RESONANT SIDE-COUPLED CAVITY ELECTRON ACCELERATORS

By

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The development of the side-coupled cavity chain as a high shunt impedance accelerator structure represents a significant change in accelerator design.[1,2] To further investigate the properties of this type resonant cavity chain accelerator system we have built and operated two short electron accelerators, and are building a 20 MeV multi-section electron accelerator. In this paper we will describe the performance of the two short accelerators, and give a progress report on the construction of the 20 MeV high current, high duty factor linac.

Side-coupled Cavity Chain

The side-coupled cavity chain has been described in detail elsewhere, and we will not discuss the synthesis of this system in this paper, but only summarize some characteristics of a cavity chain of this type. The principal advantages in using the $\pi/2$-mode accelerating structure system are the very high stability of the electromagnetic field distributions in the presence of heavy beam loading and cavity resonant frequency errors, and the exceptionally high shunt impedance attainable in this system. The high stability of the field distributions arises from general properties of the $\pi/2$-mode of a biperiodic cavity chain.[3] The exceptionally high shunt impedance is obtained by locating the alternate "empty" cavities of the $\pi/2$-mode off the beam line, giving almost complete freedom to design the on-line cavities to maximize the efficiency of the strucutre as an accelerator. Shunt impedances more than 4 times that obtainable in $\pi/2$-mode iris loaded waveguide with comperable coupling and operating at the same frequency are attainable with this system. Figure 1 shows a cutaway drawing of a side-coupled optimized shunt impedance cavity chain.

Test System

Figure 2 shows a block diagram of the system used in operating two short sections of side-coupled accelerator structure as electron accelerators. A pulsed electron gun injects electrons into the accelerator system at up to 100 keV. This injector uses a gridded configuration with the grid at the head potential and the cathode pulsed negative to turn on the beam. Communication to the high voltage head is with light links which both pulse the gun and transmit and receive set point data and commands. Total cathode current, bias voltage, and any other data desired are available remotely using this system.

The electron beam is then focused in a solenoid magnet and steered to pass through a set of beam position defining aperatures and injected into the accelerator tank. The accelerator tanks have been energized by two 805 MHz power amplifiers, one a coaxial triode capable of producing >500 kW peak power at 3% duty factor, the other a klystron driver amplifer capable of operating at 100 kW peak power and 6% duty fact. The rf amplifiers used are sections of the test stands built by the rf amplifier group at Los Alamos and have been reported upon previously.[4,5] The tank was driven through more than 100 ft of waveguide transmission line. Power into and reflected from the tank was measured by a calibrated directional coupler located in the waveguide at the tank. Tank cooling temperature was held fixed by a recirculating water system and any changes in resonant frequency of the accelerator tank with rf power level were tracked by varying the driving frequency to the amplifier.

After accelerating the beam is again focused and then may be collected on a Faraday cup, energy analyzed using a magnetic spectrometer, or extracted into the room through a thin foil.

Two accelerator sections have been used in this set up. The first, called Model L, is a 5 cavity side-coupled accelerator tank, ~1 meter long, with a synchronous particle velocity $\beta_s = 1.0$ throughout its entire length. For a synchronous particle this tank has a measured shunt impedance ZT^2 of 42 MΩ/m (ZT^2 = (energy gain/meter)^2/(power dissipated/meter), and a resonant frequency of 805 MHz. Power is coupled into the middle on-line cavity through an iris whose size is adjusted to properly match the impedance of the resonant tank to the impedance of the transmission line. The vacuum seal is made by locating a ceramic window in this iris opening. Cooling is provided by rectangular water passages attached to the outside of the tank. No cooling for the side cavities is provided. Model L is similar to the tank shown in Fig. 1.

The second accelerator tank, called Model M, is also ~1 meter long but is composed of 6 on-line cavities each of different length, to provide a match between the velocity of the accelerating electron and the electromagnetic wave. Figure 3 shows a drawing of this accelerator tank. The cavity lengths were chosen so that a continously injected beam would be bunched with the bunch centered about peak field as it traversed each cavity in the chain. This was done using a digital computer program called WATUSI which integrates the motion of the electrons stepwise through the axial fields in the resonant cavities. The fields used are experimentally determined by standard perturbation techniques. WATUSI has been used to predict the behavior of both Model L and Model M in the tests reported here.

Figure 4 shows the behavior of Model M predicted by WATUSI through each cell. At injection the beam is continous and at each 3° of input phase an electron is started through the calculation and is represented by a point on the graph. Figure 4a is the output from cell No. 1, 4B the output from cell No. 2, and Fig. 4c the output from cell No. 6, the last cell in the chain. The general behavior is as would be expected.

The radial motion has also been investigated, first with a program called LINDY[6] which was written by D. A. Swenson for drift tube linac studies and was modified for this work. LINDY uses the fields determined by LALA,[7] a program which calculated the electromagnetic field distributions in a cylindrically symmetric cavity by relaxation techniques, and traces the trajectory of a particle through the resultant 3 dimentional fields. Another program has been written, called FARM,[8] which uses the experimentally determined axial fields and Maxwell's equations to derive the off axis radial fields for the radial motion calculations. These calculations yield similar results and indicate that in Model M ~40% of the incident direct current beam is both accelerated in a fairly tight bunch and confined radially to an exit radius less than twice the entrance radius of the beam. In general the individual electron trajectories are quite complicated. Provision for focusing magnet fields, etc. have been provided for in the computer program, and rather complete beam profile studies may be made using FARM.[8]

Experimental Results

No problems have been encountered in running either of these accelerator sections as high duty factor high average current electron accelerators. Model L set up in an iron radiation enclosure is shown in Fig. 5. Extensive measurements on the energy spectrum from Model L using a magnetic spectrometer at low duty factor (0.5%) and low current (±0.5 mA peak) have verified the shunt impedance measurements made by perturbation techniques. Figure 6 shows the results of these runs. No difficulties were encountered at 20 mA peak accelerated current and 3% duty factor operation. System cooling considerations precluded higher current operation. Energies above 3 MeV have been obtained with these currents and duty factors, estimated from the depth of darkening in a stack of glass microscope slides.

Model M has been operated with a 100 kW klystron driver at 6% D.F., 20 mA peak accelerated current and ~1.1 MeV output energy. Accurate energy determinations with these high average currents have been difficult due to the high power density in the beam. It is possible to achieve a beam hot spot less than 4 mm in diameter by focusing the output from Model M, determined by the size hole melted through a 3 mm aluminum plate into a water jacket in a cooled Faraday cup.

Operation of Model M at up to 60 mA peak current with reduced duty factor has been obtained and no limit on duty factor or current due to accelerator cavity performance has been observed.

Electron Prototype Accelerator

A 20 MeV, 20 mA peak 6% D.F. electron linac is being built to investigate in detail some of the problems associated with the construction of the Los Alamos Meson Physics Linac. Figure 7 shows a schematic diagram of the accelerator system. The same electron gun and light link system described earlier is used to inject into Model M, driven by a 100 kW klystron to provide ~1.2 MeV electrons bunched at 805 MHz. These electrons are then injected into 4 accelerator tanks of 25 cells each all coupled together with bridge couplers[9] to make a 100-cell resonant accelerator tank driven by a 1 MW, 805 MHz, 6% D.F., rf power amplifier. The features of the Meson Facility linac which may be studied with this system are:

(1) Target heat dissipation and radiation damage problems.
(2) R.F. phase and amplitude control performance.
(3) Beam loading effects in the accelerator strucutre, beam induced phase shift.
(4) Transverse mode excitation (the electron accelerator is much more susceptable than the proton accelerator to this effect).
(5) Automated control system operation.
(6) Alignment and beam steering tests.
(7) Accelerator tank production problems, such as tuning procedures, tank conditioning, etc.

The accelerator is to be housed in a steel channel ~100 ft long with 3 ft thick walls, and a 2 ft thick ceiling over the target area. The roof will be placed after installation of the accelerator tanks. At this time the project is about 75% complete. The channel is in place with the alignment rails in place and 1/4 of the accelerator tanks installed. Fifty percent of the accelerator tanks are completed, and the machined parts for all of the accelerator tanks are on hand. About 4 weeks of brazing is left to finish the accelerator tanks. Figure 8 shows a photograph of the accelerator channel with the first section of the accelerator being lowered into place. Figure 9 shows a section of the accelerator.

Part of the Mockup program for the Meson Facility linac at Los Alamos has been to evaluate the possibilities of completely automated computer control of the proton linac. A small digital computer is on hand for this program and will be used to operate this electron prototype as part of its evaluation program. Provision for digital control and monitoring of all systems has been provided in the design of power supplies, current and beam position monitors, and other accelerator equipment.

We expect initial operation of this accelerator before the first of the year and full operation during the first of next year.

References

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2. E. A. Knapp, "Design Construction and Testing of R.F. Structures for a Proton Linear Accelerator," IEEE Transactions on Nucl. Sci., Vol. N.S.-12, No. 3, June 1965, p. 118.
3. D. E. Nagle, E. A. Knapp and B. C. Knapp, "A Coupled Resonator Model for Standing Wave Accelerator Tanks," To be published in R.S.I.
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5. R. A. Jameson and W. J. Hoffert, "Fast Automatic Phase and Amplitude Control of High Power R.F. Systems," IEEE Transactions on Nucl. Sci., Vol. N.S.-12, No. 3, June 1967, p. 205.
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7. H. C. Hoyt, D. D. Simmonds and W. F. Rich, "Computer Designed 805 MHz Proton Linear Cavities," RSI, 37, 1966, p. 755.
8. G. R. Swain, "FARM - A Computer Code for Accelerator Radial Motion Studies," MP-3/GRS-6, March 22, 1967, unpublished.

DISCUSSION (condensed and reworded)

M.C. Crowley-Milling (Daresbury): Do you have adequate machining accuracy, or must you tune each cavity?

Knapp (LASL): We tune each cavity to frequency by final machining of the nose cones in the laboratory.

Crowley-Milling: Why did you have a detuning with the application of rf power?

Knapp: Because of differential heating.

R.H. Helm (SLAC): In your calculations of energy gain vs power, did you use the measured or computed values of shunt impedance?

Knapp: We used the measured impedance.

Helm: Would you compare the calculated and measured values of shunt impedance?

Knapp: Calculated, 51 Mohm/M, measured 42 Mohm/m.

Helm: Why do you predict an electron instability at 40 ma intensity?

Knapp: With this linac the intensity at which we noticeably excite the TEM 111 mode is about 20 mA.

J. Haimson (MIT): Why is no water cooling manifold shown on your test setup?

Knapp: None is shown because the cooling hoses were not yet connected.

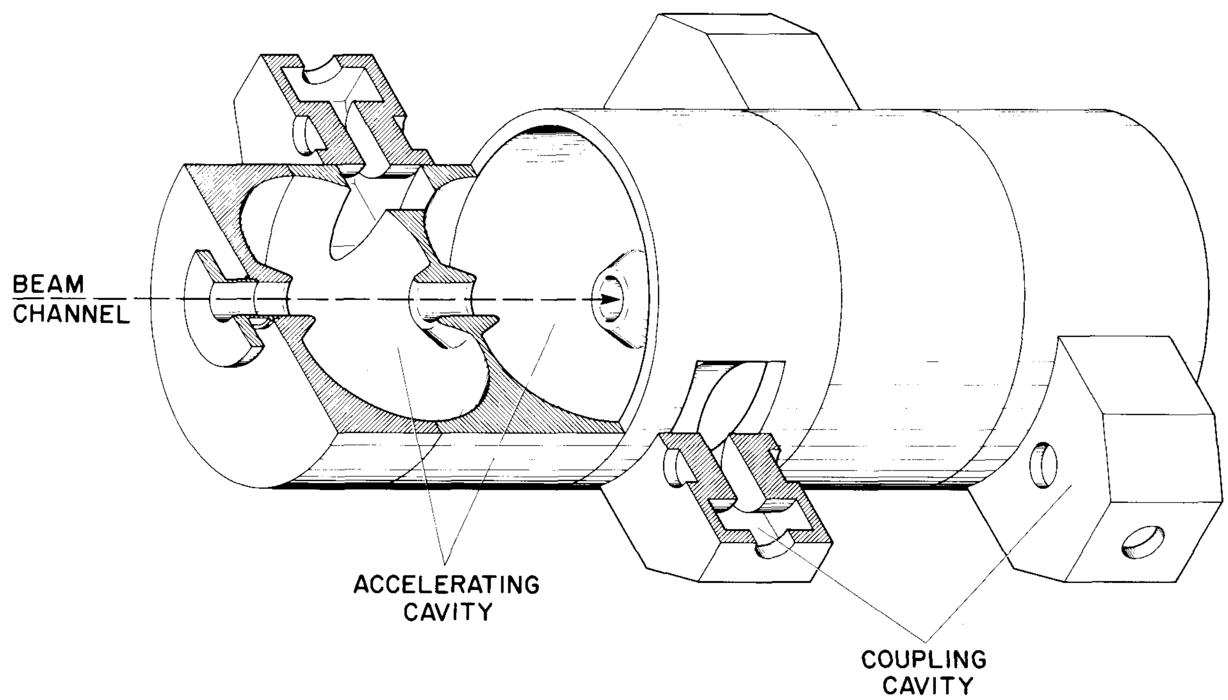


Fig. 1. Cutaway drawing of a side-coupled optimized shunt impedance cavity chain.

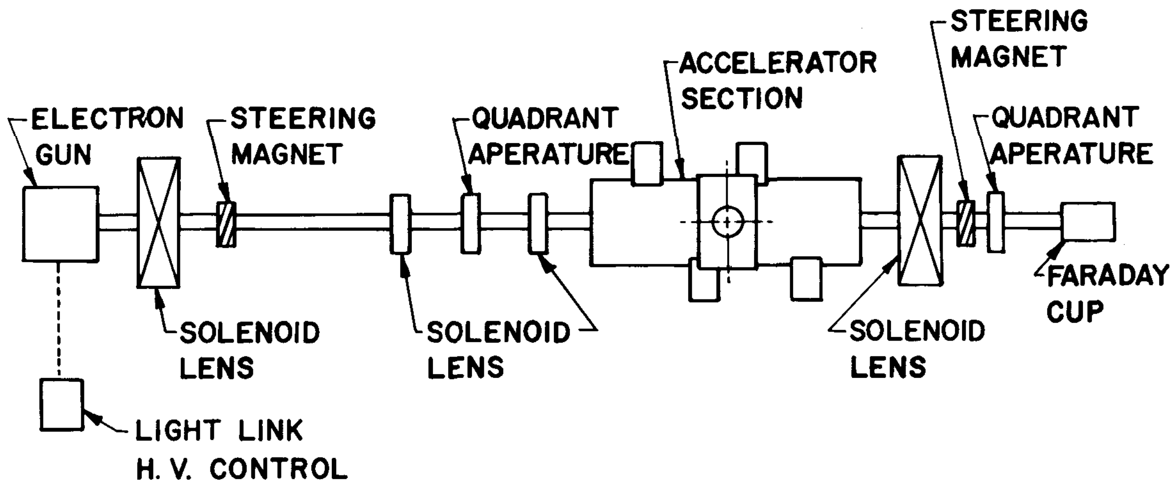


Fig. 2. Block diagram of the system used for the short accelerator section electron linac tests.

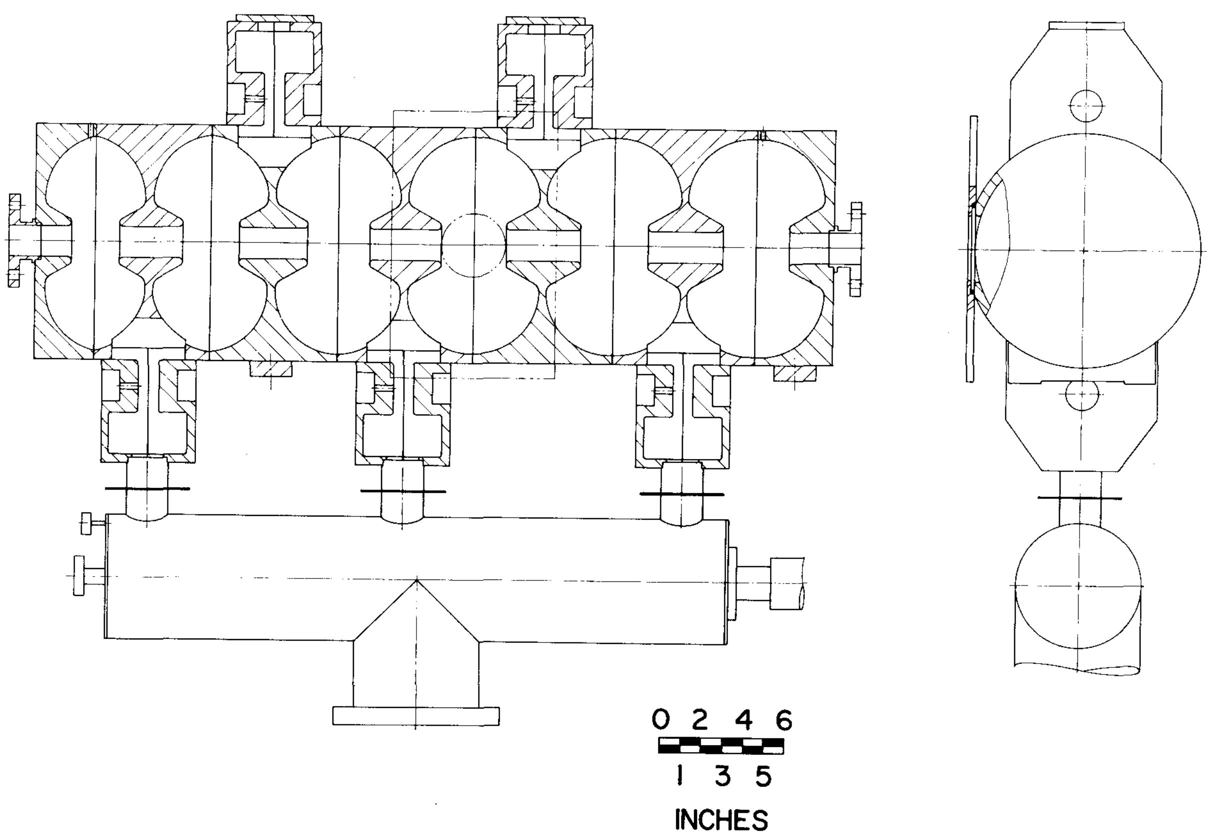
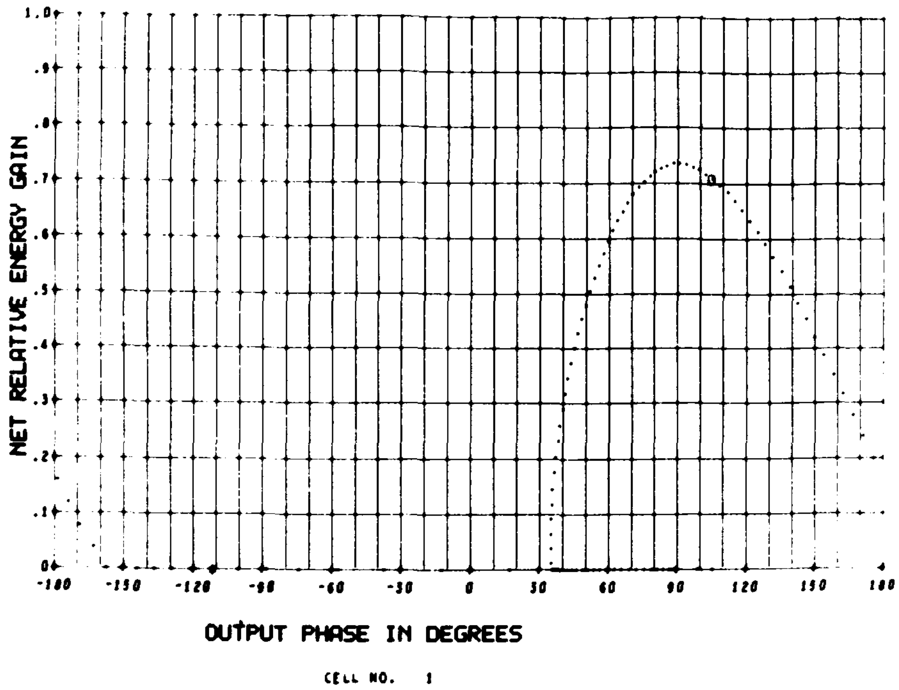
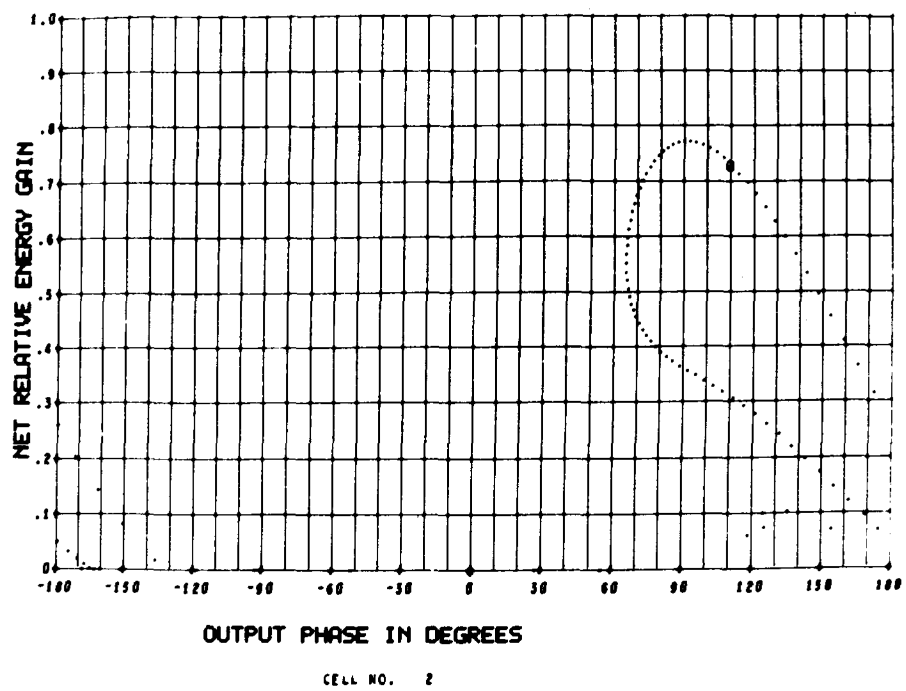


Fig. 3. Model M variable phase velocity accelerator tank. Power is fed into the tank through an iris opening in cavity 4. The system is evacuated through the 3 lower coupling cavities. Choice of cavity length is explained in the text.



EAV FOR MODEL M, 1.5 MV/M



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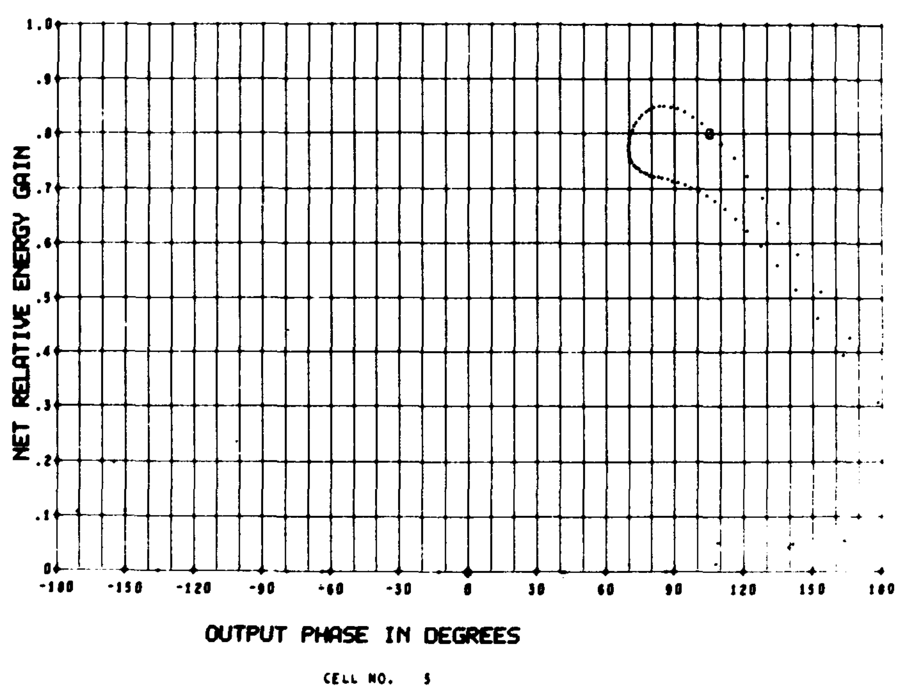

EAV FOR MODEL M, 1.5 MV/M

Fig. 4. Predicted performance of Model M from the WATUSI computer program. Output particle phase is plotted versus E_{out}/E_o, called net relative energy gain. The points in the curve are spaced at 3° intervals at injection, the point with a box is that point which enters cell 1 at the instant of zero electric field. 4a shows the output of cell 1, 4b the output of cell 2 and 4c the output of cell 6.

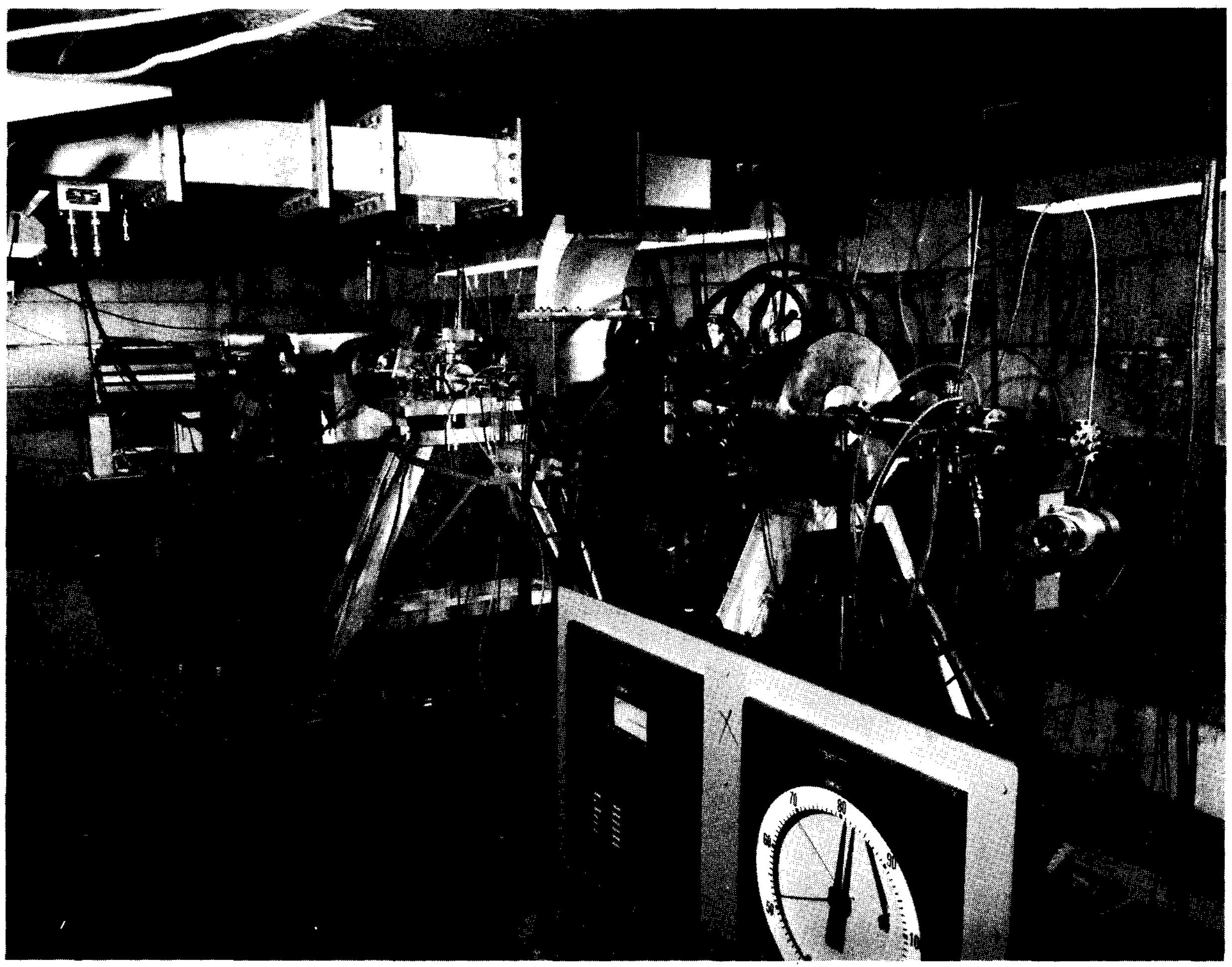

Fig. 5. Model L experimental setup.

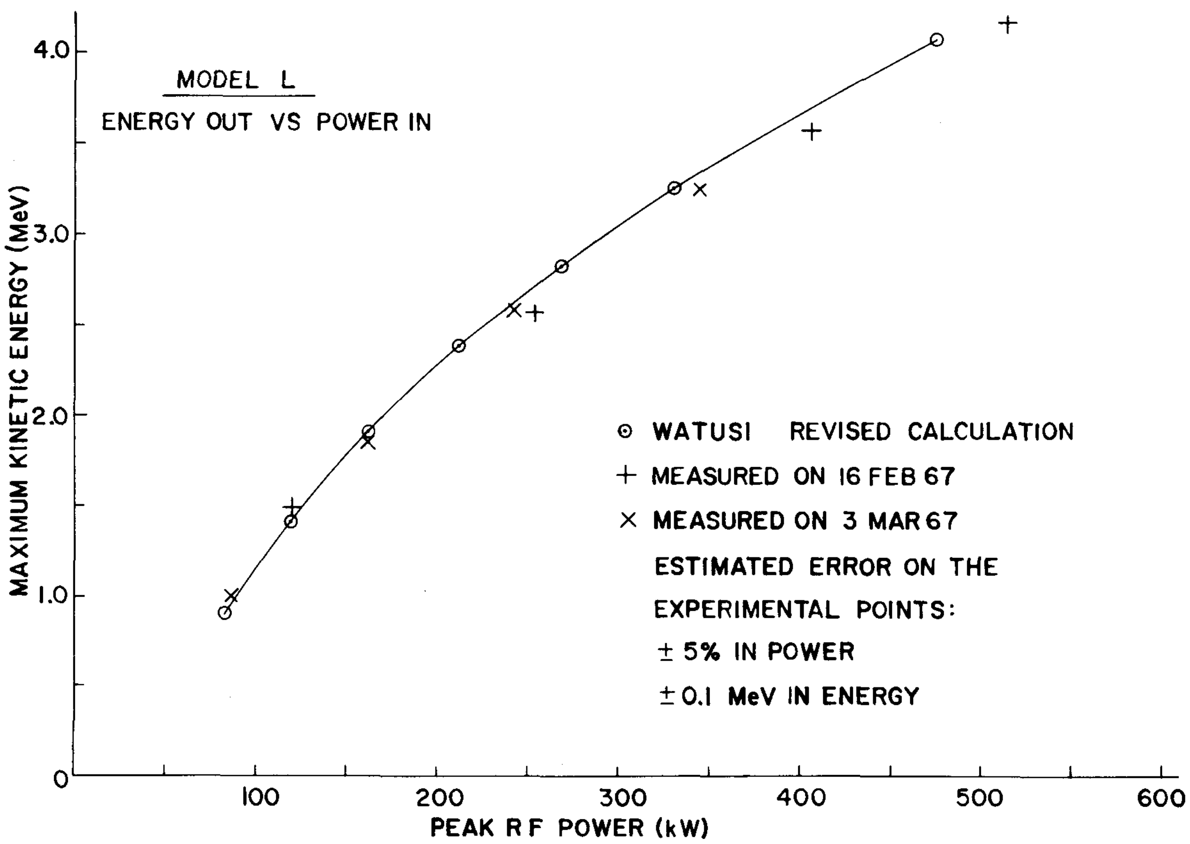

Fig. 6. Comparison of Measured and predicted energy gain for Model L.

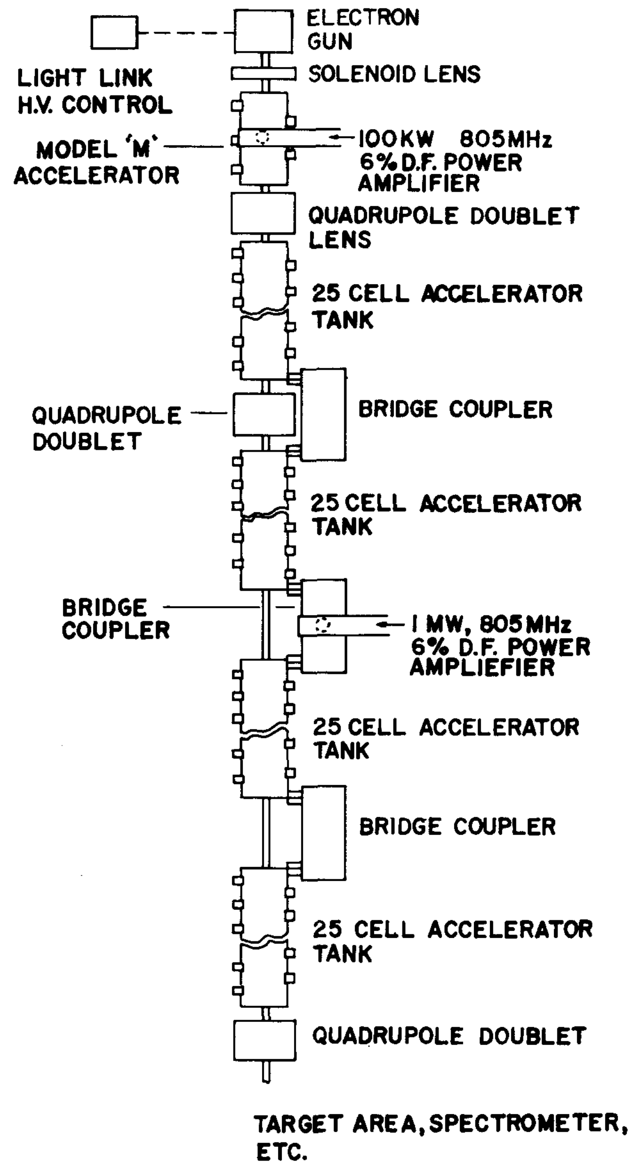

Fig. 7. Block diagram of the electron prototype accelerator. Beam position monitors, current monitors and collimators are not shown.

Fig. 8. Electron prototype accelerator channel without roof shielding blocks.

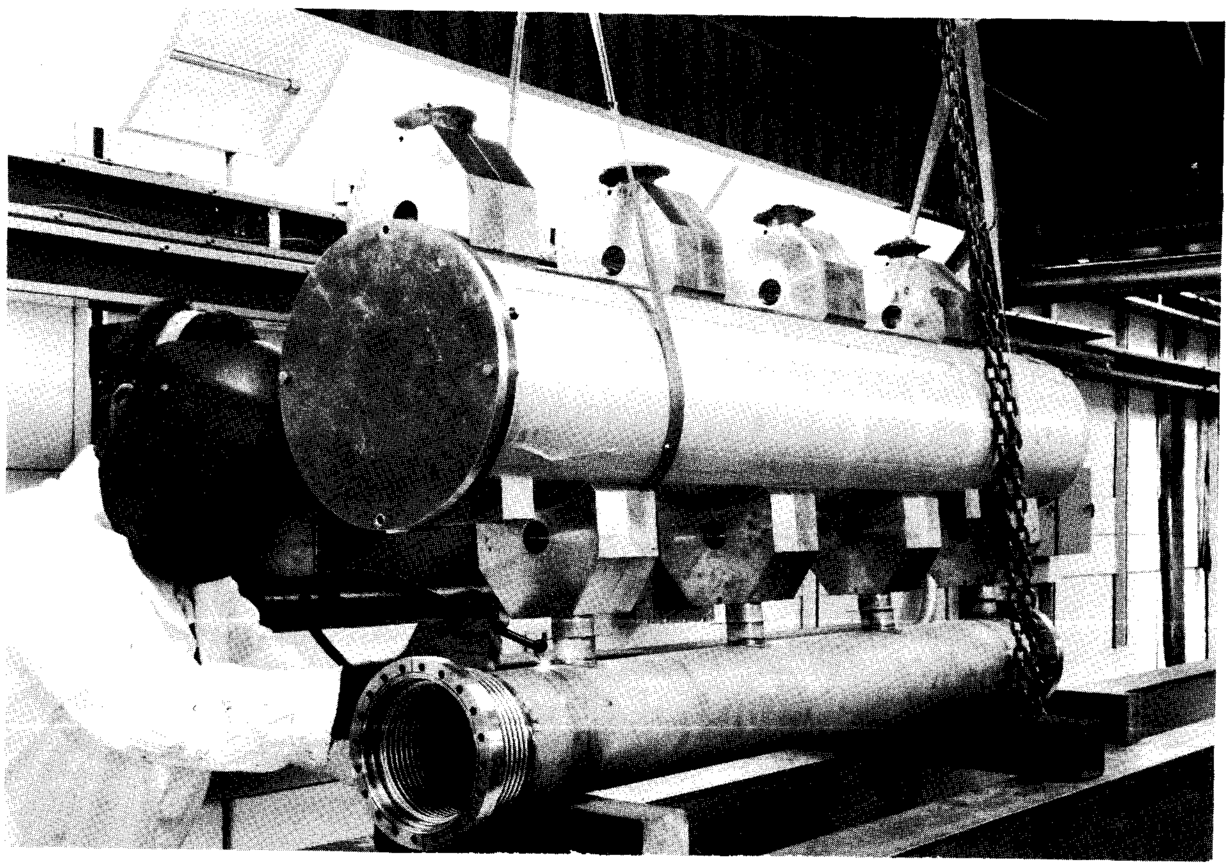

Fig. 9. An eight cell section of the Electron Prototype Accelerator.