THE STATUS OF ACCELERATOR DEVELOPMENT IN JAPAN

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abstract

This paper reviews the progress and the status of existing and planning linacs in Japan.

Electron linacs have been made since 1965. At present the number of the operating linacs exceeds 170. However, of all the linacs, about 80 percent are commercial, and used for medical and industrial purposes. The remaining linacs were made for research purposes, for example, nuclear and neutron physics, radio-chemical researches and injector for electron synchrotron. These linacs have been successfully and reliably operating.

In 1974, the first proton linac in this country was completed in KEK as the 20 MeV injector for the 500 MeV booster and 12 GeV main ring synchrotron. The linac is now operated at the beam current of 120 mA.

The first heavy ion linac (RILAC) is under construction in Institute of Physical and Chemical research, and it will be completed by 1979.

As the planning machines, the 2.5 GeV electron linac and the storage ring are proposed for the "Photon Factory" project in the site of KEK. On the other hand, Electro Technical Laboratory is also planning 500 MeV high duty electron linac.

In addition, some of the peculiar engineering and technical problems concerning linacs in this country will be reported.

Introduction

In Japan, electron linacs have been made since 1956. The first linac was built in Institute for Nuclear Studies of the Univ. of Tokyo, as the injector of the 1.3 GeV electron synchrotron. At the early period, linacs were made only for research purposes. However, since 1965, the linacs of various energies have rapidly and widely spreaded to the scientific and engineering field because of the excellent features as the radiation sources of the appropriate energy range.

In the field of industry the linacs for radiography extensively increased in number as the growth of the heavy industries such as ship-building and plant-building. On the other hand, the medical linacs were extended to all over the country according to a policy of the Government for cancer therapy.

The planning of high energy proton machine in Japan began soon after the completion of the INS 1.3 GeV electron synchrotron, because high energy physics activities were limited so long as concerning only with the 1.3 GeV electron machine.

In the early plan, the proposed machine was the 40 GeV Proton synchrotron with the 125 MeV injector linac. However, the proposed budget was reduced to a quarter by the Scientific Affairs Council of Minister of Education. Consequently, the plan had to be changed into the reduced energy machine; 12 GeV Main ring, 500 MeV booster and 20 MeV linac.

This new project was approved by the government and in 1971 the new institute, i.e., the National Laboratory for High Energy Physics (KEK) was established in Tsukuba new science town located 60 km north-east of Tokyo.

In Aug. 1974, the first proton linac began the operation, in Dec. 1974, the booster accelerated the beam to the energy of 500 MeV and in Mar. 1976, the main ring succeeded to accelerate the beam of 10.4 GeV.

The successful operation of the KEK machine promoted the development of accelerator science in this country and would be undoubtedly a realistic foundation for the further projects.

In addition, the construction of the first heavy ion linac was started in the site of the Institute of Physical and Chemical Research in 1974. Some of the representative linacs existing and constructing in Japan are listed in Table I.

In recent years, some projects are in planning, the first is the "Photon Factory" and it will be the first stage of the KEK's future project "TRISTAN". The second is the 500 MeV high duty factor multipurpose linac in Electro Tech. Laboratory and so on.

Under these circumstances, the first conference on accelerator science in Japan was held at Tsukuba in Aug. 1975, and about 300 scientists and engineers concerning the various accelerators and their applications participated to the conference, and as a sectional meeting of the conference, the meeting on linacs has been held annually since 1975.

Existing Linacs

Electron Linacs

The old injector of the INS 1.3 GeV electron synchrotron was historically the first electron linac in Japan. The designed energy was 6 MeV at the beam current of 100 mA. The klystron was home made and was pumped by a oil diffusion pump. After 2 years operation the energy was raised up to 9 MeV by replacing the klystron.

The accelerator guide including a buncher was $\pi/2$ mode and was made by means of electroforming method. This linac was a simple and extremly reliable machine. After 15 years operation (more than 80 thousand hours) as the injector, it was replaced by new designed 15 MeV linac in 1975.[1] The new 2 m long accelerator guide including a short buncher is $2\pi/3$ mode semiconstant gradient type. It was made by means of the new electro plating method. The phase fluctuation of the reprective cells was within 2° without any tuning.

In the normal operation as the injector, the energy is 14 MeV at the beam current of 200 mA and the pulse width of 4 μs. The threshold current of regenerative beam break up at the pulse width of 4 μs is about 480 mA.

In this machine, the frequency detuning phenomenon was observed at the heavy loading condition. The frequency shift at 400 mA loading is about 250 kHz as compared with the light loading condition. (Fig.1) The study of the phenomenon is now continued.

The 300 MeV Tohoku Univ. accelerator is the largest machine in the existing electron linacs in Japan. As shown in the block diagram of Fig.2, the accelerator composed of the two sections. The first section is low energy high current and the second section is high energy and low current.

The low energy section consists of eight 1 m long accelerator guides and two 20 MW klystrons and the high energy section has twelve 2 m long accelerator guides and three klystrons. The guides of the machine were made by the electroplating method.

The machine has been operated reliably since 1967. In 1976, an energy spread compression system similar to the Mainz accelerator in Germany was installed down stream of the high energy section. By the system the energy spread was reduced from 2 per

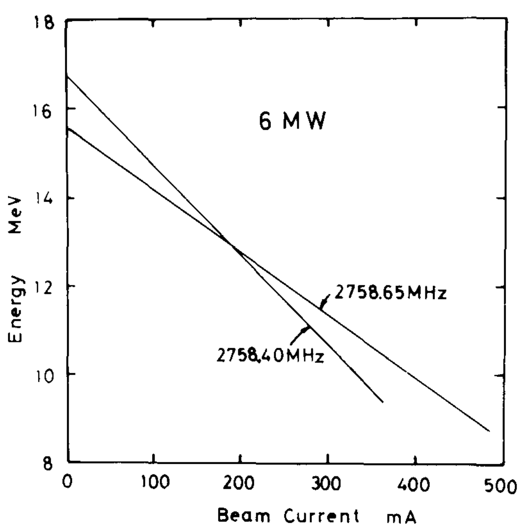


Fig.1 Optimum frequency in heavy loading is different from that of light loading.

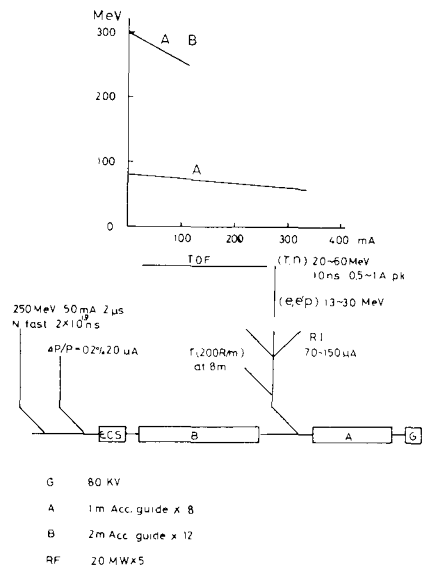


Fig.2 Layout of 300 MeV Tohoku Univ. accelerator.

Table I

Existing and Constructing Linacs in Japan

Institution	Date of first op. (Reconstructed)	Particle	Max. Energy	Current	Duty Factor	Mechanical Length	Field Mode	Frequency	Remarks
Tokyo Univ. Inst. for Nuclear Study	1961 (1975)	electron	15 MeV	100 mA 480 mA at 9 MeV	4 μs 21.5 pps	2 m	2π/3	2758 MHz	injector for 1.3 GeV ES
Japan Atomic Energy Research Inst.	1961 (1972)	electron	150	250	0.01 ~ 2 μs 1 ~ 600 pps	2.07 m × 2 + 3.00m × 3	2/3π	2857	neutron phys. rad. chem. solid state phys.
Electrotechnical Laboratory	1963 (1969)	electron	35	200	4 μs 300 pps	1.2 m × 3	2/3π	2886	rad. standard irradiation
Kyoto Univ. Research Reactor Inst.	1966	electron	46	2500	10 μs 180 pps	2.5 m + 1.8 m	2/3π	1307	neutron phys.
Tohoku Univ. Lab. of Nuclear Science	1967	electron	300	50	~3 μs 50 ~ 300	1.05 × 8 + 2.1m × 12	2/3π	2856	nuclear phys. neutron diffraction
Hokkaido Univ. Fac. of Engineering	1973	electron	45	100	0.01 ~ 3 μs 200 pps	2 m × 3	2/3π	2800	neutron diffraction pulse radiolysis
Hiroshima Univ.		electron	35		3.3 μs 120 pps	2.5 m	2/3π	2856	medical
Tokyo Univ. Nuc. Engin. Res. Lab.	1976	electron	35	2000 200	10 ns 20 pps 4 μs 200 pps	1.7 m + 2.0 m	2/3π	2856	neutron phys. pulse radiolysis
KEK	1974	proton	20	140	0.6 ~ 30 20 pps	15.5 m	Alvarez	201.08	injector for P.S.
Inst. for Physical and Chemical Research	1979	heavy ion m/e=5~20	0.8~5 MeV/nucleon	1 ~ 100 μA	100 %	3 m × 6	Widerae	18 ~ 45	nuclear phys. solid state phys.

cent to 0.2 percent, at the same time the stability of the energy was also improved.

The 150 MeV Japan Atomic Energy Research Inst. (JAERI) accelerator consists of two 2 m long $2/3\pi$ mode constant impedance guides and three 3 m long $2/3\pi$ mode constant gradient guides. Five 20 MW klystrons feed the rf power to the five guides respectively in order to simplify the phasing of the guides. (Fig.3)

Consequently, the maximum accelerating field is rather high and amounts to 13 ~ 15 MV/m.

The no load energy of the linac is 190 MeV and the energy at the beam current of 1 A and 0.5 μs pulse width is 100 MeV. The accelerator began the operation in 1972 and has been operated successfully; however, recently, the rf ceramic window placed close to the input coupler of the first accelerator guide has been successively broken. It was probably

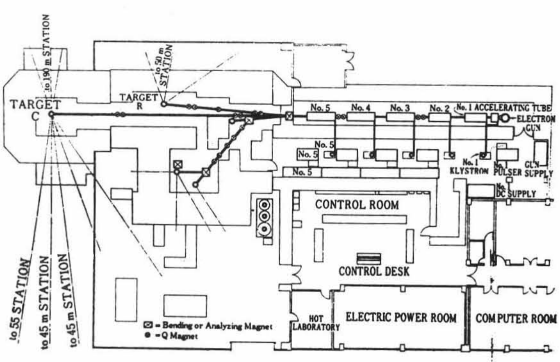
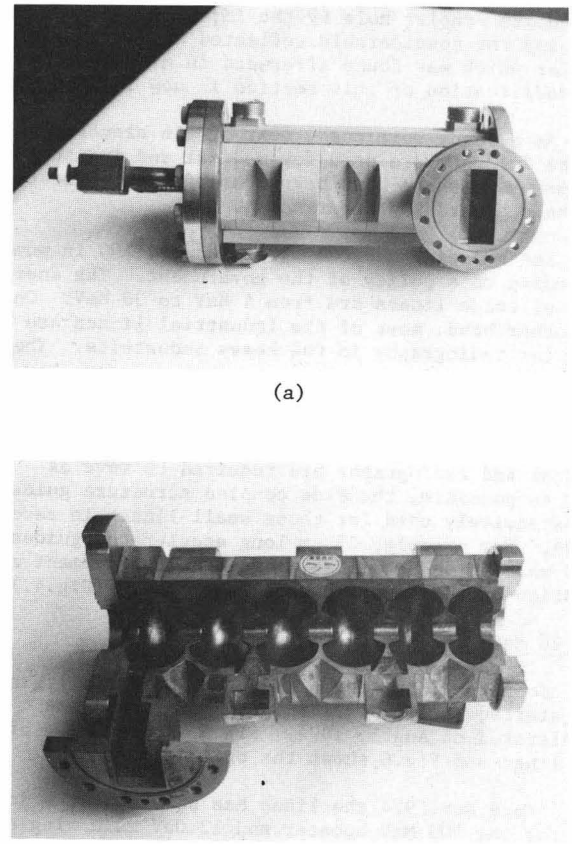


Fig.3 Layout of 150 MeV JAERI accelerator.



(a)

(b)

Fig.4 4 MeV side coupled accelerating structure (a) out view, (b) cross-sectional view

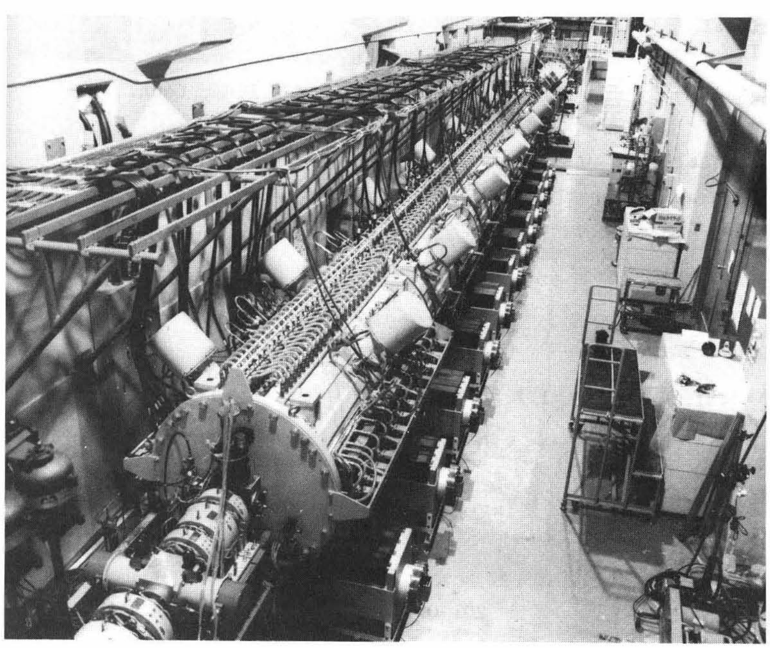


Fig.5 View of 20 MeV KEK linac.

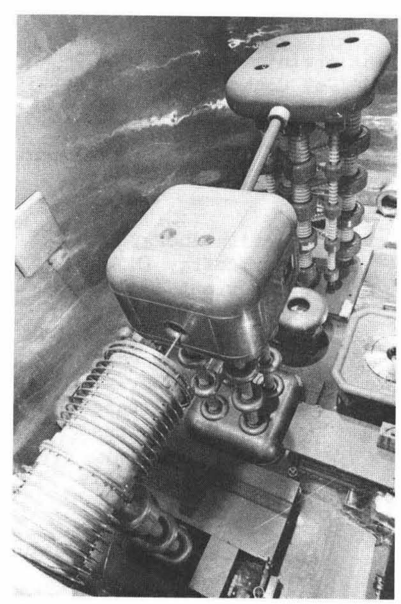


Fig.6 View of the preinjector.

due to the bombardment of secondary electrons produced around the coupler hole by the injected electron beam and the considerable reflected wave from the coupler which was found afterward in mismatching. The modification of this section is now in progress.

As already mentioned, most of the electron linacs in Japan are used for medical and industrial purposes and those have been commerially fabricated as the standardized apparatuses.

The existing medical linacs exceed 100 in number according to a policy of the government. The energies of those linacs are from 4 MeV to 30 MeV. On the other hand, most of the industrial linacs are used for radiography in the heavy industries. The linacs for chemical purposes are not so many, however, those for the irradiation will be extended thereafter. The energies of the industrial linacs range from 1 MeV to 15 MeV. Because linacs for medical and radiography are required to move as easy as possible, the side coupled structure guide is extensively used for those small linacs in recent years. For example, 25 cm long accelerator guides were made for 4 MeV linac, consequently movement and rotation of the linacs became more easy. (Fig.4.)

KEK 20 MeV Proton Linac

Construction of the KEK 20 MeV injector linac was started in Apr. 1971 and the first beam was accelerated on Aug.1, 1974. Fig.5 shows a view of the linac and Fig.6 shows the preinjector.

Since Nov.1974 the linac has served as the injector for the 500 MeV booster and 12 GeV main ring synchrotron. In Mar. 1976 the main ring accelerated the beam to the energy of 10.4 GeV.

The machine studies are now continued and the high energy physics experiments are scheduled to be started from May 1977.

The general parameters and present operational performances of the linac are listed in Table II.

The preinjector consists of a 4 stages open type 750 KeV Cockcroft-Walton generator, a duoplasmatron, a huge porcelain accelerating column named "Monster", a high voltage capacitor column with bouncer and 5 m long LEBT system.

For design of the accelerating column a special attention was paid since frequent but relatively weak earthquakes (Seismic intensity of grad III, < 25.0 gal) take place in Tsukuba area. The column consists of two big porcelain tubes bolted each other in tandem. The total length is 3 m and the inner diameter is 1 m. Each porcelain tube has 9 inside shields and 9 outside shields. Each inside

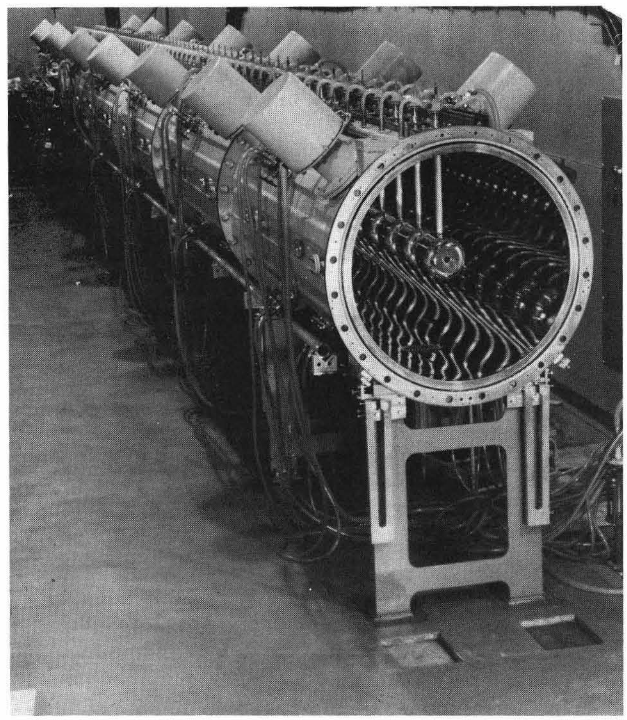


Fig.7 Support of KEK linac tank.

Table II

General parameters and Operational performancs of KEK linac

	Design	Operation	Best
Injection Energy (MeV)	0.75	0.75	
Output Energy (MeV)	20.5	20.3	
Peak Current (mA)	100	120	150
Beam Pulse Width (μs)	0.6 ~ 30	0.6 ~ 17	
Energy Spread (%)			
Without De-buncher	<±1.0	±1.2 at 120 mA	
With De-buncher	<±0.5	±0.4	±0.3
Normalized Emittance (cm mrad)	<π	0.6π at 120 mA 90 %	0.5π
Repetition rate pps	20		
Length of tank (m)	15.6		
Number of unit cells	89		
RF power			
excitation (MW)	1	1	
beam loading compensation (MW)	20 × i(A)		
Freq.(MHz)	201.25	201.08 (at 27°C)	
Pulse width (μs)	250	275	
Number of rf feeds	2 (1/4 L and 3/4 L)		

shield is connected to the corresponding outside shield passing through the holes on the tube wall. In this tube, any organic adhesive such as epoxy was not used. Recently, the break down voltage increases up to more than 760 kV by increasing the pressure in the column upto 2 ~ 3 $\times 10^{-4}$ torr, and no conditioning was needed. Consequently, the start up time of the preinjector was remarkably reduced; moreover, the sparking rate was extremely reduced.

One of the major features of the linac is that the tank was made by copper plating method. The tank is 15.6 m long and divided into 6 unit tanks in order to facilitate the fabrication. The 88 drift tubes and 2 half length drift tubes on the both end plates were also made by the plating method. The mechanical structure of the tank and drift tubes were designed so as to be suited for the plating.

Thin copper contactor and Viton "O" or "X" ring assembly was used for all the joints of the tank to make possible good electrical contact and vacuum seal.[2] Because all kind of the joints have a structure facilitating the leak detection of their own, any leak has not been detected since the first evacuation.

For tuning of the tank, 14 tuners are distributed on the tank wall and they are also available for tilting of the field distribution along the axis.

The drift tube quadrupole magnets are Danby type and are pulse operated at a field gradient of 10 kG/cm. Mechanical errors of the magnetic centers were within 20 μ, and the alignment errors to the tank axis were within ±40 μ. The coils were machined from blocks of copper instead of ordinary wire windings,[3] consequently mechanical accuracy, space factor and reliability of the coils were markedly improved. The current pulse of the magnets has a half-sine shape with 120 μs flat-top.

The support of the tank consists of 12 steel plates and U shaped pre-loaded springs. (Fig.7) The structure is very simple and consitutes so-called a soft-structure,[4] consequently it is efficient for the longitudinal thermal expansion of the tank and for the earthquake shocks.

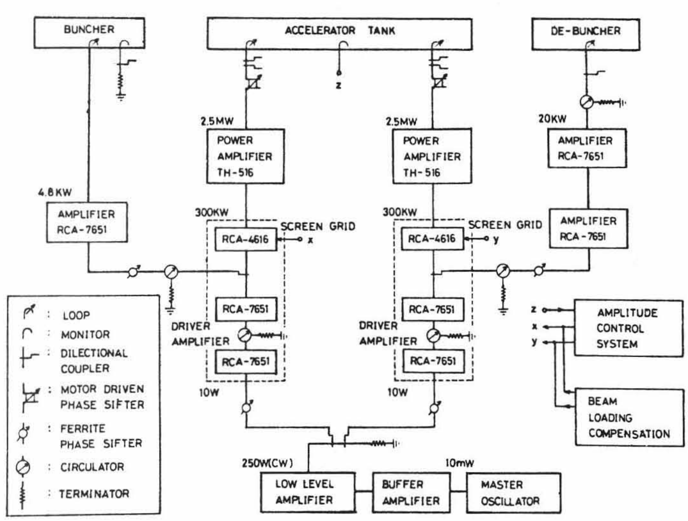
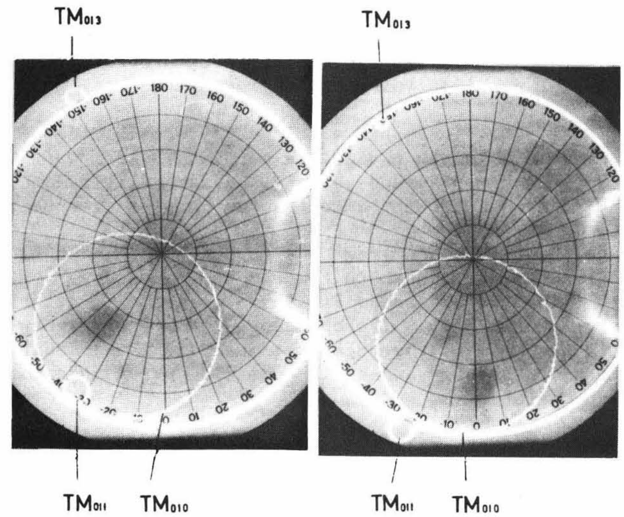


Fig.8 Block diagram of RF system.



(a) (b)

Fig.9 Dynamically balanced impedances looking into two couplers from the respective generators.

(a) coupler (1), (b) coupler (2)

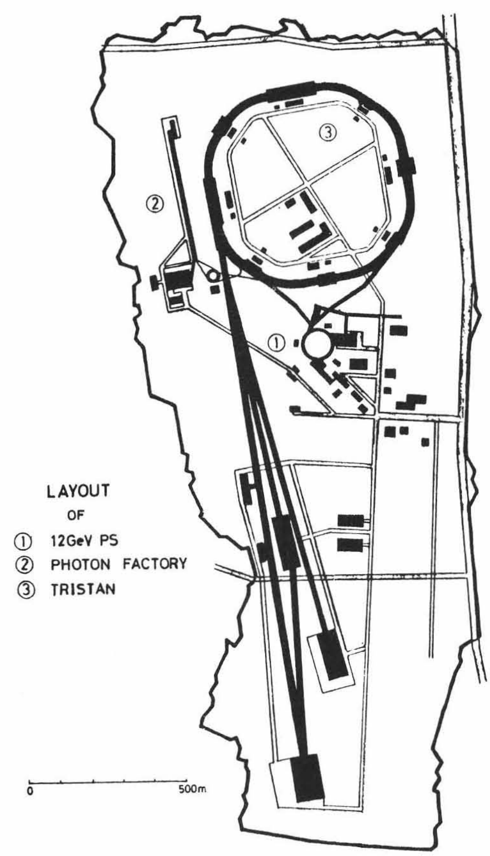


Fig.10 Layout of future projects of the KEK.

As shown in the block diagram of Fig.8 the rf system consists of a master osc. (Synthesizer), a low level amplifier, two driver amplifiers (RCA Y-1068 B) two TH-516 final amplifiers and 20.3 cm diameter coaxial transmission line system.

In order to suppress the nearby higher modes, 1/4 and 3/4 length two points coupling system was adopted. Fig.9(a) and (b) shows dynamically balanced impedances looking into the two couplers respectively.

The H.E.B.T. system consists of a main channel to transport the beam to the booster, an energy analyzing channel and a Faraday cup channel available for the beam damp. The changing of respective channels are made by the pulse magnets. By this, monitoring of the energy spread is possible during injector mode operation.

Planning Machines

The photon factory (P.F.) means a facility supplying the intensive photon beams produced by synchrotron orbital radiation (SOR) for the researches of various photo-induced phenomena. The origin of the name is something like to the "Meson Factory".

After the completion of the 1.3 GeV electron synchrotron of the Univ. of Tokyo, some solid state physicists proposed the use of SOR as a tool of studying solid state physics. In 1971, INS-SOR group started the consturction of a 300 MeV storage ring using the extracted beam from the electron synchrotron.

The Science Council of Japan advised the construction of the P.F. to the government at the end of 1974. In 1976, the P.F. committee proposed to KEK to establish the photon factory as a facility of KEK in order to get a site of 1 km × 0.5 km with a suitable environment and to get a number of accelerator scientists to construct the machine. The proposal was accepted by KEK, because the P.F. has a powerful source of high energy electrons which is necessary for the future project of KEK; "TRISTAN".

The accelerator of the P.F. consists of a 2.5 GeV electron linac as a high energy electron source and a 2.5 GeV storage ring completely dedicated to the SOR researches.

The electron linac will be the electron injector for TRISTAN. The planning layout of the P.F. and the TRISTAN is shown in Fig.10.

For the injector linac the energy of 2.5 GeV was chosen. It makes, therefore, easy to increase the circulating current in the storage ring because no acceleration is necessary, and possible to use as the electron injector for the TRISTAN. The type of the linac is an ordinary one and its main parameters and the parameters of the storage ring are listed in Table III.

Table III

Parameters of 2.5 GeV Linac

General	
Max. energy (50 mA loaded)	≥2.5 GeV
Peak current	≥50 mA
Beam pulse width	>1.0 μs
Repetition rate	<50 pps
Energy spread	<±0.5 %
Normalized emittance	<10 πcm mrad
Accelerator guide	
Type of structure	TW. Const. Grad.
Frequency	2856 MHz
Type of mode	2π/3 (+ π/2)
Length of unit guide	>2 m
Number of guides	160
Attenuation parameter	0.5 ~ 0.6
RF power	
Peak power of a Klystron	≥20 MW
Number of Klystrons	≤40
RF pulse width	3.0 μs

Parameters of 2.5 GeV Storage Ring

General	
Energy	2.5 GeV
Max. stored current	500 mA
Peak magnetic field	10 kG
Radius of Curvature	8.44 m
Mean radius of orbit	22.48 m
Revolution frequency	2.125 MHz
Radiation loss/turns (with one wiggler)	477 KeV
Magnet	
Betatron frequency	$\nu_x \sim \nu_z = 5.25$
Number of cells	16
Type	Separate function $\frac{0}{2}\, Q_F B Q_D B Q_F\, \frac{0}{2}$
RF system	
Frequency	467 MHz
Harmonic number	224
Max. radiation loss	240 kW
Peak cavity voltage (τ~1 day)	2 MV
Number of cavities	4
Total rf power	600 kW
Properties of stored beam and SOR	
Radiation damping time	
betatron osc.	6.5 ms
synchrotron osc.	3.2 ms
Energy spread of stored beam	$\pm 7.6 \times 10^{-4}$
Quantum life time	~24 h
Beam size bunch length	5 ~ 10 cm
radial	1.6 ~ 2.7 mm
vertical	~0.5 mm

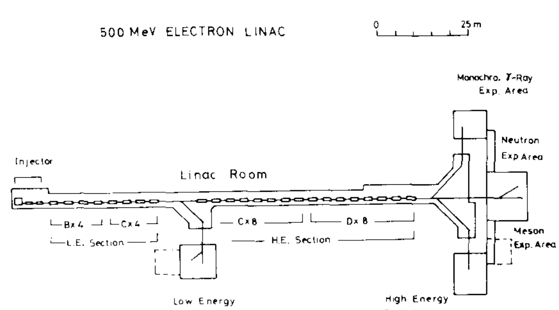


Fig.11 Proposed layout of 500 MeV Electro Tech. Lab. accelerator.

Table IV

General parameters of the Electro Tech. Lab. Accelerator

	Injector	L.E. Section	H.E. Section	Total
Length (m)	4	24	48	120
No. of acc. guides	2	8	16	26
No. of Klystrons	1	4	8	13
Max. pk. power (MW)	12	48	96	156
Max. av. power (kW)	36	144	288	468
Energy (MeV)				
no load	31	184	400	615
loaded	28(100 mA)	164 (100 mA)	367 (60 mA)	559 (60 mA)
Max. av. current (μA)	500	500	300	300

SOR	
Normal	
Wave length at Photon number max.	2.26 Å
Photons/Å sec mrad at peak	2×10^{16}
Wigger (60 kG)	
Wavelength	0.38 Å
Photons/Å sec mrad at peak	6×10^{17}

Electro technical laboratory is one of the bureaus of the ministry of trade and industry. Although the laboratory has the 35 MeV electron linac, the laboratory is now planning the construction of the 500 MeV multipurpose high duty factor electron linac with removal from Tokyo to Tsukuba. Fig.11 shows the planning layout of the machine.

The machine will be used for calibration and absolute measurements of the various radiation measuring apparatuses, pulsed neutron physics, radiochemical researches and the researches for radiation damages.

The general parameters of the linac are listed in Table IV.

Electroplating method for accelerator guides and tanks

Accelerator guides of electron linacs in Japan have been manufactured by two methods so far. One of them is a usual brazing method in which machined copper disks and cylinders are stacked inserting thin filler metals on a jig. The assembly is brazed in a hydrogen furnace at the temperature of more than 700°C. Consequently, after brazing, the frequency tuning of the respective cells are neecessary because the guide is annealed and slightly deformed.

The other is an electro-plating method. 20 years ago, we had developed the electro-forming method[6] similar to the stanford method.[7] The copper disks are machined and then assembled spacing correctly by Al-alloy spacers on a jig placed under water. The assembly is copper plated on its outside to form a solid tube of 0.6 ~ 1.0 cm in thickness, and then the spacers are removed by dissolving solution. The method made possible the accelerator guide of the en block, good rf, vacuum tight and high precision structure.

However, a few difficulties had to be overcome in order to keep the phase shifts of the respective cells within 2° which corresponds to the fluctuation of 50 kHz at 3,000 MHz.

The first was how to eliminate the slight deformations of the inner diameter of the cylinder caused by difference in thermal expansion between the deposited copper and the Al-alloy spacers.

The second was how to deposit fine and uniform crystalline thick copper as rapidly as possible. These difficulties were solved by fine control of the plating process; i.e. deposition rate, temperature

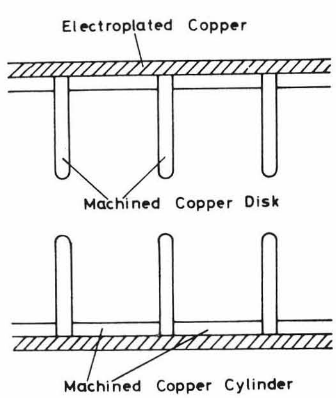


Fig.12(a) Cross section of accelerator guide by means of electro-plating method.

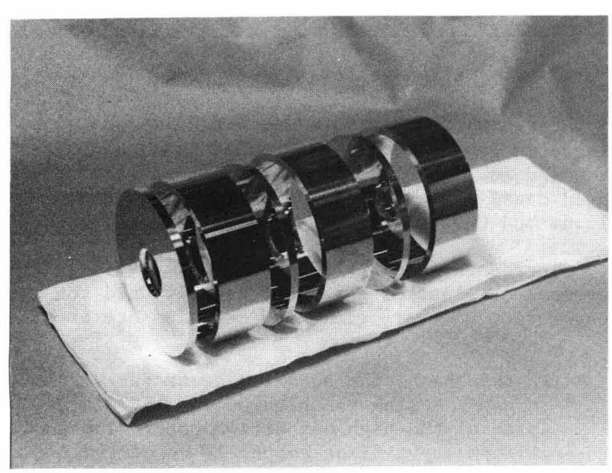


Fig.12(b) Copper disks and copper cylinders.

of the plating bath and etching solution and by fine adjustment of the diameter of the spacers.

After that a new electroplating method was developed,[8] in which machined copper disks and cylinders are inspected by means of microwave test and the parts of accepted quality are assembled on a upright jig. (Fig.12(a),(b)) The outside of the assembled long cylinder is electroplated in a upright copper bath to form a solid cylinder. The adequate thickness of the deposited copper is about 6 mm for 3 m long accelerator guide.

As above mentioned, this method requires no thermal and chemical fine controls as the previous electroforming method and completely eliminates the need of tuning because the parts are never exposed to high temperature.

For the 2.5 GeV electron linac of the photon factory, we are now developing a more improved method using automatic and high speed copper bath*[9] in order to save manpower and deposition time, and it will make possible the higher precision and lower cost accelerator guides.

As already reported[9] the tank of the KEK linac was made by the electroplating method, and the advantage was proved by the 2 years operation of the KEK linac.

In this method, all the mechanical fabrication processes such as welding and machining are finished before plating process, and after copper plating, any machining such as polishing is avoided in order to prevent scratching or contaminating the fresh and clean copper surfaces. Consequently, high precision structures having smooth and clean surfaces required for the high Q and high power rf cavities are obtained; besides, the difficulties such as hardsoldering of the large structure or machining of the soft copper are eliminated.

As the method was already reported, some of the important points of the method are described here.

1. Basic design of the structure suited for plating
2. Quality of the base metal to be plated
3. Technique of welding
4. Jigs for plating

<u>Welded bellows vacuum pipes</u>

For high repetition synchrotron, vacuum pipes placed in gaps of the magnets that is doughnuts are troublesome. If the pipes were made of metal, they would cause a significant error in the magnetic fields and they would be heated by the eddy currents.

Therefore, non-metallic material such as glass, ceremics or plastics have been usually used for the doughnuts. However, glass and ceramics are fragile

* In this bath, the addition agent (UBAC R-1) is used. Using the high speed bath, in spite of the high deposition rate, fine and uniform crystalline copper is deposited and cleaving of the deposited copper is prevented.

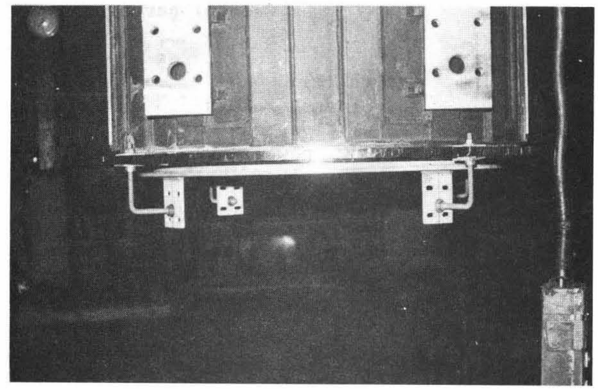


Fig.13 P.V.C. shield attached on a france of tank to be plated. Suitably shaped nonconducting shield prevents excessive deposition on edges and insures uniform deposits.

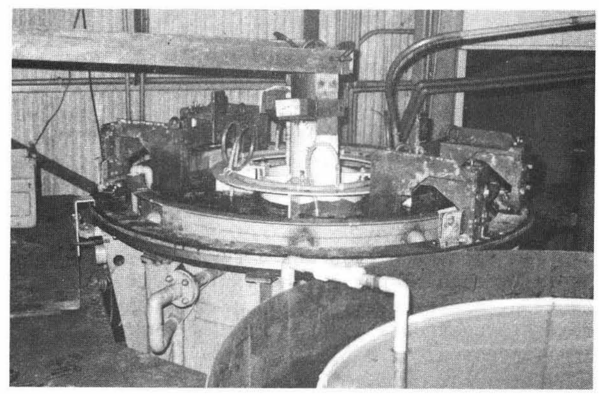


Fig.14 Electroplating bath.

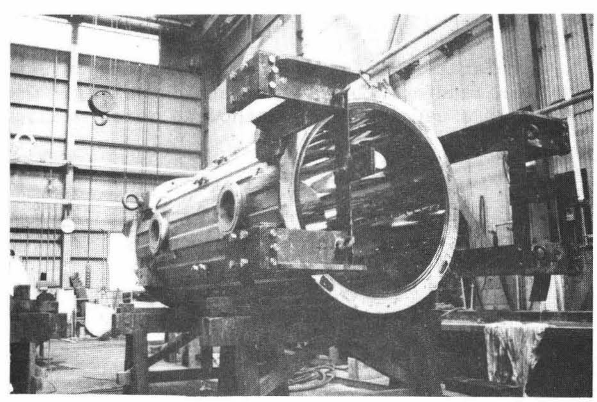


Fig.15 Copper plated unit tank.

and not handy; on the other hand, plastics are liable to be damaged by strong radiations and to release various gases.

In order to make possible a durable, handy and outgassless doughnut, a welded stainless-steel bellows was developed for the purpose.[10] Its longitudinal electric resistance is equivalent to that of a straight pipe with thickness of 0.03 mm.

The metal doughnuts have been used for the INS electron synchrotron since 1971 and for the KEK booster since 1974.

The similar welded bellows having a rectangular cross section is also used for the pulse magnets placed in the HEBT system of the KEK Linac.

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DISCUSSION

G. Dome, CERN: You mentioned difficulties with rf windows for electron linacs. How did you solve these problems?

Tanaka: We moved the window to the position far from the coupler and readjusted the rf matching of the coupler.