THE JAPANESE 12 GeV ACCELERATOR

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Introduction

After a long history, construction of the 12 GeV proton synchrotron started in 1971 at the National Laboratory for High Energy Physics in Japan (Ko-Energiebutsurigaku Kenkyusho, standing for KEK in the followings). The laboratory is located at about 70 km to the north-east of Tokyo. It is one of the major institutes in the new academic town, Tsukuba, dedicated to scientific research and education. The synchrotron will be completed in 1975; its energy was planned to be 8 GeV at the first design stage but now is expected to be increased to 12 GeV by saving budget.

Since this energy is still low in the present situation of the world high energy physics, we have worked out our design and construction plan according to the following philosophy of

1. Obtaining a high intensity beam with good quality for performing unique experiments in the possible energy range,

2. keeping flexibility both in the machine and its belongings for future improvements and refinements,

3. developing new technologies which will give distinctive feature of the machine and will make progress in the accelerator arts, and

4. leaving possibility for future extension to a higher energy range.

The main parameters of the KEK synchrotron are given in Table I. The synchrotron consists of four accelerators; i.e. a 750 keV Cockcroft-Walton preinjector, a 20 MeV injector linac, a 500 MeV fast-cycling booster and a main synchrotron. This scheme of the accelerator was chosen based upon the above design and construction philosophy. It will not only provide a high intensity beam but also notable experiences in the modern accelerator arts in Japan. An aerial photograph and the outline plan of the accelerator is shown in Fig.1 and Fig.2, respectively.[1]

Table I. PARAMETERS OF KEK PROTON SYNCHROTRON

I. Main Ring	
Kinetic Energy	12 GeV
Intensity	$>2\times10^{12}$ (1×10^{13})
(Space Charge Limit)	p/pulse
Type	Separated-Function
Focusing Order	FODO
Average Radius	54 m
Number of Superperiod	4
Number of Betatron Oscillations	7.25
Maximum Bending Field	17.5 kG
Injection Energy	0.5 GeV
Repetition Rate	0.5 Hz
II. Booster	
Kinetic Energy	500 MeV
Space Charge Limited Intensity	3×10^{12} p/pulse
Type	Combined-Function
Focusing Order	FDFO
Average Radius	6.0 m
Number of Cells	8
Number of Betatron Oscillations	2.25
Maximum Magnetic Field	11 kG
Repetition Rate	20 Hz
III. Linac	
Energy	20 MeV
Type	Single Tank D-T Linac
Cavity Length	15.5 m
Number of Cells	90
Peak Current	~100 mA
Repetition Rate	20 Hz
Preinjector	750 kV Cockcroft-Walton

Ion Source and Preinjector

The Cockcroft-Walton high-voltage generator was constructed several years ago at the Institute for Nuclear Study, University of Tokyo and moved to Tsukuba in November 1971. After being assembled again and connected to the ion-source terminal, the high voltage system was tested up to 850 kV (Fig.3).

A high brightness ion source was developed by our ion source group in collaboration with Dr. Th. Sluyters, Brookhaven, the first alien visiting scientist. It is a modified duoplasmatron ion source with a nozzle-type expansion cup. The cup contour was designed by a consideration similar to supersonic nozzles for rarefied gas flows. By shaping or biasing the cup exit, we succeeded to reduce the aberrations due to the plasma boundary and get a brightness as high as 5×10^{10} A/m^2/rad^2 at 300 mA of the proton beam.[2] The shape of the plasma cup and a typical phase space distribution are shown in Fig.4 and Fig.5, respectively.

A high-gradient accelerating column with a mean accelerating field of about 38 kV/cm is used as the preinjector. One of the peculiar problems to our accelerator construction is the effect of earthquakes. Vibration frequencies of the ground surface, the accelerator enclosures, and the accelerator components were carefully measured and most parts are safely designed against an earthquake of 0.2 g. In particular, for protecting the column from earthquakes we made it of a couple of large ceramic insulators, each 1.5 m in length and 1.1 m in diameter. The preinjector will be completed and come into operation in the course of this month.

Linac

The linac will provide a 100 mA beam with a 20 μs pulse duration at 20 MeV. The design feature of the linac is based on the extensive study on beam loading, space charge, and other high intensity effects carried out both by theoretical analyses and by measurements with model cavities.[3] Construction of the linac started in April, 1971, and the main components, i.e. the accelerator tank with drift tubes and quadrupole magnets, the RF power supply, the control system, the vacuum equipments, low and high energy beam transports, and other auxiliary components have been installed in the linac housing. The test of each component has almost been finished and the first linac beam will soon be obtained.

The accelerator tank is a 15.5 m long single cavity operating at 200 MHz with 3 MW RF power. This tank is divided into 6 units and contains 88 drift tubes and 2 half-length drift tubes on the end plates.

In order to fabricate the linac tank and drift tubes with high RF conductivity and high mechanical precision, an electro-plating method of copper onto steel was developed and gave excellent results[4] A copper bath with an organic brightening agent and bubble agitations was used. The surface roughness less than 0.3 μ of the plated copper of 1mm ± 0.1mm in thickness was obtained without any surface finishing after the plating. The measured unloaded Q-value was found to be as high as 90 % of the value calculated by using d.c. conductivity of copper (Fig.6). Field distributions along the cavity axis were measured by means of a perturbation method with a small metallic ball running through 50 cm/sec. The frequency perturbation was counted by a digital clock and displayed on a scope after a computer analysis (Fig.7).

A new manufacturing process of drift tube quadrupole magnets was also developed leading to obtain the maximum field gradient of 11 kG/cm and the deviation of the mechanical bore center from the magnetic center within 20 μ[5] The quadrupole magnets are driven by the current of a half-sine shape (1.3 ms) with a flat top of 120 μs. The ripple and pulse to pulse fluctuations of the flat top are less than 0.1 %.

The linac tank and drift tubes were assembled and aligned better than ± 40 μ in the setting errors. The tank is supported by flat steel plates with preloaded U-shaped steel springs to ensure the tank setting against the earthquake vibrations as shown in Fig.6. The transverse and longitudinal natural vibration frequencies are set lower than the typical earthquake frequencies of 2 ~ 20 Hz.

The RF power supply consists of a master oscillator, a low level amplifier, two drivers with RCA 4616 tubes, and two final stage amplifiers of FTH 516 tubes. The RF power supply is installed in the service room paralleled the tank housing and the linac tank is driven at two points each located at a quarter of the total length from the end plates. Use of the double feeds has the advantage of compensating beam loading and transient effects along the cavity length[6]

Booster

The booster is a fast cycling AG synchrotron operated at a repetition rate of 20 pulses per second. It accelerates protons to 500 MeV at the maximum guide field of 11 kG. Eight C-type magnets with a combined-function FDFO lattice are arranged around the circumference of 6 m in average radius. The average radius of the main ring is nine times larger than the booster, so that the booster injectes nine pulses into the main ring to fill up its total circumference. The number of betatron oscillations was chosen as $\nu_z = \nu_r = 2.25$ mainly from the requirement of tolerance for the magnetic fields at the beam transporting process from the booster to the main ring. The straight sections between the magnets are used for injection, ejection, and RF acceleration systems as shown in Fig.8.

The magnet cores are fabricated of oriented low-carbon steels laminated to 0.35 mm to reduce eddy current effect. The high permeability at high fields as ≳ 600 at 20 kG is obtained in the rolled direction of this specifically developed irons[7] A soft epoxy resin was employed to reduce interlamination shorts and to fix a magnet core without a stress imposed by stacking process, however it was found that a careful thermal treatment is necessary to ensure the mechanical strength of the stacked blocks. Last October, all the magnets were set on the site with the rms error of about ± 60 μ in the radial direction, ± 90 μ in the height of median plane and ± 20 mrad in the twist of the median plane (Fig.9). The field measurements have been carried out upto the full excitation and the results obtained show good agreements with the design performance expected from computer calculations. The booster magnets were excited by using a series-parallel resonant circuit with dc-biased sinusoidal excitation (Fig.10). The same type core material as the magents was also used for the energy storage choke and produced ~99.9 % coupling coefficients between secondary windings.

The useful aperture of the magnets is 12.6 cm in horizontal and 6.0 cm in vertical direction. Since the booster is a fast cycling machine, the eddy currents induced on the vacuum tube would cause a significant error in the magnetic field distribution. In order to reduce the eddy currents we have developed a corrugated stainless tube, whose effective wall thickness is 0.03 mm (Fig.11). The same type vacuum tube has been used in the 1 GeV electron synchrotron at the Institute for Nuclear Study and found to be satisfactory.

The fast-cycling low-energy booster also requires a development of RF acceleration system which enables us to change the frequency and the voltage in a wide range with an adequate power loss. The harmonic number of the RF system was chosen as one from the consideration on the beam-transporting process as discussed later. A single cavity with two accelerating gaps is used, the resonant frequency of which is changed from 1.6 MHz to 6.0 MHz during the acceleration by an ordinary ferrite tuning system. A study on RF properties of various ferrites led to develop a material having large μQf values over the frequency range, however it was found that the Q value remarkably decreases by the fast repeating excitation. To avoid local heating of the stacked ferrites, is provided a cooling channel adjacent to every ferrite sheet of 50 cm in outer-diameter and 2.5 cm in the thickness (Fig.12). The whole RF system consisted of RF power supply, ferrite bias supply and control units will be assembled during the next month. A computer calculation on the synchrotron oscillations led an RF voltage program capable of 80 ~ 90 % RF capture of the injected beam[8] The proposed RF program is shown in Fig.13.

The linac beam is expected to be ready to inject into the booster by the fall of this year, so that the booster will come operation in the end of 1974.

Main Synchrotron

For flexibility, a separated-function type FODO lattice was chosen in the main synchrotron. There are four superperiods, each containing seven unit cells, two of which have a missing-magnet straight section of 5.5 m long. These straight sections are used for injection, fast and slow ejections and RF accelerations. Fig.14 shows the cell structure of the main ring. The average radius of the main ring is 54 m, and the nine pulses from the booster are injected into the main ring in 0.5 second while the main ring guide field is held constant at 1.5 kG. The acceleration takes place in the following 0.8 sec (0.5 sec), and a 12 GeV (8 GeV) proton beam will be obtained at the guide field of 17.5 kG (12 kG).

The main synchrotron enclosure and most of the auxiliary or the service buildings were completed in 1973 and sink of the foundation has been investigated. All of 48 bending and 56 quadrupole magnets have been installed in the main ring tunnel with setting error of about 1 mm (Fig.15). From orbit analysis, the position errors of magnets are required to be less than ± 0.1 mm, and precise alignments will hereafter be pursued.

In contrast to the usual separated-function synchrotron, we have decided to use the C-type bending magnet because of its better accessibility which makes beam handling and maintenance much easier than the H-type magnet machine.[9] By using oriented low carbon steels (lamination thickness = 1 mm) a maximum field of about 18 kG can be obtained at the gap of the bending magnets. The same material was also used for the quadrupole magnets. The design of magnets was done as a consequence of field computations with the magnetic field computer programs. For quadrupole magnet design, the computer program LINDA was modified to include the core-orientation effect.[10] The computations have been compared with the field measurements and the results show agreements within 0.5 % between computations and measurements.[11] Typical results obtained by field measurements are given in Fig.16 - 18, where use of the oriented core also shows the advantage of reducing octupole components in the quadrupole magnets.

The main magnet power supply is manufactured in Fy '73 and '74* and will be installed in a service building. The bending magnet power supply is divided into 2 × 3 groups and operated in accordance with an inverter-converter combination program shown in Fig.19. The power supply for quadrupole magnets is also divided into two parts and operated at a similar condition. This system of power supplies was chosen to reduce the ripple voltage at the injection and flat-top operations in addition to the flexible programmable controls. One of the problem we met concerning the power provision is a negotiation with the electric company on cost estimates to the reactive power, protection of commercial lines from flickers and higher harmonics produced by a pulsed operation, and campaign of the inhabitants against the installation of high-voltage power transmission line to the laboratory. For protecting the voltage fluctuation, a thyristor reactive power compensator has been developed together with a large AC filter system against wave form distortions.[12] The commercial high voltage line is barely managed to reach the laboratory by October, '74, and after that the test of the power supply will be started.

The RF acceleration system is located in a long straight section and consists of three cavities somewhat similar to that of the booster. The RF frequency is varied over a frequency range from 6 MHz to 8 MHz corresponding to the harmonic number of 9. A beam-control system will be used to control the phase and radial position of accelerating particles.

Since we aim at a high intensity beam, a special attention should be paid on the problem of radiation damage. As an example, we decided to avoid any organic elements from the vacuum system of our synchrotron. For this purpose we have developed a new type of metal gasket called "H-type gasket", which is shown in Fig.20. The H-type gasket works well at a compressive force of less than 7 kg/mm, and can be used several times repeatedly. An all metallic gate-valve using the H-type gasket is also being developed and tested.

All of other equipments necessary for the main synchrotron operation will be constructed during this fiscal year so that we expect to have an accelerated proton beam by end of 1975.

Control and Beam Transporting System

The operation of KEK Synchrotron will be controlled from a central control system.[13] A network computer system consisted of six Melcom-70 type computers will be used for data logging, processing and analysis, information display, and transmission of control commands. The main control computer with 16 bit w, 32 kw of core memory, 2.5 Mw disk memory and 2 magnetic tapes is assisted by five satellite computers each containing 8 kw core memory. The main computer communicates with the operator, stores the data collected from satellite computers, produces displays of accelerator parameters and develops various application programs. One of the satellite computers will assist data-collection at the control room and other four will collect data from or send commands to the distinct parts of the accelerator such as the linac with the preinjector, the booster, the east- and the west-part of the main ring. The main magnet power supply will be controlled by an additional computer system that communicates directly with the equipment.

All of the control modules such as on-off, up-down and interlock units have been standardized, and the monitoring equipments and information display system are being developed. A single control console at the central control room will be used for the entire machine operation, while several local control stations will also have their own consoles.

With the aid of computer programs, beam transport systems between the preinjector and the linac, between the linac and the booster, and between the booster and the main ring have been designed.[4] Each sub-system has successively been constructed from the low energy side. The low energy beam transport installed between the linac and the preinjector includes a prebuncher, beam monitors and emittance measuring devices (Fig.21). The beam from the linac is debunched by a debuncher to reduce longitudinal space-charge effect and passes through the phase-space matching section and achromatic system. The achromatic matched beam is injected into the booster by multiturn injection using a set of the septum and bump magnets. We left a space for a future increase of the linac energy between the linac and the booster. The linac beam can also be switched out to the beam measuring devices.

The proton beam accelerated by the booster is ejected by a set of the fast-kicker, bump and septum magnets, and injected into the main ring by a similar system consisted of the kicker and septum magnets. In the transport line between the booster and the main ring, the beam matching is performed not only for the transverse phase space but also for the momentum dispersion function.

In addition to the transverse matching, the bunched beam from the booster should be matched to the longitudinal phase space of the main ring. It is required for this to synchronize the phase of the booster bunch with the phase of the main ring RF bucket. Since the frequency of synchrotron oscillations in the booster is relatively low in such a low energy booster, the usual synchronization methods proposed or used for the NAL accelerator and other high energy machines would suffer from technical difficulties. Taking advantage of the single bunch acceleration in the booster (harmonic number = 1), we shall use a new method utilizing phase slip due to a small difference between the RF frequency of the booster and that of the main ring.[4] Near the maximum field of the booster, we switch off the booster beam feed-back control system and keep the booster RF frequency constant at about 10 kHz less than the main ring RF frequency which is synchronized with the design energy, i.e. 500 MeV. Then the booster bunch slips with respect to the main ring RF bucket and coincides with the latter once in every 100 μs. A coincidence circuit detects the phase coincidence and triggers the ejection system from the booster into the main ring. The variation of the magnetic field near the top energy is within 10^{-4} during 100 μsec and the shift of the radial beam

* Japanese fiscal year starts from April 1 and ends on March 31.

position due to keeping the RF frequency constant is within 0.1 mm. This synchrotronization method is simple, fast and independent of synchrotron oscillations.

Extractions and Experimental Facilities

The first proton beam accelerated by the KEK synchrotron is expected in the end of 1975 and the scheduled experiments will start from early 1977. Two experimental halls are designed, one of which will be used for bubble chamber experiments and the other for counter experiments. Three beam channels are planned for experiments; a fast extracted beam for the bubble chamber, a slow extracted beam and an internally converted secondary beam for the counter experiments. The fast extraction system from the main ring is planned to use an electrostatic septum combined with a fast kicker magnet, leading to produce a few μs beam pulse with an improved emittance. The design study of the slow extraction system from the main ring is in progress including a choice of the resonance used.

A considerable amount of money for preparing and developing experimental instruments including a bubble chamber (.75 m/1mϕ) has been provided so that the experimental program can be started at the moment of the accelerator completion. The experiments will be performed not only by the KEK physics group but also by the scientists from other universities and institutions as the national accelerator for common use.

Future Option and Improvements

Since the total budget for machine construction is limited to 4000 M yen*, first we aim at obtaining 8 GeV in energy and $\gtrsim 2 \times 10^{12}$ ppp in intensity. However, for performing unique experiments in the possible energy range, we will proceed with the successive improvements and refinements. The attainable energy will soon be raised up to 12 GeV with a small modification in the power supply and the cooling system. The intensity will be able to reach to 10^{13} ppp during a few more years. Beam quality and stability for experiments will also be improved gradually. In particular, we will make continued efforts on ensuring reliability and exploiting flexibility in the machine operations.

Although the design philosophy of employing a booster in our synchrotron is on rasing the space-charge limited intensity in the main ring, the booster will also be used for intermediate-energy nuclear science, pulsed neutron experiments, or medical applications as a future option. One of the straight sections in the booster is remained for extracting the beam to an experimental hall which will be constructed at that time. Possible acceleration of polarized protons both in the main ring and the booster are being studied[15] and a serious resonance effect is pointed out in the booster caused by a choise of the ν value of 2.25. Such a high ν value was taken from the requirement that, in order to make beam transport easier, the transition energy of the booster should be much higher than the booster energy. However, some addiitonal quadrupole magnets for reducing ν value to 1.75 or less in the vertical direction will be necessary for accelerating polarized protons in the booster. Taking advantage of using a separated-function type lattice, the polarized beam may be accelerated upto the maximum energy in the main ring without any serious resonance effect. A development study of an intense polarized ion source is now started. Not only acceleration of protons, but acceleration of deuterons or polarized deuterons will also be studied for future applications to nuclear physics experiments.

At last, extension of the present synchrotron to higher energy range should be the most important goal of our project. In a separate paper, a preliminary design study on a possible plan of the future extension, i.e. so-called "Tristan project" will be reported in this Conference.[16]

* 11~13 M$ depending upon the fluctuation of current currency.

Acknowledgement

The construction of the synchrotron reported here is a collaboration work in the KEK Accelerator Department and I would like to thank all of my good colleagues for their excellent collaborations. In addition, I am grateful to many outside collaborators, particularly to the visitors from foreign laboratories, for their valuable contributions in the various stages of our project.

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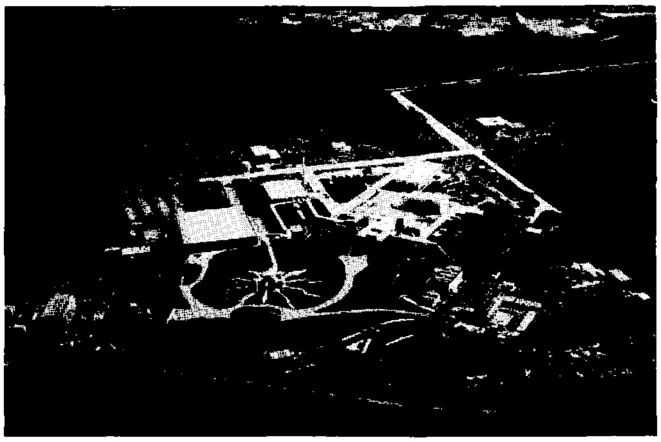


Fig.1 Aerial View of KEK Synchrotron

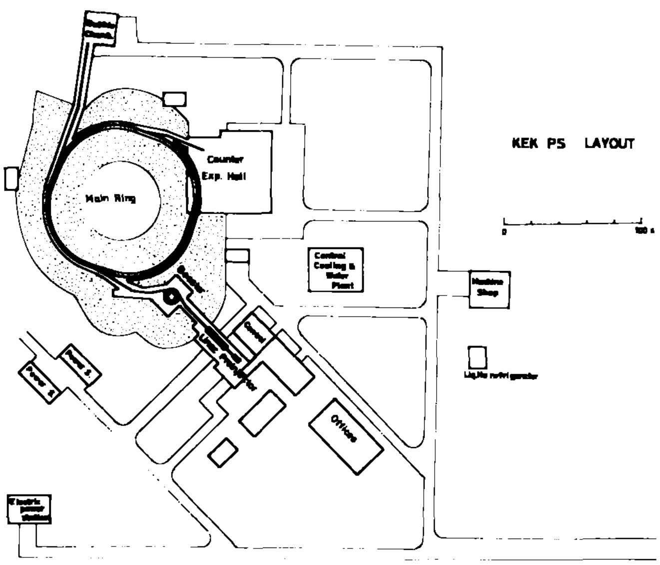


Fig.2 Layout of KEK Synchrotron

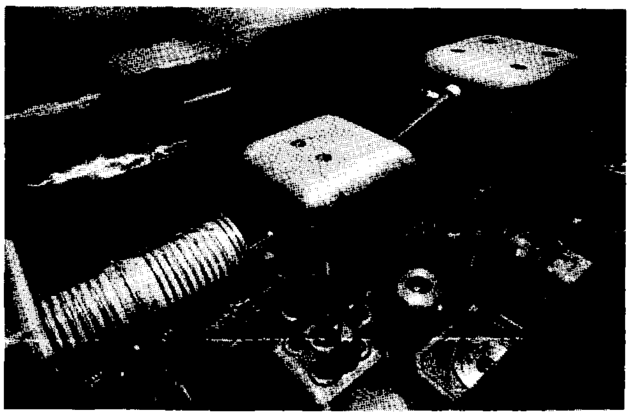


Fig.3 KEK Preinjector

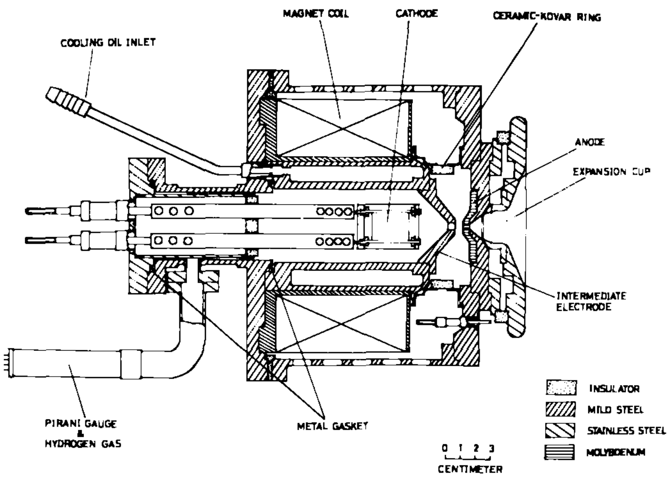


Fig.4 Duoplasmatron with a Nozzle-type Expansion Cup

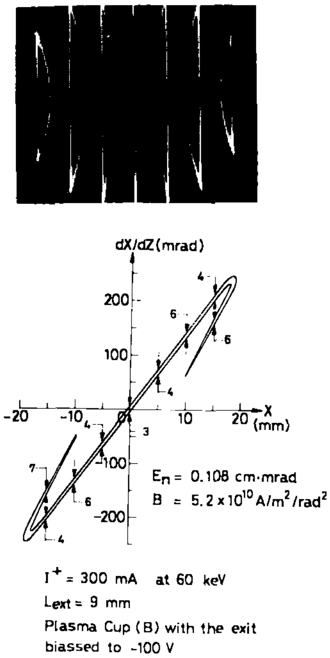


Fig.5 Beam Image and Emittance Diagram of a 60 kV, 300 mA beam

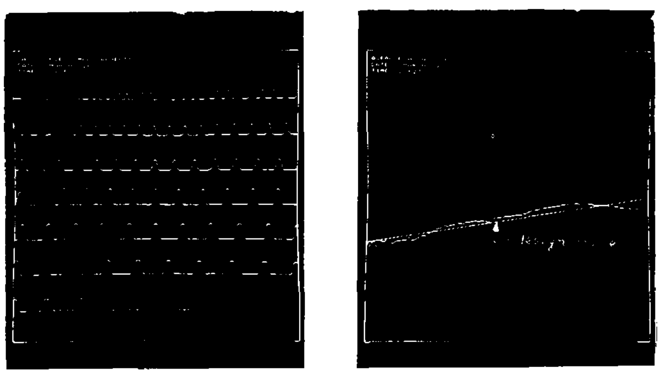


Fig.7 Field Distributions along Linac Cavity. Display of Frequency Perturbations (left) and Average Field in Comparison to Design Valve (right).

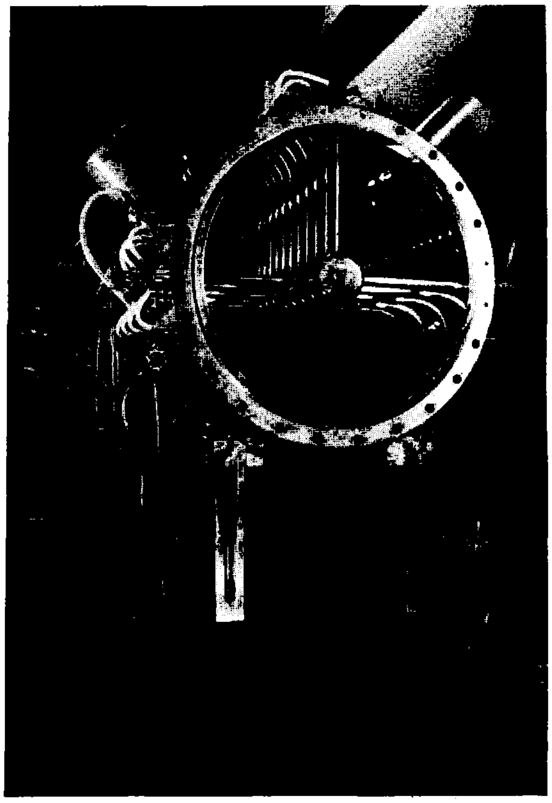


Fig.6 KEK Linac

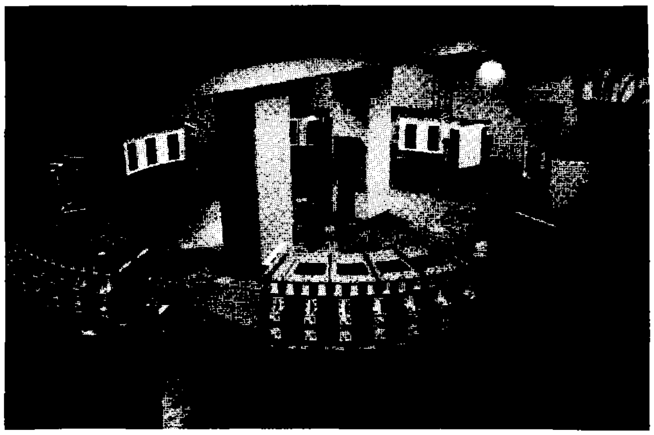


Fig.9 Photograph of KEK Booster

Fig.11 Corrugated Vacuum Chamber being installed between Magnet Gap of Booster

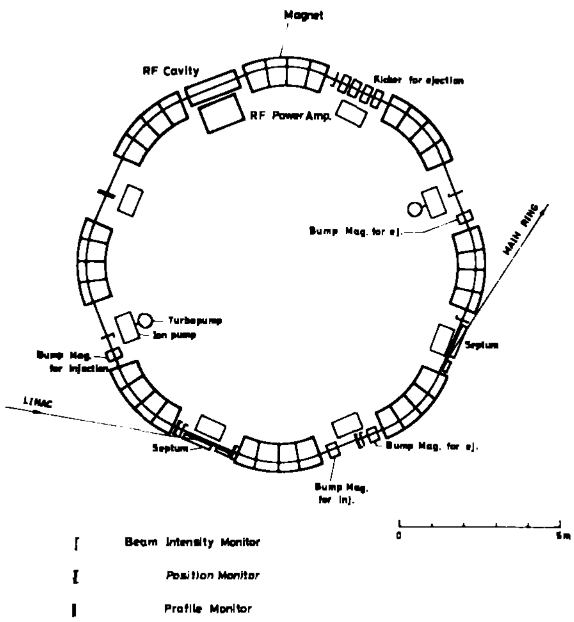


Fig.8 Layout of KEK Booster

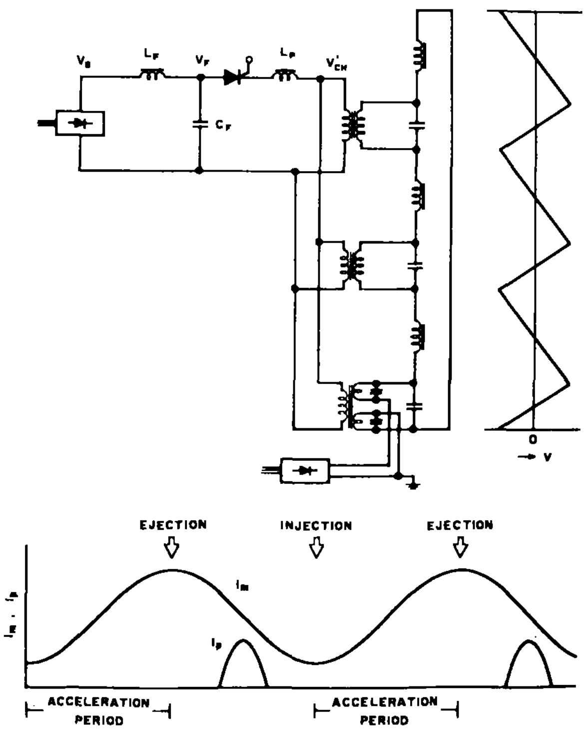


Fig.10 Basic Diagram of Booster Power Circuit

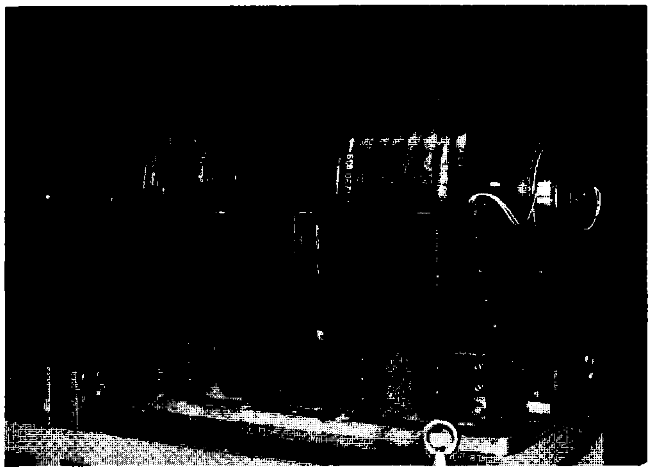


Fig.12 Booster RF Cavity

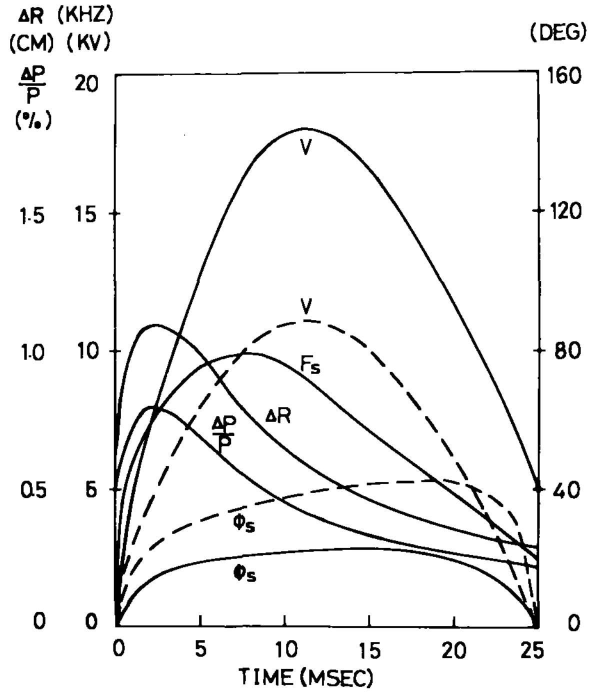


Fig.13 RF Program of Booster. Broken Curves show Necessary Minimum Voltage and Corresponding Phase Stable Angle. F_s gives Frequency of Phase Oscillations.

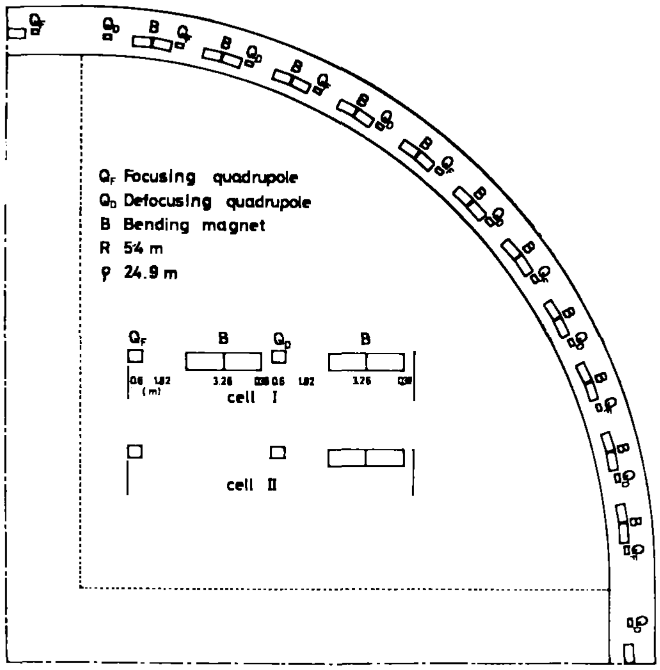


Fig.14 Cell Structure of KEK Main Ring

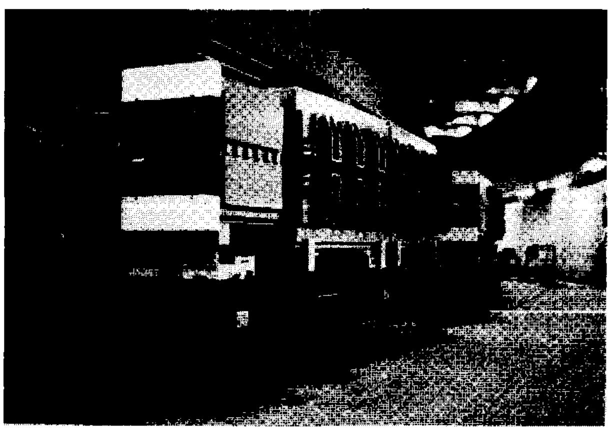


Fig.15 Photograph of KEK Main Ring

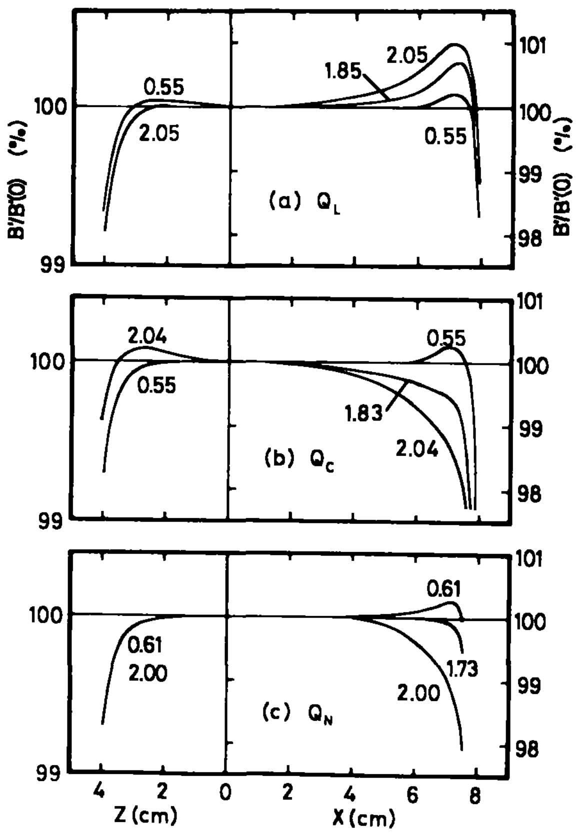


Fig.16 Horizontal and Vertical Gradient Distributions of Quadrupole Magnet. See ref.11.

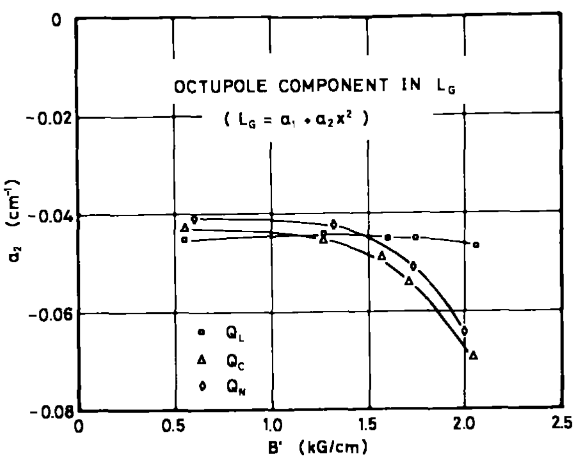
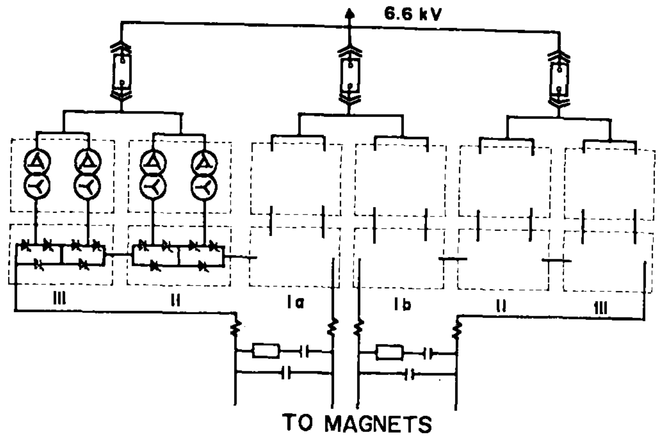


Fig.17 Octupole Component of Effective Length of Quadrupole Magnet



RECTIFIER GROUP / PERIOD	I_a	I_b	II	III
Injection Porch	Conv.	Inv.	Bypassed	Bypassed
Acceleration	Conv.	Conv.	Conv.	Conv.
Flat Top	Conv.	Conv.	Bypassed	Bypassed
Deceleration	Inv.	Inv.	Inv.	Inv.

Fig.19 KEK Main Ring Power Supply and Operation Program

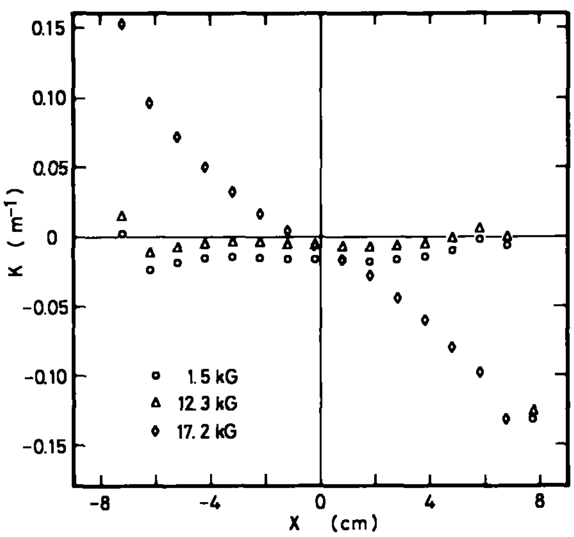
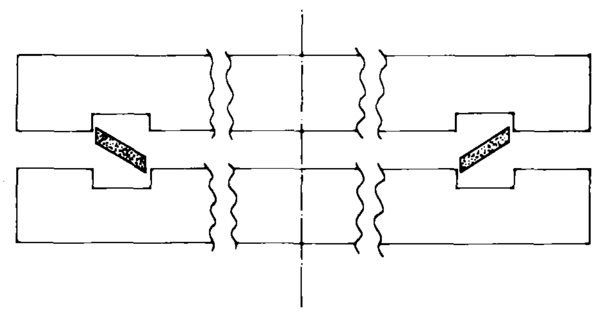


Fig.18 Gradient Distribution of Bending Magnet



Merits :

- Self-aligning structure
- Sexless flange
- Sealing point is hardly damaged.
- Small force required ~ 7 kg/mm

Demerits :

- Shape of gasket is complicated.
- Deformation of gasket for ≳ 100 kg/mm

Fig.20 H-type Gasket

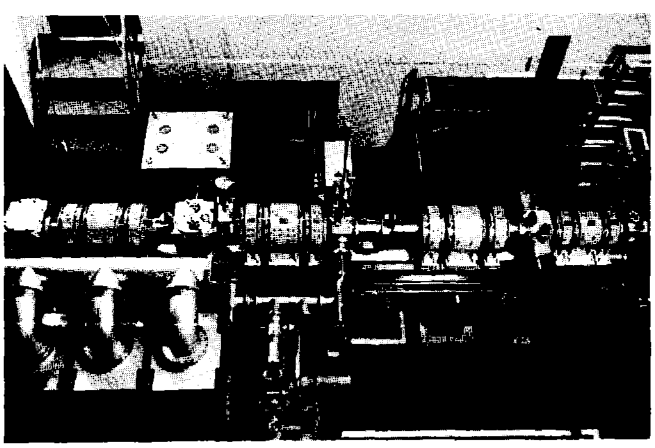


Fig.21 Low Energy Beam Line between Preinjector and Linac

DISCUSSION

Andrei Kolomensky (Lebedev Institute): Do you plan to do nuclear physics with this machine?

Nishikawa: We are also planning to use the machine for nuclear experiments, particularly using low-energy K-meson beams.

Milton White (Princeton): I didn't understand the vacuum chamber design in the booster.

Nishikawa: It is a corrugated vacuum chamber to reduce eddy current effects. The stainless-steel bellows of 0.2 mm in thickness are welded leading to the effective thickness of the wall of 0.03 mm.

Boyce McDaniel (Cornell): How much space do you lose in the magnet gap due to the corrugations?

Nishikawa: We lose 1.5 cm due to the corrugation.

Willard E. Jule (LASL): Were the field measurements in the linac made at high power and under vacuum?

Nishikawa: No, the measurements were made in air at a lower field level.