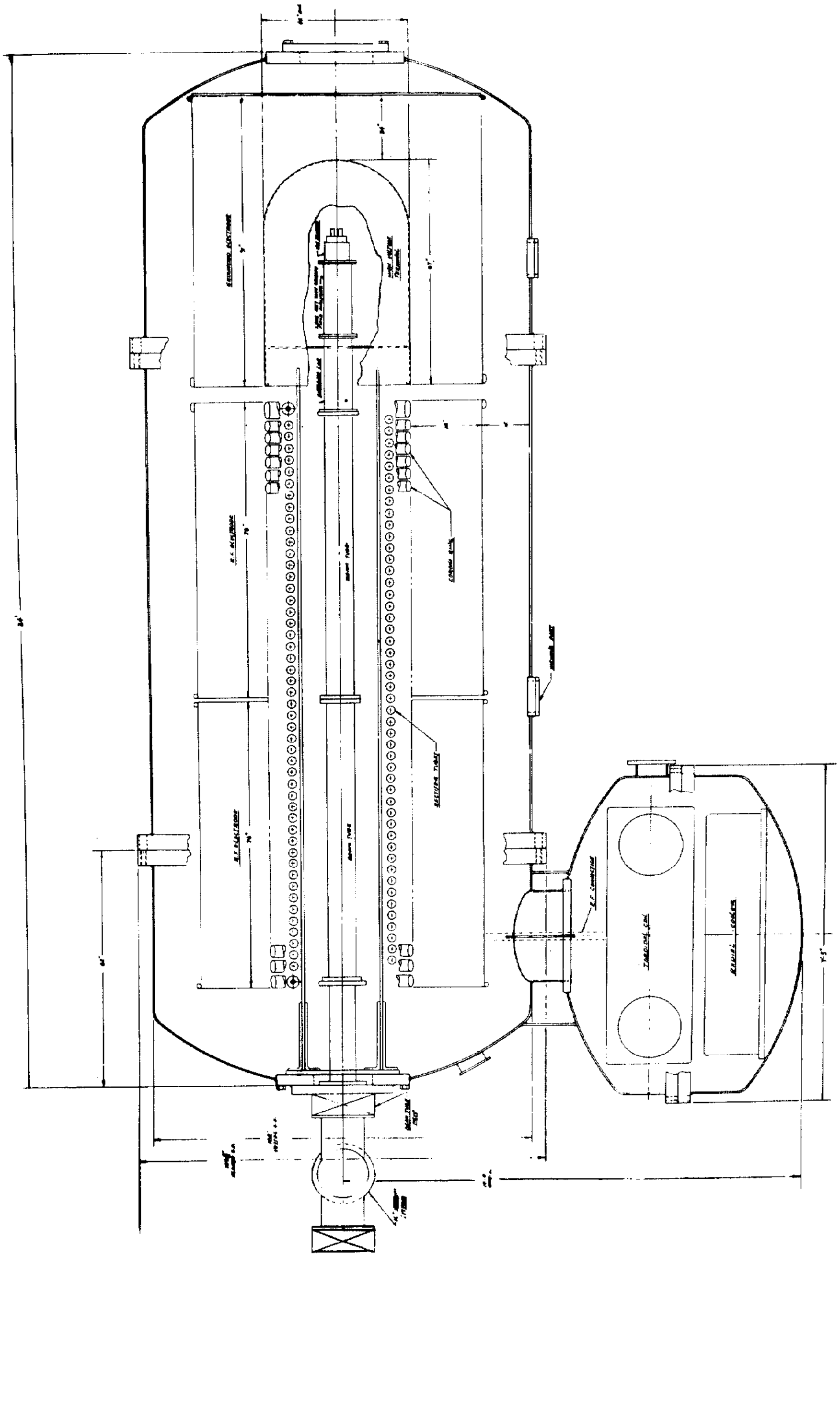


Fig. 11. Layout of a 4.5 Mv model with provisions for tandem conversion.