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Design and Construction of JAERI-Linac

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The design and construction of a new linear accelerator at the JAERI (Japan Atomic Energy Research Institute) is described together with it's performance.

The machine is constructed from five accelerating waveguide section, two of which have a length of 2 m each, the remainder have 3 m each. The electron beam current of 1 mA at 190 MeV energy, and 600 mA at 100 MeV with a pulse width of 0.5 μ sec is obtained when a RF power of 20 MW with a frequency of 2,857 MHz fed into each accelerator section. The range of the pulse width of the electron beam is from 0.01 to 2μ sec and the current amplitudes from the dark current threshold to 600 mA, and the repetition rates are from single shot to 600 pps.

The main research program in the use of this linac is to obtain nuclear data needed for the development of nuclear reactors. In addition, the linac is used as a strong electron and X-ray source in the studies of neutron physics, nuclear physics, solid state physics, radiation chemistry, and shielding technology, *etc.*

INTRODUCTION

In 1961 JAERI installed its first 20-MeV linac,[1] and its research program on neutron physics and nuclear physics began. After several years operation, among physicists using the machine there has grown up a strong demand for the power of the electron beam to be raised by a factor of hundreds. So a new linac was proposed which has a maximum energy of 150 MeV and a beam power of 50 KW.

In 1970 JAERI got a budget for this machine, and its design and construction was started in that year, and was completed in April 1972. In July 20-MW RF power was fed into each of five accelerator sections, and an electron beam of 250 milliamperes at 150 MeV was obtained. In August the neutron cross section measurement and the production of radioisotopes began.

The main research program in the use of the new linac is to obtain nuclear data needed for the development of nuclear reactors. The need for nuclear data of high accuracy is increasing more and more, connecting with the progress in studies on the economy and safety of power reactors. The accuracy of nuclear data depends strongly on the neutron intensity to be used in the measurement of these data. The rate of neutron production of the new linac is several hundred times that of the old one, so that measurements with high accuracy could be made on various neutron cross sections of many reactor material especially in the KeV neutron energy region, these are the measurements that have been most urgently needed to develop fast breeder reactors. In addition, the new machine is used as a strong electron and X-ray source in the studies of nuclear physics, solid state physics, radiation chemistry, and the technology of shielding, and also used in the production of radioisotopes.

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ACCELERATOR

A diagram illustrating main components and a layout of the accelerator is given in Fig. 1, and buildings and a neutron T–O–F system are shown in Fig. 2.

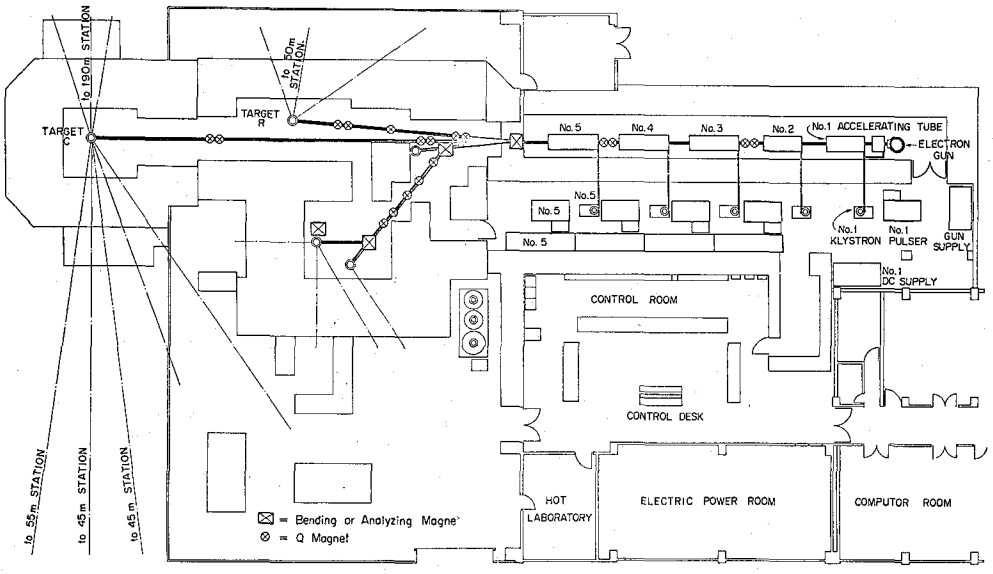

Fig. 1. Main components and layout of JAERI-linac.

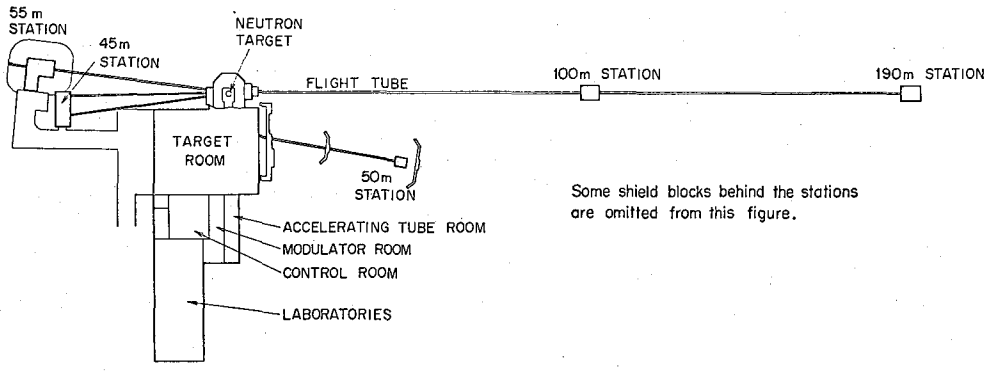

Fig. 2. Buildings and neutron T–O–F system.

The linac injector consists of the following components:
1) A Pierce-type triode gun. 2) Two thin lenses and steering dipoles. 3) A pre-buncher. 4) A gate valve.

Electron beam emitted from the cathode of the gun is accelerated by an anode voltage pulse of 100 KV with a width of 4 μsec. The amplitude of the beam current is controlled by varying the cathode heater current, and the width of the beam controlled by the grid. A range of the beam current amplitute is from 5 amperes down to the dark

current threshold, and that of the pulse width is from 0.01 to 2 μsec., and the repetition rate is variable from 600 pulse/sec to a single shot.

A beam of 100-KeV electrons from the gun is initially bunched by a prebuncher, which is a re-entrant resonant cavity of stainless steel. The Q-value of the prebuncher is 300, and the gap voltage in the cavity is 15 KV at the drive power of 2 KW.

The design value is that about 60% of the electrons passed through the prebuncher is bunched into a 60° interval in phase angle after drifting the 20-cm space between the prebuncher and the buncher.

The first accelerator section[2] consists of the following:
1) An input RF window 2) An input coupler 3) A buncher 4) An accelerating waveguide or an accelerator 5) An output coupler 6) An output window 7) A water–load

The buncher and accelerator sections are copper disk-loaded waveguides and are traveling-wave structure. The buncher is brazed to the accelerator to form a single assembly.

The buncher is 7 cavities long and operates in a $2\pi/3$ mode with an RF phase velocity of 0.95C where C is the velocity of light. The accelerator is 78 cavities long and operates in the $2\pi/3$ mode with a phase velocity of C. The RF input and output couplers are iris couplers and are brazed to the waveguide.

A ceramic RF window (RCA: 8568) is furnished for each coupler to separate the vacuum of the accelerator section from the high-pressure of the power-transmitting waveguide or the water load.

A high power water load (Varian: 284 BC4) is attached to the RF window of the output coupler and absorbs the excess RF power passed through the accelerator section to prevent the RF power from reflection.

When the 20-MW power RF power is fed into the input coupler of the accelerating waveguide, the electrons passed through the prebuncher are bunched furthermore and accelerated in the buncher section. The designed value of phase angles of a half of the total electrons from the gun are within 10 degrees after passing through the buncher.

The 20-MW RF power is transmitted in a pressurized SF_6 (3 kg/cm^2) filling rectangular waveguide from a Klystron to the input window. The voltage-standing-wave–ratio (VSWR) through the input window into the accelerating waveguide section is less than 1.1: 1 over a bandwidth of 4 MHz centered at 2856.75 MHz.

Two bidirectional couplers are installed on the rectangular waveguides joined with the input and the output couplers of accelerator section, and the RF power passing in the forward direction is monitored by the RF signal from the bidirectional couplers. Interchanging the termination and the signal cable of the coupler permits checking the reflections of the RF power from the water load.

The installed first accelerator section and its associated focussing and cooling devices are shown in Photo. 1.

The structure of the second accelerator section is the same as that of the first except that the seven buncher cavities are replaced by the same number of regular cavities. The total number of cavities is 85. The first and the second accelerator sections were made by Mitsubishi Electric Company.

The third accelerating waveguide section has the constant gradient structure[3]

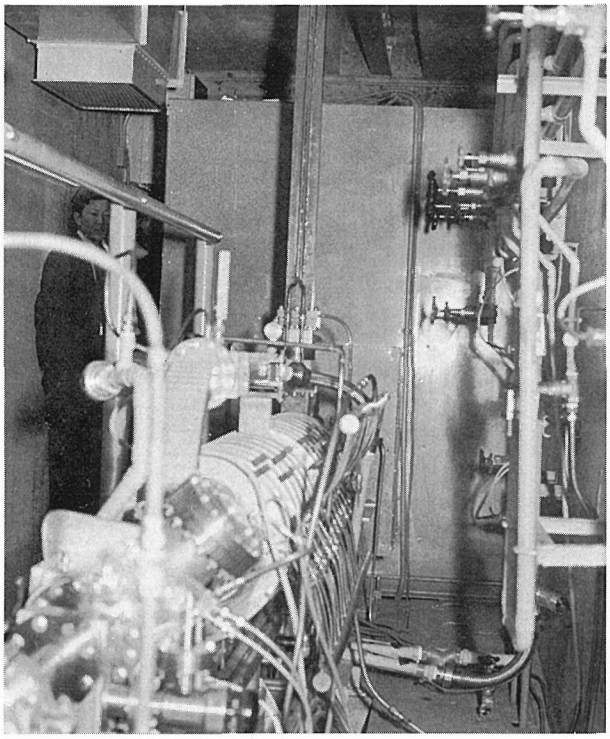

Photo. 1. First accelerator section and its associated equipments.

and operates in the $2\pi/3$ mode. The input and output iris couplers compensated for assymmetry are brazed to the accelerating waveguide. The RF windows and the water load are the same as those of the first accelerator section.

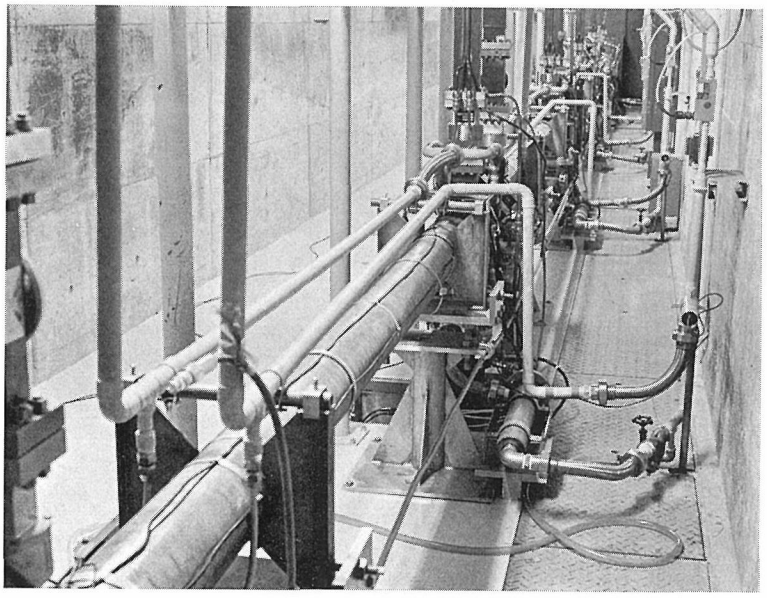

Photo. 2. Fifth accelerator section.

Table I. Characteristics of Accelerating Waveguides.

	Mitsubishi (Japan)	ARCO (USA)
Mode	$2/3\pi$,	$2/3\pi$,
Structure	Constant Impedance	Constant Gradient
Frequency	2,856.75 (MHz)	2,856.75
Power Rating	20 (KW, Average), 20 (MW, Peak)	20. 20
Shunt Impedance	49 (MΩ/m)	53
Attenuation Coef.	0.110 (nepers/m)	0.186
Initial Group Velocity	0.0233	0.0204
Length	2.07 (meters)	3.00
Number of Cavities	57	85
Q	13,000 (No. 1, No. 2)	14,850 (No. 3) 14,800 (No. 4) $>$13,540 (No. 5)
Operating Temperature	40°(C)	40
No Load Energy	27 (MeV, 20 MW input)	45
Beam Loading Factor	-10.5 (MeV/amp)	-36.2
Filling Time	0.33 (μsec)	0.83

The structure of the fourth and the fifth accelerating waveguide is same as that of the third. The VSWR through the windows into the accelerating waveguide sections are less than 1.5: 1 over a bandwidth of 5 MHz centered at 2856.75 MHz. These three sections are made by Applied Radiation (USA). The fifth accelerator section is shown in Photo. 2 and the characteristics of the waveguides are shown in Table I.

RF POWER SOURCE

The RF power sources are five high power Klystron amplifiers. These tubes, each of which has a capability of 21-MW peak output power, were made by Radio Cooporation of America (RCA–8568). The RF output power of 20 MW is transmitted in a pressurized SF_6 filling water cooled rectangular waveguide to each of the associated accelerating waveguide section.

The pulse to the Klystron is supplied by a pulse transformer made by Pearson Electronics Inc. (USA). A stepup-ratio of the transformer is 12: 1. To drive the primary of the transformer a pulse forming network (PFN) is used. The PFN consists of twelve fixed value capacitors and twelve uncoupled slug-tuned inductors. The capacitors specified 0.02 μF and 50 KV operation voltage are made by Shizuki Electrical Mfg. Co. The inductor consists of six turns of copper tubing, and tubular aluminum slug is inserted in the coil. The inductance of the coil can be varied by interconnecting the desired turns by the copper strap, and fine adjustment are made by varying the depth of insertion of the tunning slug in the coil. A maximum inductance of the coil is 1.6 μH, and the characteristic impedance of the PFN is 7 Ω.

The flat-top ripple of the cathode pulse induces a frequency moduration of the output wave of the Klystron, so that the adjustment of the inductance must be done carefully. The voltage of the output of the pulse transformer is 250 KV at 250 A, with a rise time of 0.4 μsec, a duration of 2.8 μsec, and a fall time of 0.8 μsec.

The end-of-line clipper[3] is connected across the last PFN capacitor to provide a low-impedance load for the collapsing field of the PFN inductors after a Klystron fault.

The RF Drive System Consists of the Following

(1) An oscillator, its construction is that a traveling-wave tube is coupled with a cavity of a low thermal expansion coefficient through a rectangular waveguide, an uniguide, a phaseshifter and an attenuator. A continuous RF wave with a power of 2 W is obtained. The frequency of the wave can be varied in the range of 2 MHz by tunning the cavity. The center frequency is 2,856.75 MHz, and the stability of the frequency is 1×10^{-5}.

(2) A pulsed triode (Machlett: ML–8534), which amplifies the output of the oscillator to a 50-W pulsed wave.

(3) A main booster Klystron (Sperry: SAS–61) that amplifies the input power up to 5 KW. A hard tube pulser supplies a voltage pulse to the anode of the booster Klystron, and the wavefrom of this pulse is adjusted carefully to avoide a frequency moduration of the RF wave.

(4) A rectangular waveguide which transmits the drive power from the booster to each directional coupler.

(5) Five directional couplers that divide 500-W power to each of the five high power Klystrons mentioned before.

(6) Five attenuators and phaseshifters that adjust the amplitude and the phase of the drive power of the each high power Klystron properly.

BEAM TRANSPORTATION AND VACUUM SYSTEMS

A pair of Q-magnets is installed between each accelerator sections and behind the last accelerator section. The accelerated electrons leaving the last pair of Q-magnets go straight ahead or are deflected by 5° to either side of the central axis by a switching magnet, and then are transmitted to three directions in a respective extension tube. To focus the electron beam pairs of Q-magnets are provided along these extension tubes also.

Beam monitoring and steering devices are provided along the beam line, and to compensate for the earth magnetic field, degaussing wires are also provided. A deflected beam passes through 0.075 mm-thick titanium foil of a vacuum window and hits a phosphorescent screen to produce a spot. Beam tuning is performed by watching the spot on the screen with a television camera.

The all metal-packing high-vacuum system maintains the accelerator sections and the beam transporting system at the vacuum of 10^{-7} torr. A 200-liter/sec ion-getter pump are located between the gun and the first accelerator section and a 30-liter/sec pump evacuates each of the remaining accelerator sections. Five 100-liter/sec pumps are used to evacuate the extension tubes.

COOLING-WATER SYSTEMS

The accelerator waveguides, the high power transmitting waveguides, and the water

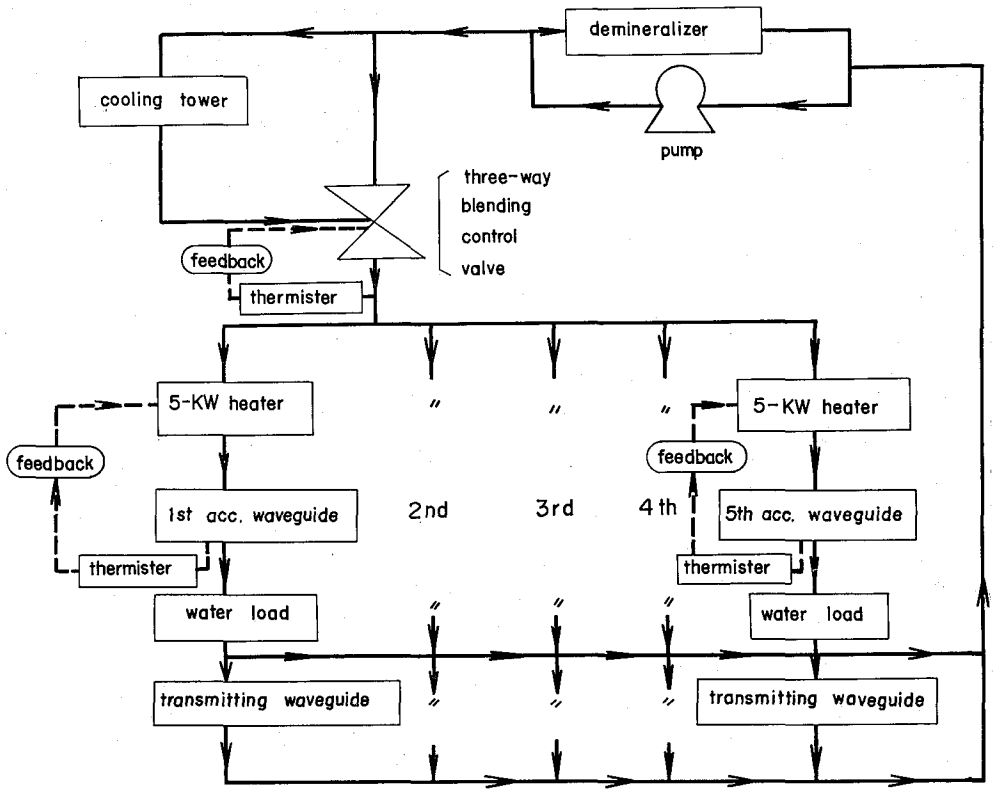

Fig. 3. Block diagram of cooling-water system for accelerator sections.

loads are designed to operate at 40°C and should be maintained within approximately ±0.5°C for a satisfactory system operation. The block diagram of a cooling system for these components is shown in Fig. 3.

A three-way blending control valve is provided in the cooling system to control the temperature of the accelerator sections. The temperature signal from a thermister mounted in an inlet-stream of the accelerator sections is fed back to the stem position of the three-way valve and the water temperature is held constant.

A 5-KW heater is inserted in each inlet part of an accelerating waveguide cooling loop and a temperature signal is taken from the copper wall of each accelerating waveguide, and is used as a feed-back signal to the heater current. The inlet-water temperature is controlled by this feed-back system, and each accelerator section is held at 40°±0.5°C. The cooling water is always demineralized by ion-exchange resin to prevent an activation of the water by irradiation.

There are other two cooling systems. The one is the system for targets, slits, and collimators of the electron beam, and for magnet coils, and vacuum chambers of magnets. The cooling water is also demineralized for the above mentioned reason.

The other is the system for Klystrons. The outlet-water temperature of the Klystron is kept bellow 70°C by the system.

BEAM CHARACTERISTICS

The design current and the corresponding energy for the linac are given by

$$E=2\times\left\{(2P\tau_1L_1)^{1/2}\times\frac{1-\exp(-\tau_1)}{\tau_1}+ir_1L_1\times\left[\frac{1-\exp(-\tau_1)}{\tau_1}-1\right]\right\}$$
$$+3\times\left\{(Pr_2L_2)^{1/2}\times[1-\exp(-2\tau_2)]^{1/2}-\frac{ir_2L_2}{2}\left[1-\frac{2\tau_2\exp(-2\tau_2)}{1-\exp(-2\tau_2)}\right]\right\}$$

where

E = energy
P = input RF power to each accelerator
τ = RF attenuation
r = shunt impedance
L = length of accelerating waveguide
i = peak current

A suffix "1" denotes either the first and the second accelerator section and "2" denotes one of the third, the forth, and the fifth accelerator section.

Inserting the design parameter of the JAERI-linac into the above equation, the values of the current and the energy are obtained, which are shown in Fig. 4. Typical energy spectra actually obtained by the beam energy measurement are shown in Fig. 5.

The highest energy obtained is 190 MeV at 1 mA and the largest current is 600 mA at 100 MeV for a pulse width of 0.5 μsec. The energy spread width at half-maximum is 10 to 15%. The accelerated beam is very stable for long run operation. The beam

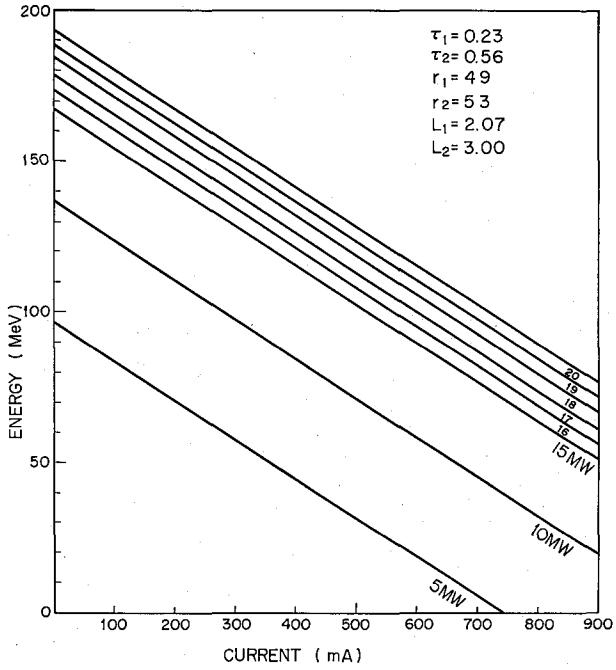

Fig. 4. Beam energy *vs* beam current of JAERI-linac.

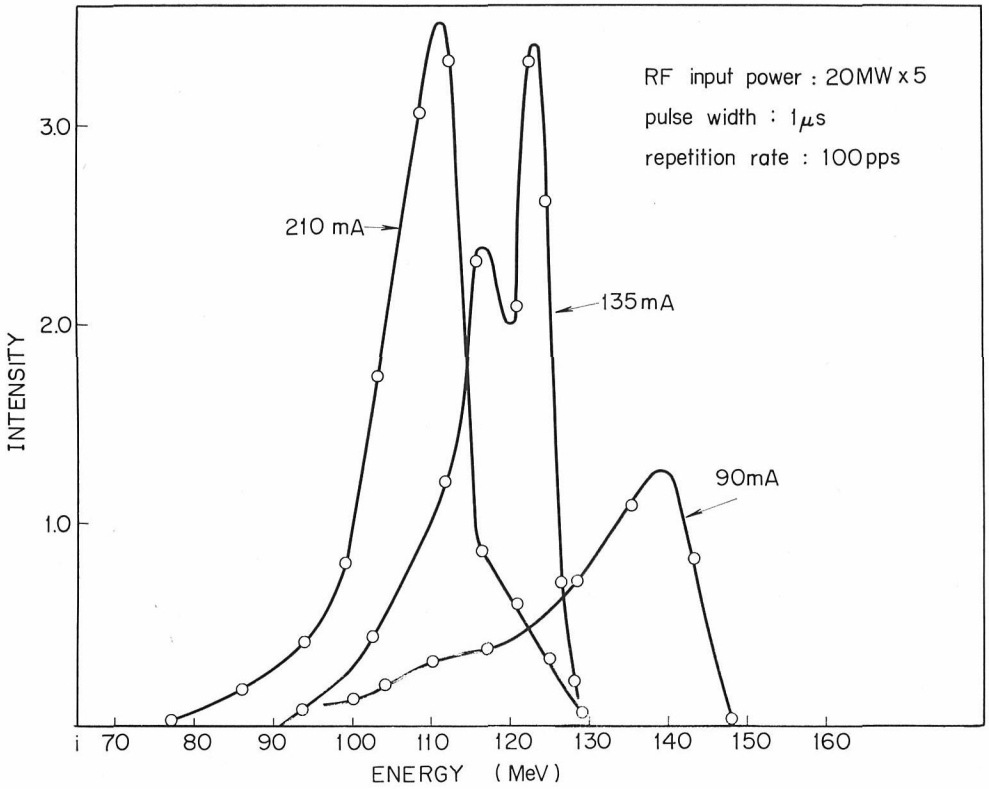

Fig. 5. Energy spectra under different beam conditions.

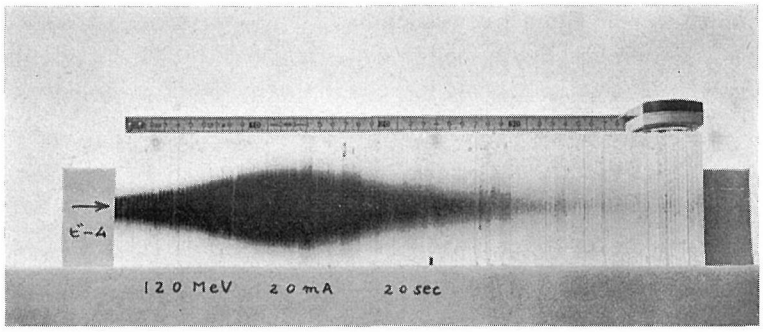

Photo. 3. Coloration of a stack of soda-glass plates induced by injection of 120–MeV electron beam. Length of the stack along beam direction is 45cm.

diameter is approximately 8 mm. Photograph 3 shows the coloration of a stack of soda-glass plates induced by injection of a 120-MeV electron beam. The length of a stack along the beam direction is 45 cm.

EXPERIMENTS

Neutron and nuclear physics experiments at the linac require very fast acquisition and reduction of multiparameter-multichannel data, the number of channels of which

frequently exceeds 8-K channels (K = 1,024), and more than two independent experiments are to be performed in parallel. To meet this requirement, an on-line computer system is installed at the Linac Laboratory. The system is composed of a 16-K 20-bit word core memory, a 64-K word drum, two 9-track magnetic tape units, an interface for ADC's, and several I/0 units. The commercial name of the computer is ICD–507, made by Tokyo Shibaura Electric Co. The direct access capability to the core has data acquisition speed of 1.8 μsec, including the add-one function.

The present interface accepts four ADC's for the pulse-height analysis and four ADC's for the neutron time of flight analysis, and has the event-recording mode of operation in addition to the normal one.

Research on neutron physics is done using the time of flight technique, and the neutron target for this purpose is shown C in Fig. 1. From this target six neutron flight tubes extend, four of which are installed outside the accelerator building and the other two are inside the building, as shown in Fig. 2.

The neutron target is a stack of tantalum plates cooled by water; just under the target is a paraffin moderator, the center of which is the crossing point of the center axes of most flight tubes.

At the 190-m and 100-m stations, neutron transmission experiments are carried on with high resolutions of around 0.5 nsec/m, and the total cross sections will be determined up to 100 KeV. The resonance parameters of various nuclei will be obtained in the energy range of up to about a few KeV, and the statistical properties of resonance levels will be investigated. The detector consists of seven ^{6}Li-glass scintillators (5″ dia. × 1/2″ thick).

Data of the neutron transmission measurement for a natural uranium sample is shown in Fig. 6. Above a few hundreds KeV another type of detector is required, and a plastic scintillator is now under construction.

The 55-m station is heavily shielded by concrete and earth. In this station, neutron capture cross section measurements is made with a large liquid scintillator tank, 3,500

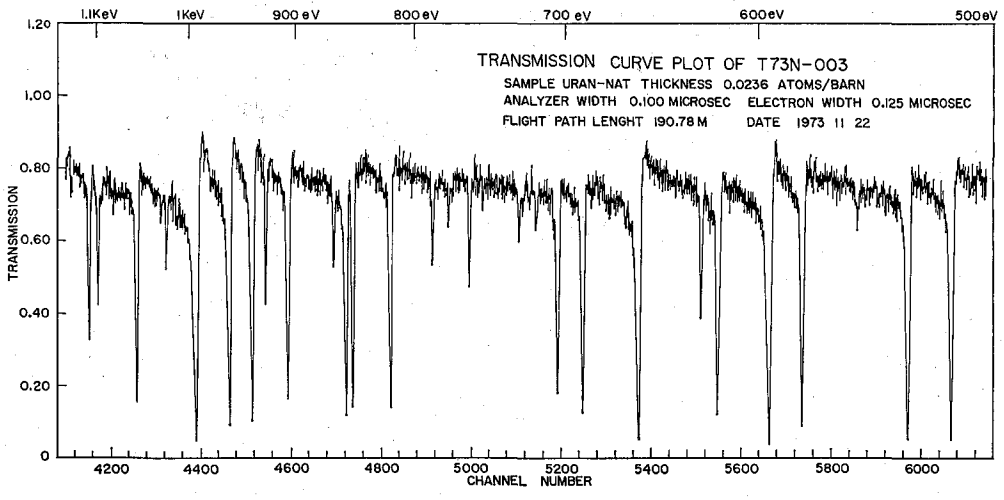

Fig. 6. Neutron transmission measurement for natural uranium sample.

liter in volume, the scintillator being a mixture of p-terphenyl, α-NPO, and xylene. With this detector the energy region to be covered in the measurement of the cross section extends up to a few hundreds KeV.

In the 45-m station, measurements on neutron elastic scattering is made using a ^{6}Li-glass scintillator. A ^{7}Li-glass scintillators is also used to compensate for a γ-ray effect on ^{6}Li-glass. Another scattering detector is designed to be able to measure angular distributions of scattered neutrons at a few angular points, and the detector is now under construction.

Besides these measurements mentioned above, other types of measurements are planned, one on fission cross sections and another on γ-rays associated with neutron capture. These measurements will be carried out with the remaining flight tubes.

Nuclear structure study with radioisotopes produced by intense γ-rays is going on. At the target position, R shown in Fig. 1. An X-ray converter is installed, which is a thin platinum plate cooled by water, and a pneumatic tube for sample transportation is connected to the converter. With this device very short-life radioisotopes can be studied. This new JAERI-linac greatly expands the capacity of radioisotope production in production-rate and species. The radioisotopes obtained by (γ, n), (γ, 2n), (γ, 3n), (γ, p), (γ, α) reactions, are useful for the nuclear spectroscopic study of short-lived nuclei.

ACKNOWLEGMENTS

The construction of the JAERI-linac has been the result of the combined efforts of a large number of people and the author wishes to acknowledge the work of his colleagues.

The design and the setting-up of the machine was carried out by the members of Linac Laboratory and Machine Shop of JAERI.

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