12 MeV LINEAR ELECTRON ACCELERATOR FOR FAPIG RADIATION RESEARCH LABORATORY

By Hideo Nakano
&
Minoru Yoshida
(Atomic Energy Sect., Design Dep't.)

I. INTRODUCTION

Under close co-operation with Kobe Kogyo Corp., the first 12 MeV linear electron accelerator was completed and installed at FAPIG Radiation Research Laboratory in Miura Peninsula in Kanagawa Prefecture. The results of performance test in March 1961, was satisfactory, and 13 MeV of the electron energy was obtained. This equipment is favourably under operation as an irradiation apparatus. A linear electron accelerator can produce high energy electron beam in large quantity so it is expected to be developed not only as apparatus for experiments of nuclear physics but as one for industrial use. It must be meaningful to have performed the 12 MeV linac of the highest energy in Japan by solving many technical problems, which came forth in designing, making and testing it. According to this circumstance, we believe firmly that we confirm the techniques to propel a home-produced linear accelerator and open up the way to be utilized by many customers. The details of 12 MeV linac are stated in this paper. Main specifications of this equipment are shown in *Table 1*. The external appearance of it, the Lichtenberg's figure obtained by giving a little cut to acryl after irradiation and dark coloured glass, are shown in *Fig. 1* & *2* respectively, *Fig. 3* is the general view of FAPIG Radiation Research Laboratory.

Table 1 Main specification of equipment

Item	Specifications
Electron energy	2~12 MeV
Beam power	1.8 kW max.
Mean beam current	350 μA max.
Beam pulse width	5 μs
Pulse repetition rate	100~300 pps (variable)
Peak microwave power	4 MW (klystron)
Microwave frequency	2,765 Mc
Total length of accelerator body	ca. 5 m (upright type)
Power source	AC 3ϕ 220V, 120 kVA

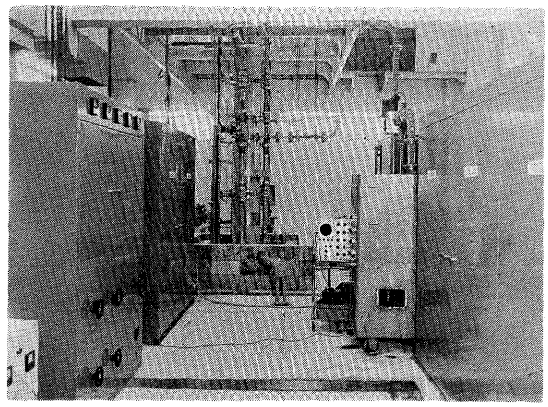

Fig. 1 General view of 12 MeV liner electron accelerator

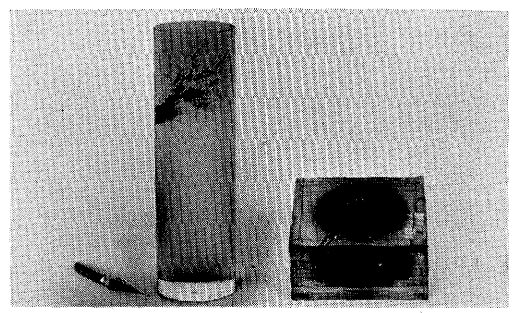

Fig. 2 Glass and acryl after flash over electron

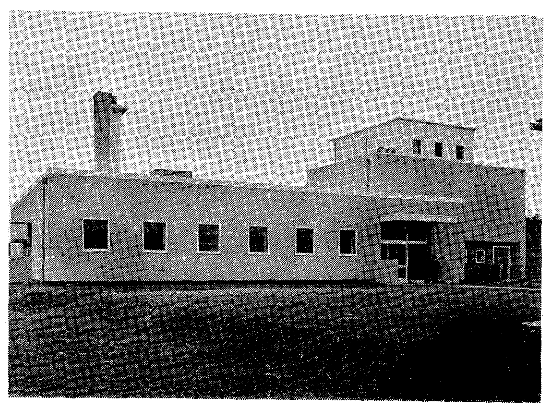

Fig. 3 General view of FAPIG Radiation Research Laboratory

II. STRUCTURE OF EQUIPMENT AND PRINCIPALE OF ACCELERATION

The structure of this equipment is shown in *Fig. 4* as a block diagram. The exciter power 2,765.0 Mc, peak power 300 W, repeated frequencies 100～300 c/s, pulse width 7 μs which is obtained by 324 multiplication of about 8.5 Mc frequencies from the quartz oscillator, is supplied to a klystron amplifier.

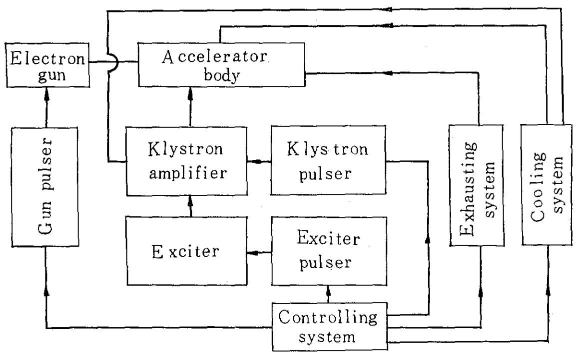

Fig. 4 **Block diagram of equipment**

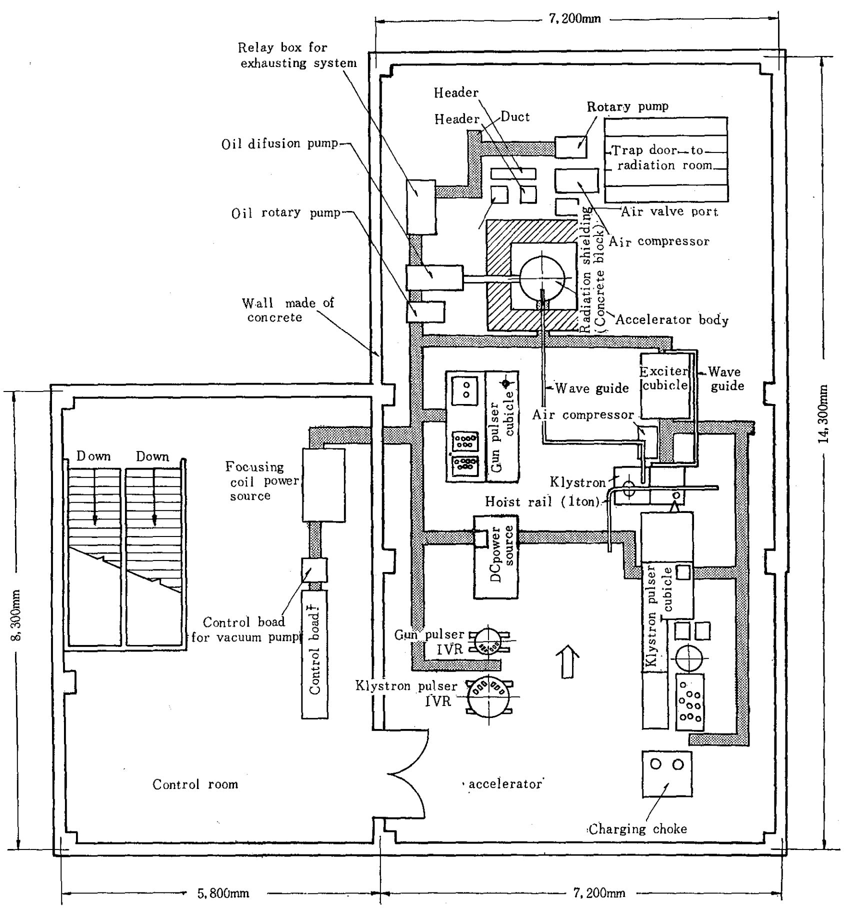

Fig. 5 **Arrangement of equipment (plain view)**

This 300 W microwave power is amplified till 4 MW peak power by the klystron amplifier, become the pulse power of repeated frequencies 100～300 c/s, pulse width 6 μs, and fed into an accelerator tube transmitted by a wave guide. The klystron amplifier is operated by the klystron pulser of peak voltage 160 kV, peak current 120 A and peak power 19 MW.

On the other hand, the electron flow with the velocity of 0.5 C (C represents light velocity), obtained from an electron gun operating by the gun pulser of peak voltage 80 kV, peak current 16 A, is injected into an accelerator tube from one end of it, synchronized with the period of pulse formed microwave power from the klystron. This accelerator tube 3.5 m in total length, consists of cylindrical wave guide with 8.5 cm inner diameter, and in its wave guide 150° pieces of 5 mm thick disks with iris are loaded in a row leaving each a suitable space, in order that 0.5 C velocity of injected electrons and phase velocity of microwave in the tube have the same period, and electrons are accelerated getting at the crest of microwave. In this case, the micowave which is used for acceleration is a TM_{010} mode, having electrical field of travelling direction. The accelerated electron flow is pulled out directly in the air, through an alminium foil of the final end of the tube, or after sweeping 20 cm in width by a magnet, it takes out in the air. A remaining microwave power, penetrated through the tube, is absorbed into dummy load. The body of accelerator, about 5 m in total length, having the accelerator tube, is installed upright and consists of, besides the tube, the focusing coils around the tube which prevent electrons from being out of a normal orbit, the phase shifter in the middle of the tube which changes the phase between electron and microwave and also varies the energy of electrons, the electron gun, the dummy load, the sweeping magnet and the steel supporter on which all those parts are installed.

Besides those body of accelerator, electron gun pulser, klystron and klystron pulser, exciter, the exhaust sets consist of two 6 inches oil diffusion pumps and two rotary pumps maintain high vacuum inside of the tube, and the water cooling system for accelerator tube, focusing coil, and klystron, are situated. There is a control board for operation in the control room. The arrangement of those instruments is shown in *Fig. 5*. All implements except the control desk are installed in the accelerator room, 7.25 m by 14.3 m. *Fig. 1* is the general view looked from a direction of the arrow indication marked in accelerator room of Fig. 5. As shown in Fig. 1, a part of the room where the body of accelerator is installed are about 8 m in height and the platform on which the electron gun pulsers, pulse transformer and a part of vacuum pump are put is seen at 3.7 m in height.

The high speed electron beam, obtained by acceleration in the tube, is introduced in irradiation room (*Fig. 6*) under the accelerator room and irradiate samples arranged on conveyer belt. γ ray can be got secondarily from metal target by exposing to this electron beam. In any case, the concrete-wall stands for radiation shielding being considered that radiations do not leak out unnecessarily from the radiation room. The operations of this equipment are done on a control board in the control room (8.3 m by 5.8 m area) next to the accelerator room, so that operators do not exposed to radiation over permissible level even in the operation.

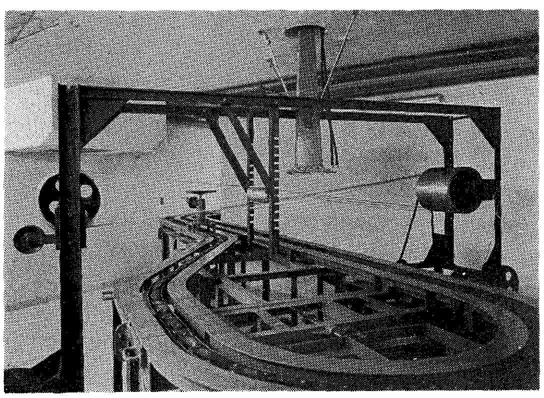

Fig. 6 Irradiation room

III. BODY OF ACCELERATOR

The body of accelerator is one of the main parts of this equipment. It involves the accelerator tube in which electrons are accelerated. The general view of accelerator's body is shown in *Fig. 7*. As shown in this figure, this body 5 m or so in total length, is installed upright and has the accelerator tube of 3.5m in total length. This accelerator tube is made divided into five portions. The two upper tubes are called " bunching section " and in structure, have a purpose of making great increase the phase velocity of microwave field from 0.5 C up to almost light velocity, in order to accelerate the electron injected with half the velocity of light. This structure is considered so that in the bunching section the velocity

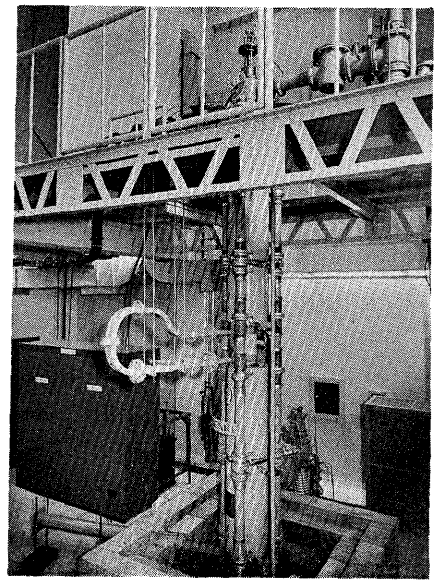

Fig. 7 Accelerating unit

of electron and of microwave field does not slip off from the synchronization because the electrons which are injected with 0.5 C velocity from the electron gun installed in the upper part of accelerator tube get almost light velocity during running the first one meter, after that the electron velocity increases slightly and the energy increases rather by increasing of the mass. Practically it was not easy to decide sizes of these accelerator tubes, the designs were made in the manner to obtain larger electron currents using the shorter tubes as possible and besides to minimize width of the beam energy spectrum. For these purposes FACOM-128 digital computor was used for the calculations to analize electron orbits in the bunching section. The structure of accelerator tube results so to speak, $\pi/2$-mode type in which an interval between disks equals to $1/4$ wave length and its properties are decided to have 0.5 C at the entrance, almost light velocity at the exit in phase

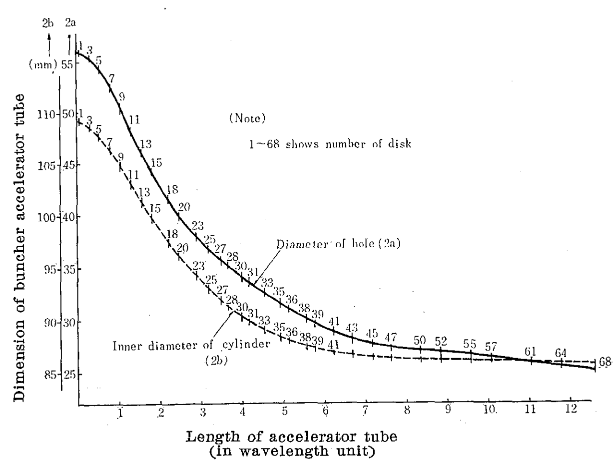

Fig. 8 Dimension of buncher accelerator tube

velocity of the microwave field, and 0.47 MV/m, 4.7 MV/m respectively in field intensity, and also to maintain 60° phase difference between electrons and microwave. The dimensions of buncher accelerator tubes are shown in *Fig. 8*, as shown in this figure, there are 66 pieces of disk, hole diameters and outer ones of which become smaller as they go from the entrance to the exit, on the contrary the intervals of these disks are gradually wide.

But in a regular section, the electron velocity is almost near to the velocity of light, since a large shift between electron and microwave field does not occured even if the phase velocity of microwave field is chosen the constant velocity of light. For this reason the phase velocity is made constant in the tube, determining 25 mm as hole diameter and outer one of disks and also the intervals between them as a constant value. In this case, the dimension determined by the caluculation were only approximate estimates, finally to fill up wants, the measurements of test cavity for half wavelength were done for resonance frequencies and Q values.

Practically one of the most important problems is a degree of precision required in manufacturing the accelerator tube. This problem arises from the fact that the error of sizes and the surface roughness must be held below 10 μ, 0.3 μ respectively. Because of the extreme precision in manufacture an electroforming is adopted as a manufacturing method of accelerator tube. This method is to machine separately aluminium spacers and copper disks and place these alternately in a row, plate outer surface of the cylindrical shape with copper 9 mm in thichness, and subsequently to melt away unnecessary aluminium spacers pouring inside caustic potash. As a result of continuous study of manufucturing method, the error of sizes and the surface roughness have been held below 10 μ, 0.3 μ respectively working in temperature controlled room.

The electrical properties of the accelerator tube, manufactured by electroforming were satisfactory and it showed more than 8,000 in Q value below 150 Kc in spread width of resonance frequencies in each accelerator tube. Precision disks and spacers are shown in *Fig. 9*, An external appearance of the complete accelerator tubes installed flunges and jackets which are intended for cooling the wall round is shown in *Fig. 10*.

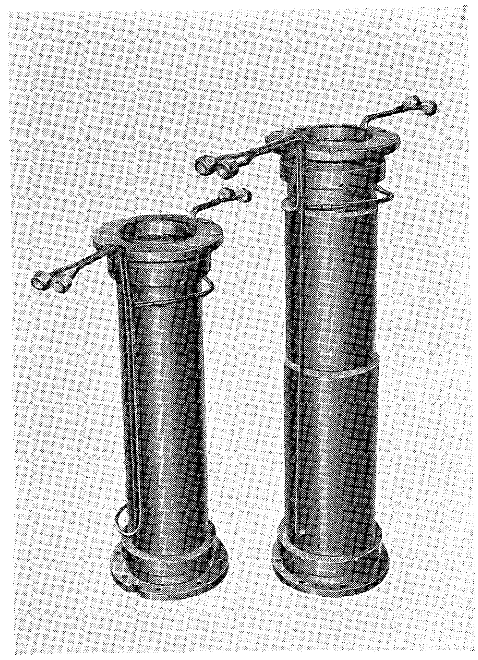

Fig. 10 Accelerator tube

Microwave circuit such as a mode transformer which transforms H_{10} mode microwave into E_{01} mode, a dummy load which absorbs remaining microwave power at the exit of accelerator tube and a phase shifter standing between the bunching section and regular one which transfers the phase position of electrons travelling on microwave field changes electron energy, are attached to the accelerator tube. The voltage standing wave ratio of these microwave circuits including the accelerator tube is 1.18 and microwave attenuation is about 7db.

Focusing coils which surround the accelerator tube to prevent electrons running away from the normal orbits, are installed inside three steel supports together with the accelerator tube. These coils made of square copperwire 2 mm by 4 mm have about 1.3×10^4 turns, produce maximum flux density of 1,000

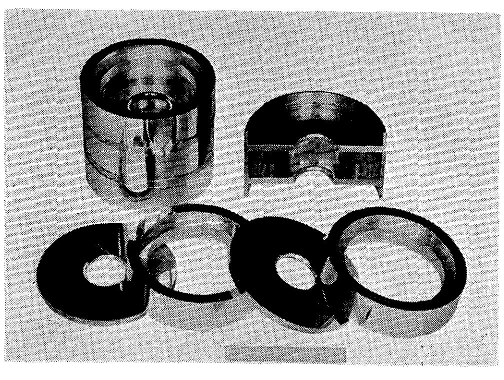

Fig. 9 Copper disks and aluminium spacers

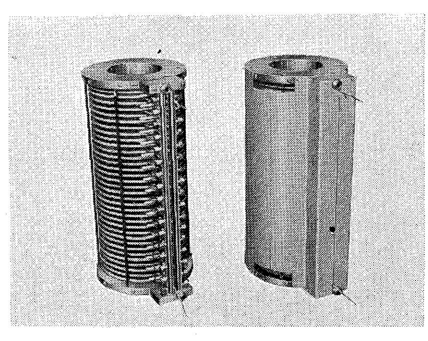

Fig. 11 Focusing coils

gausses at the axis when 30 A exciting direct current flows. The source of direct current using silicon rectifiers has six capacities of sum of DC 45 kW (6 × 250 V × 30 A). External views of the focusing coils manufactured dividing in five are shown in *Fig. 11.* Two 6 inches oil diffusion pumps of exhaust velocity 820 *l*/sec operated by two rotary pumps of 500 *l*/min evacuate air from upper, middle and lower parts of the accelerator tube. An extent degree of vacuum in the tube is $6 \sim 7 \times 10^{-7}$ mmHg. A quantity of cooling water for the accelerator body is about 110 *l*/min.

IV. KLYSTRON AMPLIFIER

A klystron amplifier exciter power of 300 W obtained from a quartz oscillator, up to peak power of 4 MW and feeds this power into the accelerator tube. It holds on important parts of microwave source. The external view and character of klystron amplifier are shown in *Fig. 12*, *Table 2*, respectively.

Table 2 **Character of klystron amplifier**

Item	Specification
Frequency	2,700~2,800 Mc (variable)
Peak output power	4 MW
Pulse width	6 μs
Pulse repetition rate	100~300 pps (variable)
Power gain	50 db or more
Efficiency	25%
Peak anode voltage	160 kV max.
Peak anode current	120 A max.

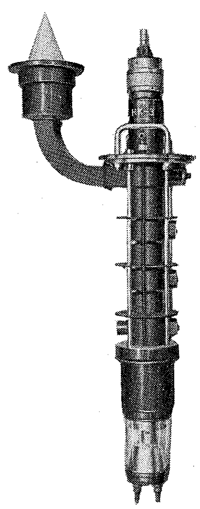

Fig. 12 Outer view of klystron

This klystron consists of an electron gun, a drift tube with 4 cavities, a coaxial attachment of input power, an output waveguide with ceramic window for vacuum seal. The electron gun part generates the electron of beam current 120 A, voltage 160 kV. A matrix cathode is composed of spherical capfigured plate, 60 mm in diameter on which surface, Ni-mesh and Ni powder are sintered. The high speed beam ejected from the cathode enters into a drift tube. Since the beam must be brought into focus as a parallel one in this tube, focusing magnets are divided into four and each can be regulated separately. An electrolitic bath experiment was done for the determination of shape of focusing electrodes. A neck magnet produce the reverse field and shields suitably the force of the magnetic field on front of the cathode. As the result of it, a penetrating rate of the beam without microwave power is almost 100 percents and 85 percents at maximum output power.

The beam current and voltage were determined assuming efficiency as 25 percents and perviance 21 $\mu A/V^{3/2}$ The beam from the electron gun enters a drift tube through cavity portion suffers velocity modulation. At this time, there were many problems about the determinations of the length of drift tube, cavity gaps and drift tube radius.

The drift tube radius was designed, considering beam conductance, gap coefficient, beam penetration rate and prevention of oscillation caused by a feedback of microwave through drift tube.

The gaps of the cavity were determined, mainly to take the gap coefficients and the conductance into consideration and also the length of the drift tube, applying at first the wave theory and finally the pursuit theory. The dimensions of cavity connected with the drift tube are finally determined from the measurement of resonance frequency. Besides there is a tuning mechanism used bellows and the resonance frequency is adjustable.

For the input part of klystron, coupling of coaxial cables is used to prevent discontinuity of focusing magnetic field. Stabs are placed in the circuit and adjusted to minimize the reflection of input microwave power. On the other hand an output part is a wave guide circuit, efficiency of which reaches almost 100 percents as the result of decreasing loaded Q of output circuit compared to unloaded Q.

A microwave power, introduced from this output wave guide is taken out through circular cone shaped ceramic window sealed for vacuum. Its structure is shown in *Fig. 13*. The problem of destruction of this window by run away electrons, especially microwave sparking, was solved, adopting circular cone shaped ceramic window connected with bent wave guide.

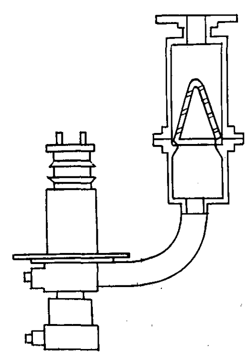

Fig. 13 Output part of klystron amplifier

The output character of the klystron was obtained from measuring microwave power by the temperature rise of water through dummy load feeding the klystron output through pressurized wave-guide. The output character is shown in *Fig. 14*.

V. EXCITER AND PULSER

Exciter supplies the microwave power to klystron already described before, and microwave power origi-

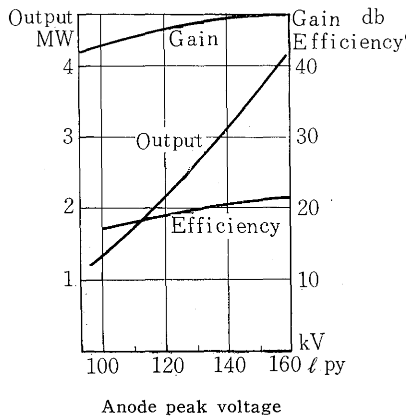

Fig. 14 **Gained character of klystron**

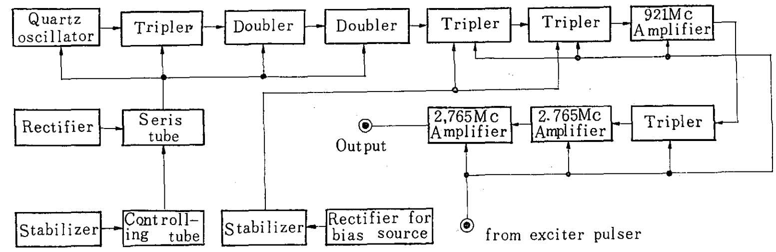

Fig. 15 **Block diagram of exciter**

nates from quartz oscillator in order to maintain its frequency stability. As shown in blockdiagram (*Fig. 15*), original microwave of frequency 8.5 Mc which is generated by the pierce circuit consisted of quartz and vacuum tube 6AU6, is multiplied by 36 by power amplifiers of class C, and by 9 to 2,765 Mc by disk-sealed tube of 2C 39 A, operating under pulse modulation. There was a little problem in pulse operation of 2C 39A, but satisfactory results were obtained after improving of its cavity and increasing of its efficiency. The character of exciter is shown as follows.

Frequency of quartz oscillator	8,533.9 kc
Stability	3×10^{-5} max
Multiplication	324
Output frequency	2,765.0 Mc
Output power (peak)	300 W
Modulation	Pulse modulation
Pulse width	7 μs $\pm$ 0.7 μs

There are three pulse modulators which operate klystron, electron gun, and exciter respectively. Those three pulsers are operated under the same triggering signal varying its repetition frequency from 100 c/s to 300 c/s continuously.

Klystron pulser supplies the power to klystron of HK3 which feeds the microwave to the accelerator tube. Its character is shown as follows.

Pulse voltage	150 kV
Pulse current	110 A
Pulse width	6 μs
Pulse trans step up ratio	1 : 10
Impedance of pulse forming network	15 Ω
Hydrogen thyratron	1,257

The outer view of klystron pulser is shown in *Fig. 16*.

Gun pulser supplies the power to the electron gun and generates the electron beam of velocity 0.5 C. Its character is shown as follows.

Pulse voltage	90 kV
Pulse current	18 A
Pulse width	5 μs
Pulse trans step up ratio	1 : 10
Impedance of pulse forming network	50 Ω
Hydrogen thyratron	5,949

The outer view of gun pulser is shown *Fig. 17.* Though electron beam current is 0.6 A, much larger value of 18 A was chosen as pulser current, because the impedance of electron gun is too large to match with the one of pulser's output. To avoid this difficulty dummy load of 5 kΩ which consists of series of non inductive resistances is adopted as parallel circuit with the electron gun. As result of it, output impedance of pulser matched with the one of load, so well

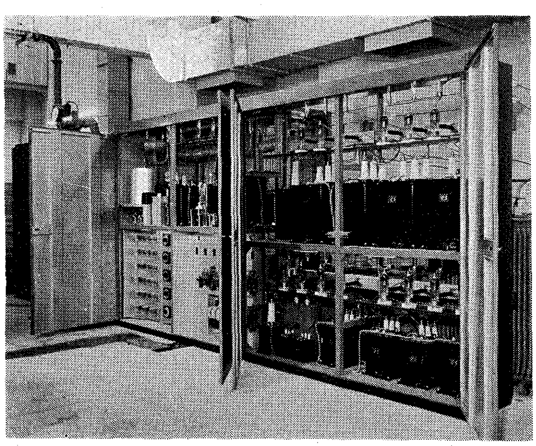

Fig. 16 **Outer view of klystron pulser**

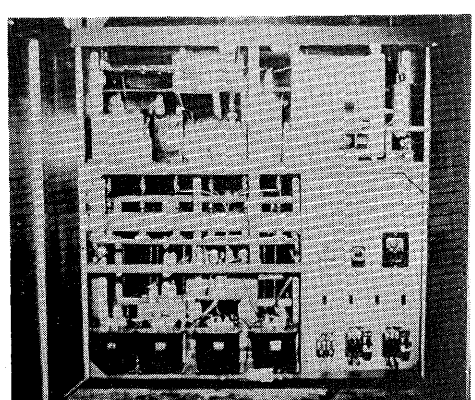

Fig. 17 **Outer view of gun pulser**

shaped pulse wave only as tension for the electron gun is obtained pulse width of gun pulser is chosen 5 μs delayed 1 μs compared with 6 μs of klystron pulser, considering the microwave filling time of the accelerator tube, and the end of both pulse waves are ceased at the same time.

VI. PERFORMANCE TEST RESULTS

13 MeV electron was recorded as beam energy at the microwave power 4 MW, and peak beam current reached until 250 mA. The details of performance test is described with explaining data and methods of measurements.

In order to feed perfectly the all output power of klystron to the accelerator tube, the adjustment of microwave circuit which consisted of feeder wave guide, transformer to the accelerator tube and coruggated wave-guide, dummy load was done. As the accelerator had the resonator character which showed about 8,000 as Q value, so stable microwave power source was necessary to measure the impedance of the microwave circuit. The exciter power operating without pulse modulation varying its circuit satisfied this demand. The result of measurement is shown in *Fig. 18*. To utilize over 90% of klystron power, the voltage standing wave ratio must be under 1.05, so inductive window was inserted just before the transformer for the purpose of compensation.

Then high power microwave from klystron fed into the accelerator tube evacuated inside till 10^{-6} mmHg and output power was measured at the dummy load using calorimeter. Power attenuation ratio was calculated from the ratio of input power to output one. As shown in *Fig. 19*, the minimum value of it was about 10 db at the operating frequency. This value involved the power loss of two ceramic window and others which were estimated about 3 db. Tbe feeder wave-guide was pressurized till 2 kg/cm² to prevent electrical discharge caused by strong electrical field of microwave.

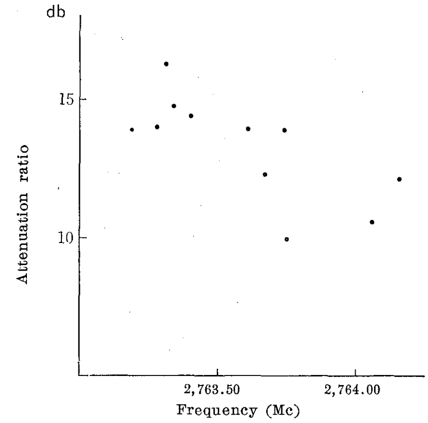

Fig. 19 Power attenuation ratio vs microwave frequency

Without feeding of microwave only the electron beam of velocity 0.5 C was injected into the accelerator tube, and the current at the end of the tube was measured using collector made of brass. After the adjustment of the axis of focusing coils mechanically moved to get coincidence with the one of the accelerator tube, the penetration rate of the electron through the tube was measured and result is shown in *Fig. 20*. The beam shape and dispersion ejected from the electron gun was the most important character which decided the penetration rate and beam diameter at the exit. The result of measurements

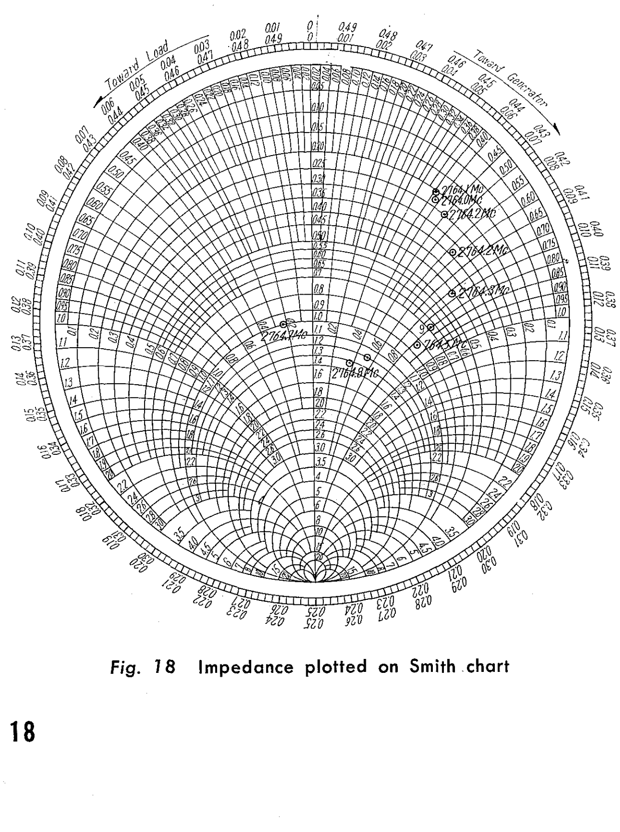

Fig. 18 Impedance plotted on Smith chart

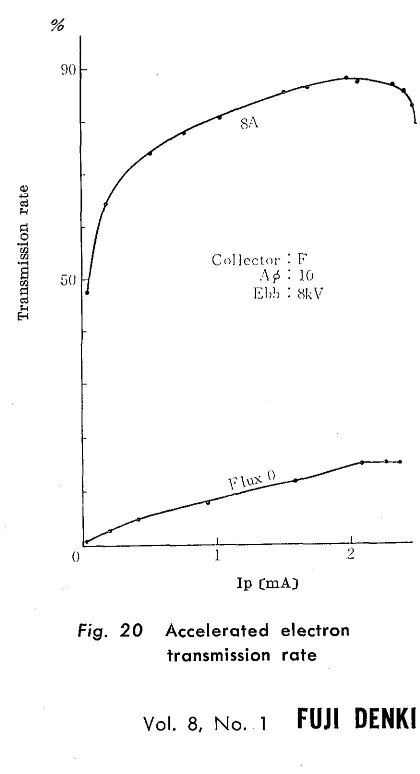

Fig. 20 Accelerated electron transmission rate

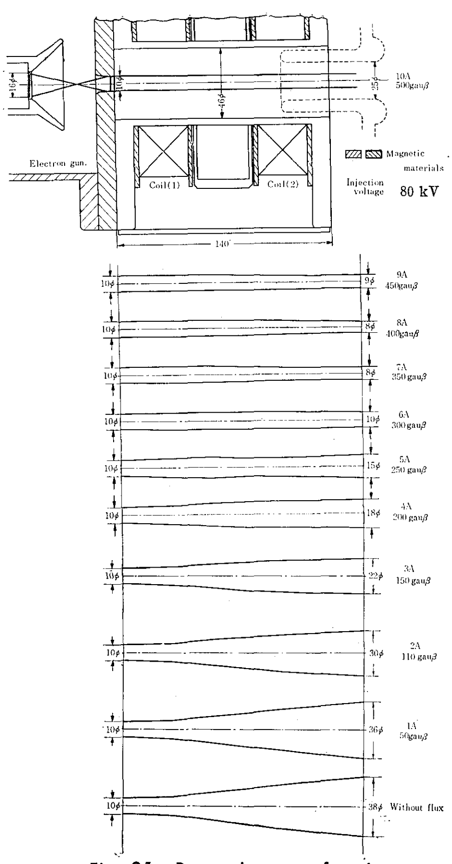

Fig. 21 Beam shape vs focusing magnetic flux

are shown in *Fig. 21.*

The energy of the electron beam which was taken through alminium foil at the exit of the tube was measured by the range of irradiated glass shown in *Fig. 2.* Specific density of glass was about 2.3 g/cm^3 so 20 mm in thickness of dark coloured glass corresponded 10 MeV of the electron energy. The temporary arrangement and test of only bunching section were done in order to know the character of it. Its

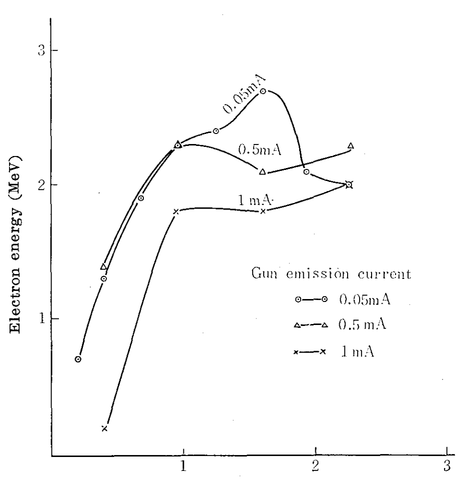

Fig. 22 Microwave power~electron energy

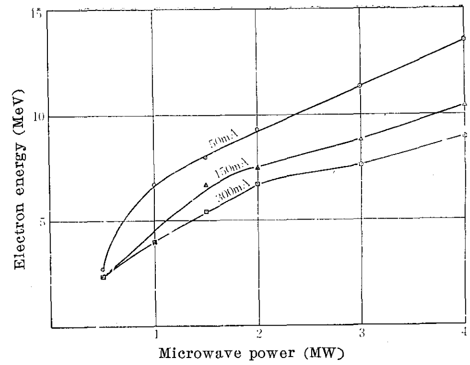

Fig. 23 Microwave power~electron energy

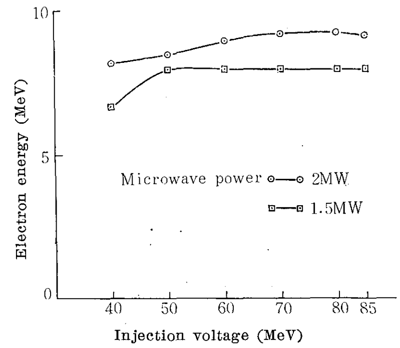

Fig. 24 Microwave frequency~electron energy

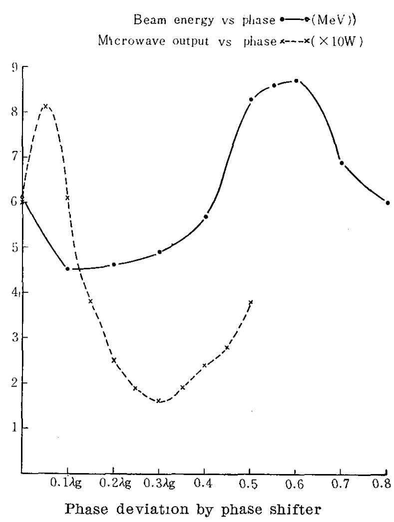

Fig. 25 Microwave phase shift~electron energy

character is shown in *Fig. 22.* The character including regular section is shown in *Fig. 23.* When the microwave frequency, microwave phase in regular section, the velocity of injected electron were varied, the character changed as shown in *Fig. 24. 25.* and *26.* respectively.

The beam current was measured by Faraday cup, the beam power by calorimeter, the beam diameter by the thin plastic plate.

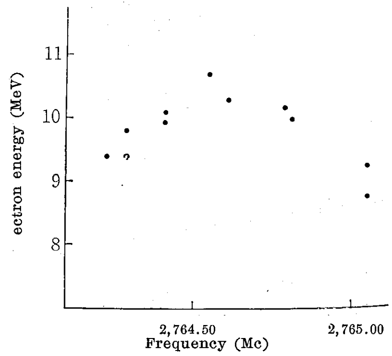

Fig. 26 Injection voltage~electron energy

VII. CONCLUSION

As described the results were satisfactory one, now this equipment being used as irradiation apparatus. The research of radiation application will be expected to develop using this equipment.

Another 4 MeV linear electron accelerator using magnetron as microwave power source has been completed in September 1961, and was delivered to Hokkaido University for nuclear experimental uses.

From now on, linear electron accelerator will be used in the field of nuclear experiments especially electron processing, industrial irradiation services, medical X-ray, and radiographic examination.