A 1,000 MeV ALTERNATING GRADIENT ELECTRON SYNCHROTRON

By

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I. GENERAL

The accelerator development has been contributing to the nuclear physics during the last 25 years. At times, the series of the new theories would spur the development of the higher energy accelerators and at the other times the experimental results obtained by a newly developed or invented accelerator would stimulate the new progress in theory.

In each type of accelerator, its maximum size has been limited by some technical or economical reasons. In the electrostatic generator its maximum energy has been limited by the phenomena of electrical breakdown. In the case of the cyclotron, the size was limited by the relativistic increase in mass of the accelerated ions.

The sequence of the development is roughly as follows, that is the Cockcroft-Walton voltage multiplier, the electrostatic generator, the cyclotron, the betatron, the synchrocyclotron, the proton synchrotron and the alternating gradient synchrotron. The increase in energy of each accelerator is illustrated in Fig. 1.

In the alternating gradient synchrotron, we can allow the use of much smaller vacuum chamber as well as of lighter and cheaper magnet for a given accelerating energy, although it requires much more severe accuracy for installation.

The 1,000 MeV alternating gradient electron synchrotron is installed in Institute of Nuclear Study of Tokyo University in Japan and will enter in operation in the middle of 1960. Our Company took the part of the design and construction of its huge magnets whose weight was roughly 70 tons and size over 11 meters in diameter, in cooperation with staffs of the Institute mentioned above. The construction of the magnet was completed in march, 1959.

At the present time, this accelerator is the largest one in Japan both in size and in its final accelerating energy. But it is only the preliminary project for obtaining technical informations or experiences to build another larger alternating gradient proton synchrotron in the near future.

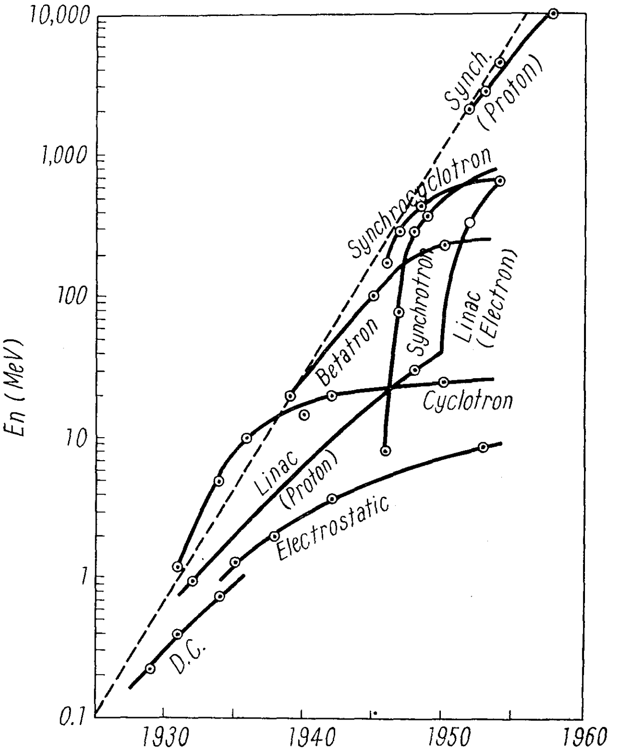

Fig. 1. Development of accelerators during the last 25 years

II. ROLE OF HIGH ENERGY ACCELERATORS

The high energy accelerators are used for investigation of the elementary particles in a nucleus and of the characteristics or properties of the forces in the short range between these particles. The nuclear force which binds nuclei together and leads to the concentration of the energy released in fission and in thermonuclear process, is not well understood. It is, however, the general conviction among theoretical physicist in the present days that the perfect explanation of nuclear forces will involve meson fields in the nucleus. For studying meson properties and hence for grasping the true features of the nucleus, high energy accelerators are used as the most essential devices.

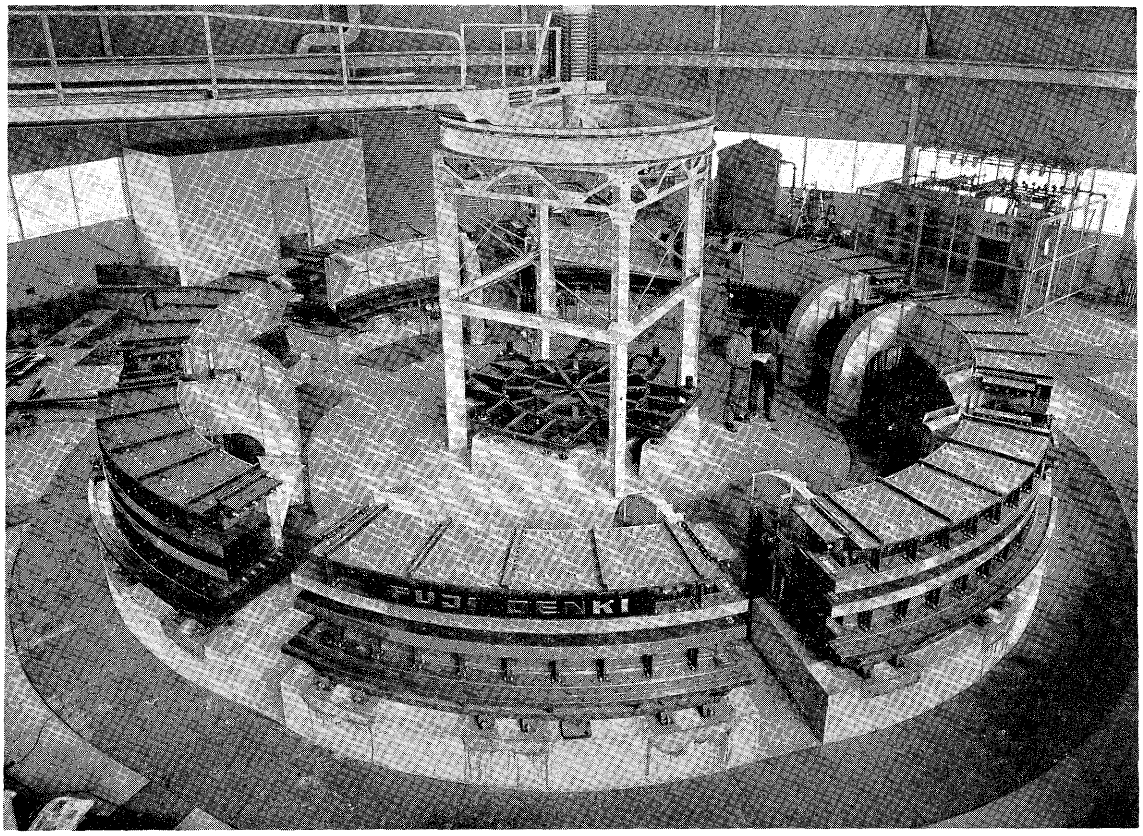

Fig. 2. General view of magnet of 1,000 MeV alternating gradient electron synchrotron

In any reaction of producing, a new particle the energy, which is equivalent to the rest energy of the particle, will be required. The range of 200 to 500 MeV has been used for the production of π mesons through the process of series of reactions for example, as follows.

$$\gamma + p \rightarrow n + \pi^+$$
$$\gamma + p \rightarrow p + \pi^\circ$$
$$\gamma + p \rightarrow p + \pi^-$$

where γ, p, n and π stand for a γ ray, a proton, a neutron and a π meson respectively. The suffix $+$, $-$ and 0 to π show the signs of electric charges where 0 is neutral. It is also a generally accepted prediction that there should be several heavier mesons than π meson. For producing these heavier mesons, much higher bombarding energies, above 1,000 MeV, will be required.

For the reason mentioned above, we can find the significance of the construction of the 1,000 MeV electron synchrotron, whose maximum energy will be raised to 1,300 MeV by superposing the direct current excitation to the alternating one for the purpose of providing enough energy for K meson production, as one of a few machines which exist in the world at the present time.

III. PRINCIPLE OF ELECTRON SYNCHROTRONS

1. Ordinary type

In an ordinary synchrotron, electrons will be accelerated in running round an orbit having the constant radius by means of a radio frequency electric field applied across a gap at one point of the orbit. Electrons are constrained to move in their circular path by means of magnetic field which increases with time.

The pole faces are so shaped as to provide a magnetic field which decreases slightly with increasing radius. This radially decreasing field can be specified in terms of an index n as

$$B_Z = B_{Z_0}\left(\frac{r_0}{r}\right)^n \quad \cdots\cdots (1)$$

where B_{Z_0} is the magnetic field on the median plan at the orbit r_0 and B_Z is the magnetic field at a nearby radius r. The index n can be expressed by

$$n = -\frac{r}{B_Z} \cdot \frac{dB_Z}{dr} \quad \cdots\cdots (2)$$

Electrons are usually accelerated for a short time by induction until they reach an energy of 2 to 4 MeV at which their velocity is nearly equal to that of light. In the induction or betatron acceleration the following relation between the flux ϕ linking the orbit and the flux density B_{Z_0} at the orbit is required, that is

$$\frac{d\phi}{dt} = 2\pi r_0^2 \frac{dB_{Z_0}}{dt} \quad \cdots\cdots (3)$$

The magnetic force Fm, which is directed toward the center of the orbit, is expressed by

$$Fm = e\,B_Z\,v \quad \cdots\cdots (4)$$

and the centrifugal force F_C, which is directed radially outward, is given by

$$F_C = \frac{mv^2}{r} \quad \cdots\cdots (5)$$

at the equilibrium orbit r_0,

$$F_m = F_C \quad \cdots\cdots (6)$$

Due to the decreasing of the magnetic field with increasing radius, in the cases of both $r < r_0$ and of $r > r_0$, there will be a restoring forces to pull the deviated electrons into the equilibrium orbit.

Any motion under a restoring force which is proportional to the displacement is oscillatory in nature. The ordinary synchrotron has a limitation in n value given by $0 < n < 1$ and hence, has both radial and vertical oscillations called betatron or free oscillations due to the restoring forces. The frequency of these oscillations are given by

$$f_r = \sqrt{(1-n)}\,f_0 \quad \cdots\cdots (7)$$

$$f_Z = \sqrt{n}\,f_0 \quad \cdots\cdots (8)$$

where f_r is the frequency of the radial oscillation
f_Z is the frequency of the vertical oscillation
f_0 is the orbital frequency of the electron revolution

The phase relations between an electron and the electric field are illustrated in Fig. 3. In the figure, the normal phase of an electron crossing the gap supplied an electrical field is zero. If an electron crosses the gap at an earlier phase, such as t_1, it will gain energy and its orbital frequency will decrease due to the stronger centrifugal force acting on the electron and hence the larger orbital radius. This will lead the electron in delay slightly in subsequent cycles at the gap as illustrated in Fig. 3 by points t_2, t_3 and so on. The electron will continue this migration in phase until it crosses the gap at zero phase. If the situation is reversed and an electron loses its energy, the orbiatl frequency will increase and the electron will return to the zero phase again. As a result, the electron will be able to continue its stable revolution round a constant orbit.

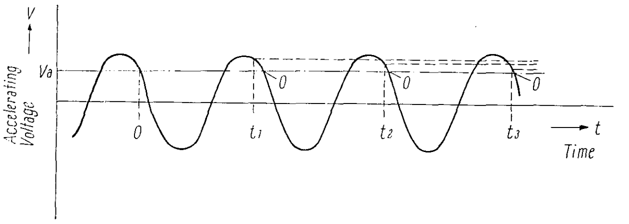

Fig. 3. Variation of accelerating potential with time

2. Alternating gradient type

A series of alternately converging and diverging magnetic field of equal strength, which are properly arranged around an orbit, can provide a strong restoring forces to an electron toward the orbit.

This strong restoring forces, as mentioned above, lead to free oscillations of much higher frequency and much smaller amplitude than those of the ordinary one.

The amplitudes of oscillations for a given momentum are also reduced. This fact allows to use much smaller size vacuum chamber and lighter or cheaper magnet for producing the guiding magnetic field.

The magnitude of the focusing forces is directly related to the value of n which can be made very large if necessary.

Let us assume that the circular orbit consists of N sectors of equal length with different values of field index n_1 (positive) and n_2 (negative) in alternate sectors. Then the equations of vertical and radial oscillations are,

$$\frac{d^2z}{d\theta^2} + n_1 Z = 0 \quad \cdots\cdots (9)$$

$$\frac{d^2r}{d\theta^2} + (1-n_1)\,r = 0 \quad \cdots\cdots (10)$$

$$\frac{d^2z}{d\theta^2} + n_2 Z = 0 \quad \cdots\cdots (11)$$

$$\frac{d^2r}{d\theta^2} + (1-n_2)\,r = 0 \quad \cdots\cdots (12)$$

where Z is the vertical displacement
r is the radial displacement

The solutions for the equations (11) and (12) will be given by,

$$Z = Ae^{i2\pi\mu_z} \quad \cdots\cdots (13)$$

$$R = Be^{i2\pi\mu_r} \quad \cdots\cdots (14)$$

where μ_Z is the vertical betatron phase shift over one unit
μ_r is the radial betatron phase shift over one unit

μ_Z and μ_r in the equations (13) and (14) are defined as follows,

$$\cos 2\pi\,\mu_Z = \cos\frac{2\pi\sqrt{n_1}}{N}\cos\frac{2\pi\sqrt{n_2}}{N} - \frac{n_1+n_2}{2\sqrt{n_1 n_2}}\sin\frac{2\pi\sqrt{n_1}}{N}\sin\frac{2\pi\sqrt{n_2}}{N} \quad (15)$$

$$\cos 2\pi\mu_r = \cos\frac{2\pi\sqrt{1-n_1}}{N}\cos\frac{2\pi\sqrt{1-n_2}}{N} - \frac{2-(n_1+n_2)}{2\sqrt{(1-n_1)(1-n_2)}}\sin\frac{2\pi\sqrt{1-n_1}}{N}\sin\frac{2\pi\sqrt{1-n_2}}{N} \quad (16)$$

where N is the number of focusing units around the orbit

If the motion has to be stable for both radial and vertical displacements, the limits are established by the conditions,

$$-1 < \cos 2\pi \mu_Z < 1 \quad \cdots\cdots(17)$$

$$-1 < \cos 2\pi \mu_r < 1 \quad \cdots\cdots(18)$$

These limits can be plotted as Fig. 4. The figure indicates that the range of stable values of n is widest when N is large and $n_1 = -n_2$

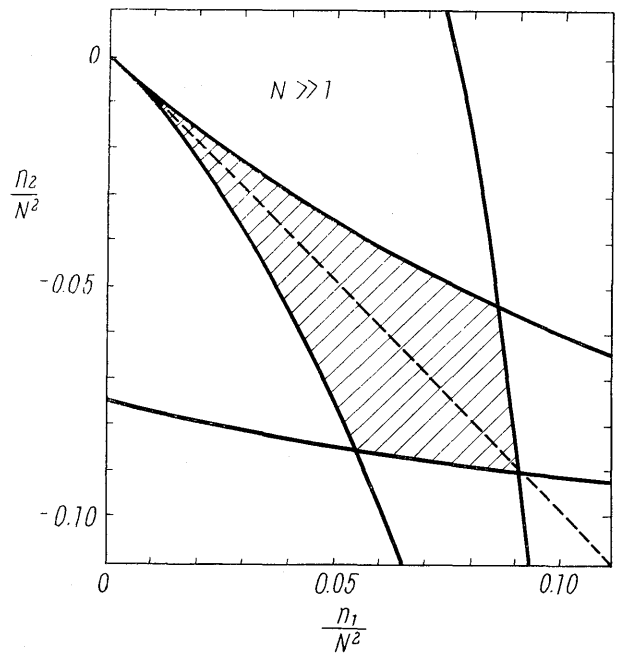

Fig. 4. Stability diagram for an ideal alternating gradient accelerator

The further detailed considerations, however, have modified the above conclusion and pointed out the problem of resonance build-up of oscillation amplitudes in the case of the frequency of betatron oscillations being an exact multiple of the frequency of the orbital revolution. In the alternating gradient synchrotron, the frequency of betatron oscillations can be written down as,

$$f_r = \frac{\mu_r N}{2} f_0 \quad \cdots\cdots(19)$$

$$f_Z = \frac{\mu_Z N}{2} f_0 \quad \cdots\cdots(20)$$

Therefore, for the large values of n and N, the frequency of betatron oscillations is high. These considerations have resulted reducing the values of n and N as well as increasing the accuracy required for the alignment of the magnet.

IV. PARAMETERS OF APPARATUS

The 1,000 MeV alternating gradient electron synchrotron, whose magnets have been manufactured by Fuji Denki, have an orbit of 400 cm radius and can be raised its magnetic field to 6,250 gauss at the orbit by the alternating current excitation and to 10,800 gauss by superposing the direct current excitation to the above a-c one. The excitation of 6,250 gauss and 10,800 gauss correspond to the final accelerating energy of 750 MeV and 1,300 MeV respectively.

The table 1 is a summary of the main parameters of this apparatus.

Table 1. A summary of the 1000 MeV alternating gradient synchrotron

Magnet:	
Max. kinetic energy	750MeV (without d-c bias) 1,300 MeV (with d-c bias)
Max. magnetic field	6,250 gauss (for 750 MeV) 10,800 gauss (for 1,300 MeV)
Orbit radius	400 cms
Number of unit magnets	8
Number of straight sections	8
Unit magnet length	310 cms
Straight section length	120 cms
Circumference of orbit	3,440 cms
Magnet gap at orbit	5.4 cms
Width of pole face	17 cms
Inner aperture of vacuum chamber	4×10 cm^2
n value	14
Phase shift per revolution	4.5π (both for radial and vertical oscillations)
Total iron weight	60 tons
Exciting coil:	
Number of turns	34
Electrical resistance (20°C)	0.0840 ohms
Inductance of a unit magnet	21.3 mH
Total copper weight	8.2 tons
Exciting power:	
A-c frequency	21.5 c/s
A-c voltage	3,450 volts
A-c power	235 kVA
D-c voltage	220 volts
D-c power	175 kW
Resonance condenser	5,200 μF, 3,450 volts 21.5 c/s
Injector:	
Type	Linear accelerator
Energy	6 MeV
Peak current	More than 50 mA
Pulse repetition rate	20 c/s
Magnetic field at injection	54 gauss
Frequency	2,800 Mc
Peak power	4 MW
Pulse length	2 μ sec
Radio frequency acceleration:	
Orbital frequency	8.7 Mc
Orbital period	0.11 μ sec
Harmonic order	16
Applied radio frequency	140 Mc
Max. R.F. acceleration	11 kV
Peak R.F. voltage	20 kV (for 750 MeV) 74 kV (for 1,300 MeV)

V. MAGNET FEATURES

1. General

During the design period, numbers of experiments required for the design of the magnet were conducted by Institute of Nuclear Study of Tokyo University using a d-c magnet of half scale, an a-c magnet of half scale and an a-c magnet of full scale. From these experiments, the proper profile of the pole face, the leakage factor of the magnetic field and the magnitudes of disturbances in the magnetic field due to the eddy current produced inside the adjacent metallic materials have been examined.

The arrangement of 8 unit magnets is illustrated in Fig. 5. The figure indicates that the orbit radius is 400 cms. According to the theoretical analysis, the accuracy required for the arrangement of these unit magnets is ± 0.2 mm for both radial and vertical directions.

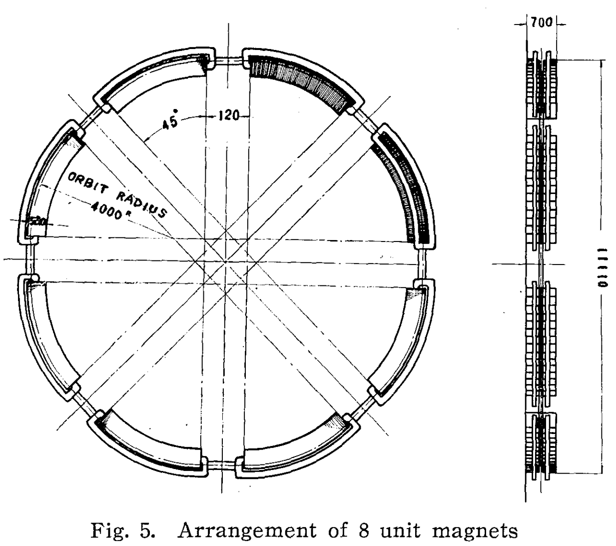

Fig. 5. Arrangement of 8 unit magnets

2. Design of magnet

A unit magnet, whose total length is about 310 cms, is divided into three sectors. That is a focusing sector of a quarter of the full length at one end, a defocusing sector of a half in the middle and a focusing sector of a quarter at another end. According to the theoretical analysis, this arrangement of magnet sectors gives the stability pattern as illustrated in Fig. 6. It indicates that the working point should be 14 in n value under the conditions of

$$4\pi < \mu_r < 5\pi,\ 4\pi < \mu_Z < 5\pi$$

or

$$\mu_r = \mu_Z = 4.5\pi$$

The amplitude of the betatron oscillation for the orbit radius 400 cms and for the magnetic field

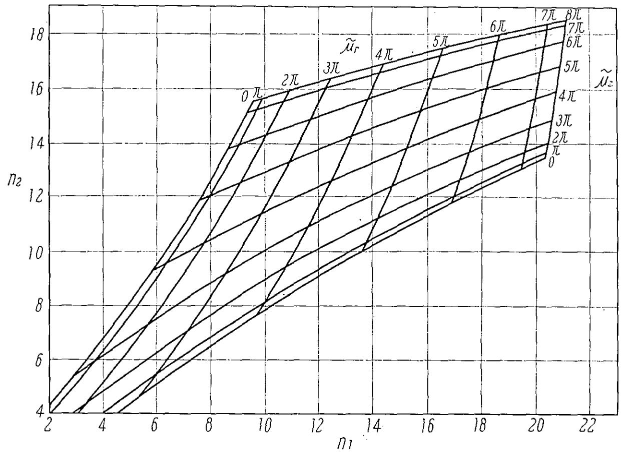

Fig. 6. Stability pattern (octant 8 cells)

deviation $\frac{\sqrt{\Delta B^2}}{B}$ along the orbit by 10^{-3}, will be given by

$$\frac{0.7}{\sqrt{1-\cos\mu_Z M}}\ \text{cms} \quad \cdots\cdots\cdots\cdots \quad (21)$$

in the vertical direction where M is the number of unit magnets, and

$$\frac{0.5}{\sqrt{1-\cos\mu_r M}}\ \text{cms} \quad \cdots\cdots\cdots\cdots \quad (22)$$

in the radial direction. The magnetic field deviation by 10^{-3} is equivalent to the displacement of pole pieces from the right position by 0.03 cm or 0.3 mm.

A unit magnet consists of 128 magnet blocks as illustrated in Fig. 7. Each block is made of silicon steel plates of 0.35 mm thickness whose iron loss is 0.9 W/kg, and is bonded with a adhesive epoxy resin " Araldite " keeping the final dimension within the required accuracy.

Besides the dimensional accuracy, the uniformity of the magnetic properties of the magnet block is

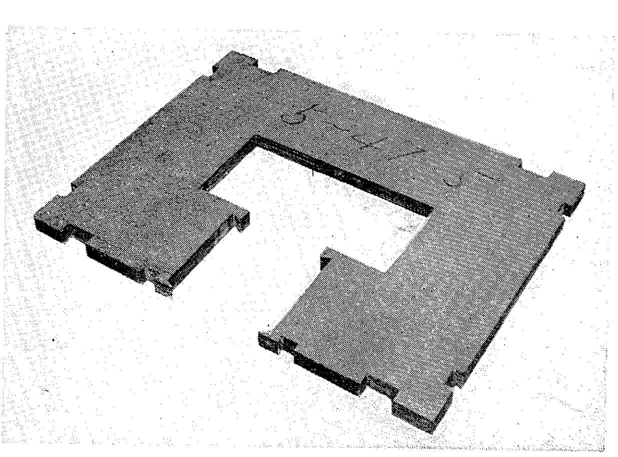

Fig. 7. Laminated magnet yoke block bonded with an epoxy resin " Araldite "

required. It is impossible to expect being supplied with the large amount of silicon plates which have uniform magnetic properties. In fact, the plates used for this apparatus had the non-uniformity of the magnetic coercive force as Fig. 8. The only solution for this problem is the proper mixing or shuffling of these plates at the stage of stacking for giving the satisfactory uniformity of the magnetic field.

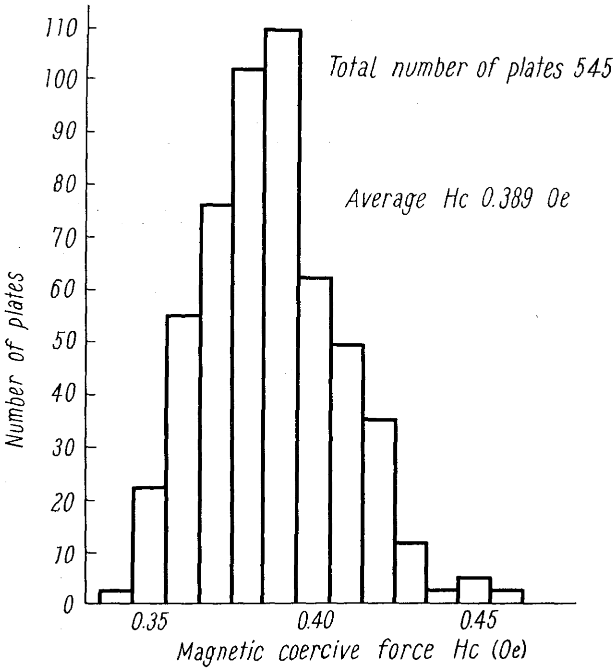

Fig. 8. Histogram of magnetic coercive force of silicon steel plates

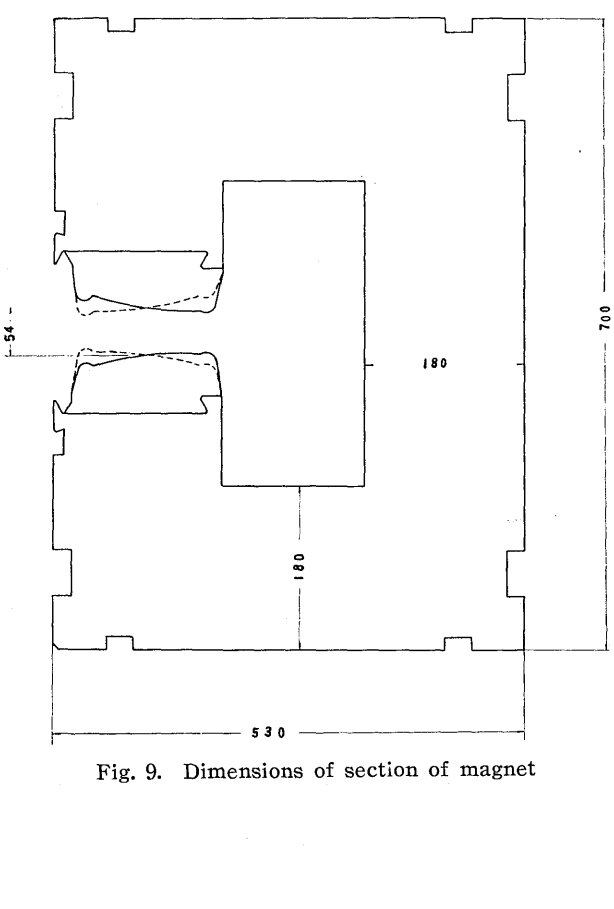

Fig. 9. Dimensions of section of magnet

Fig. 7 shows a yoke block of the unit magnet. For completion of a magnet block, another two blocks of pole pieces will be clamped to the yoke block with the aid of bolts and nuts. These clamping materials should be non-metallic because of avoiding disturbances to the magnetic field due to the eddy current produced inside clamps. We adopted phenol resin or Bakelite for them.

Fig. 9 shows the sectional dimensions of the yoke with two pole pieces.

The magnets are cooled by forced circulated air carring off the iron loss of 23 kW.

3. Results of magnet

For estimating accurately the inductance of the exciting coil of a unit magnet for the purpose of determining the capacity of the resonance condenser, it is essential to know exactly the value of the leakage factor of the magnetic field between the two pole pieces. Using the a-c magnet of half scale, the leakage factor defined by,

$$L.F.=\frac{\text{(Maximum flux passing through the yoke)}}{\text{(Flux density at orbit)}\times\text{(Width of pole piece)}} \quad \cdots\cdots (23)$$

were measured as shown in Table 2 where B_0 is the flux density at the orbit.

Table 2. Relationship between flux density at orbit and leakage factor

B_0 (gauss)	710	1420	2150	2860
L. F.	1.74	1.69	1.68	1.67

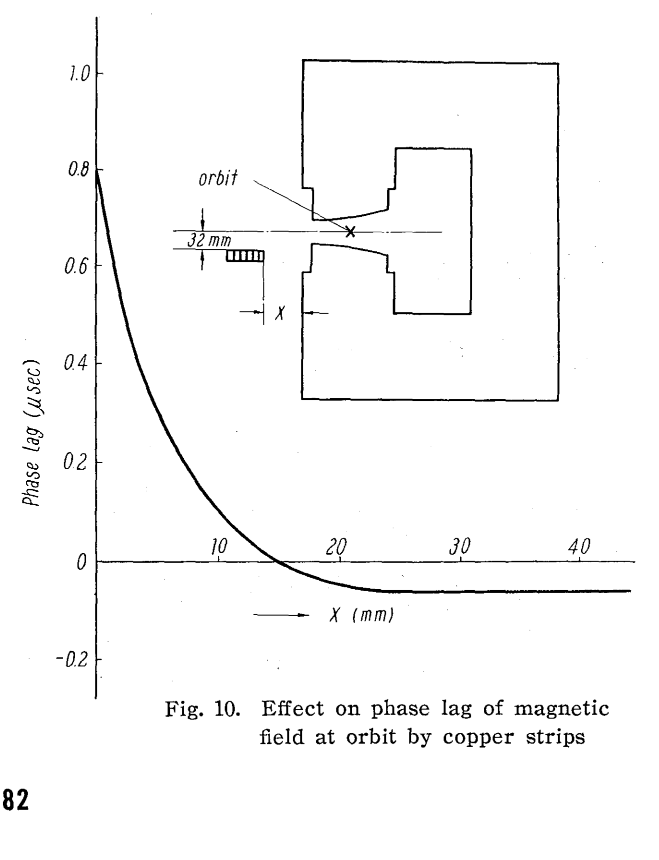

Fig. 10. Effect on phase lag of magnetic field at orbit by copper strips

Among the disturbances to the magnetic field at the orbit due to the eddy current produced inside the adjacent metallic materials, the one by copper conductors of the exciting coil is mostly effected. Due to the eddy current inside copper conductors, the phase of magnetic field at the orbit will be lagged. This was examined by the a-c magnet of half scale by arranging six copper strips (dimensions of a strip is $20 \times 10\ \mathrm{mm}^2$) apart x mm from the edge of the pole piece as illustrated in Fig. 10. The figure shows that there is no phase lag in the magnetic field due to the eddy current in copper strips if they were arranged apart farther than 15 cms from the edge of the pole piece.

Fig. 11 and 12 indicate examples of the bumps of the magnetic field of the full scale magnet in the both radial and azimuthal directions respectively.

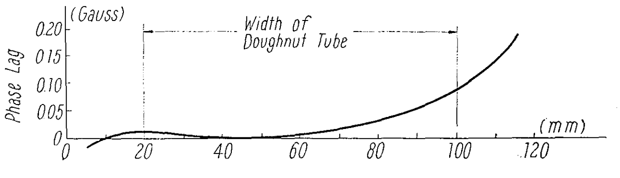

Fig. 11. Bumps of magnetic field in the gap

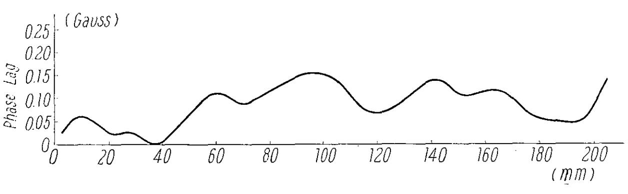

Fig. 12. Bumps of magnetic field at the orbit

4. Exciting coil

The copper conductor used for the exciting coil of the magnet has a rectangular shaped hole through which the cooling water flows. The sectional dimensions of this conductor is $25 \times 20\ \mathrm{mm}^2$ with a hole of $11 \times 6\ \mathrm{mm}^2$. Fig. 13 shows this conductors.

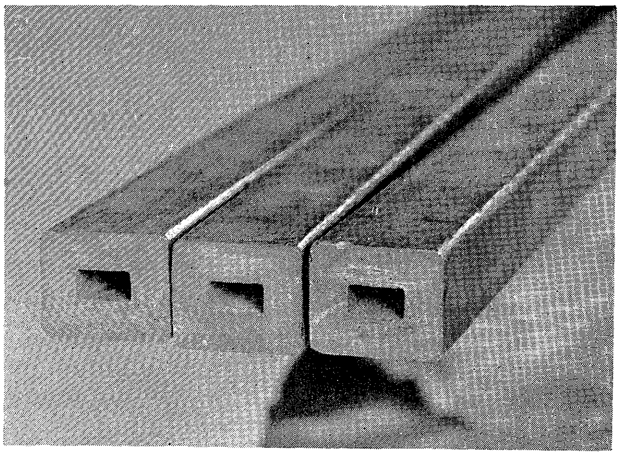

Fig. 13. Copper conductors used for exciting coils of unit magnet

The cooling water carries off copper loss of 19 kW generated in a unit magnet and keeps the temperature rise less than 10°C. The water is always maintained its electric resistance above $10^5\,\Omega$-cm by means of a ion exchanging device. Fig. 14 shows a exciting coil with cooling water inlet and outlet.

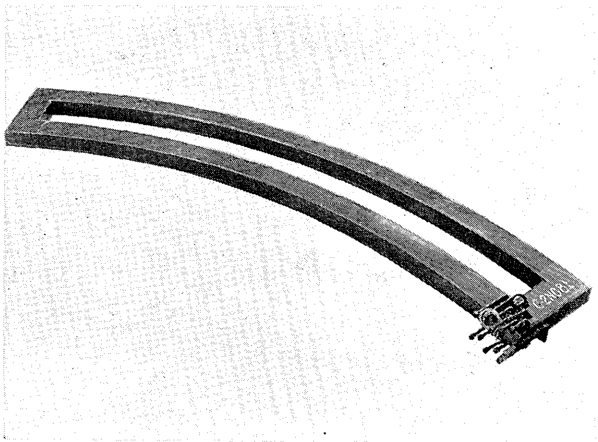

Fig. 14. Exciting coil of unit magnet

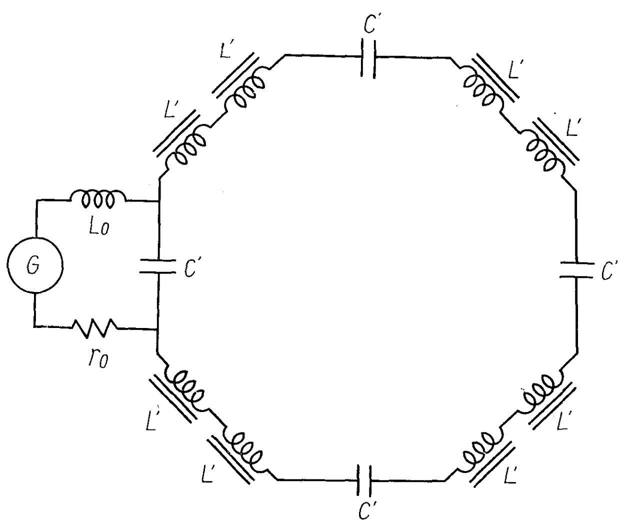

Fig. 15. Series resonance circuit without d-c bias

The exciting coils are connected with resonance condensers and form a closed circuit as shown in Fig. 15. In this figure, L' stands for the inductance of exciting coils of a unit magnet and C' is a resonance condenser which forms a series resonance with $2L'$ for a certain frequency. Each unit magnet has two exciting coils, one of them is shown in Fig. 14, and has a resonance voltage of 1,725 volts across the both coils so that each exciting coil has only about 863 volts between the both ends in the resonance condition.

The type of the resonance circuit, which we adopted, has advantages of keeping the corresponding points in the circuit in the equal phase and potential as well as of lowering the terminal voltage between the both ends of a exciting coil as mentioned above. This resonance circuit is the one which was proposed by the research group of Prinston accelerator for its 3 BeV proton synchrotron. We examined this type of resonance as well as its transient behaviours. Fig. 16 (a), (b) and (c) show transient behaviours in the cases a) of the breaking down of one of condensers C' in Fig. 15, b) of the sudden cutting off the electric supply and c) of the sudden insertion of the electric supply respectively. The index of 1, 2, 3 and 4 in the oscillographs stand for the voltage across the condenser C' which is coupled with an a-c generator G, the current through the generator G, the voltage across the exciting coils $2L'$ and the voltage across the coils $2L'$ and condenser C' respectively as shown in Fig. 15.

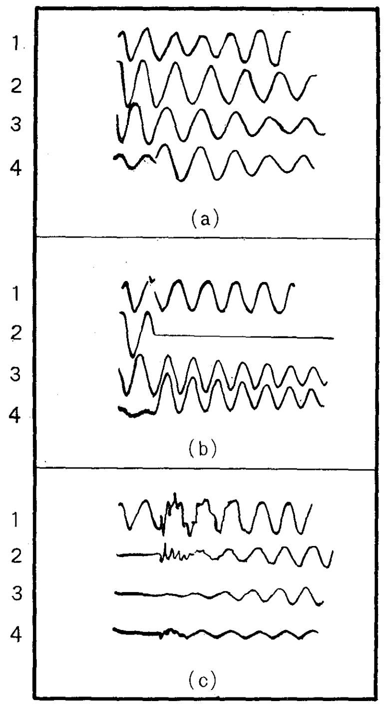

Fig. 16. Oscillographs of transient behaviours of series resonance circuit

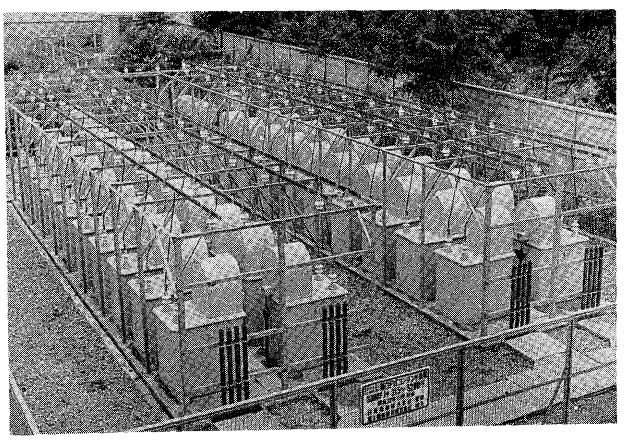

Fig. 17. Condensers for obtaining series resonance with magnet coils

Fig. 17 is showing resonance condensers which are installed outside the synchrotron building. The total capacity of these condensers is 5,200 μF, 3,450 volts and 21.5 c/s, as described previously.

VI. MAGNET CONSTRUCTION

Each unit magnet is bolted to a rigid iron bed which is sitting on the concrete foundation. This foundation is common to 8 unit magnets beds and is separated from the foundation of the building. Fig. 18 is the sectional view of a unit magnet showing the yoke and pole pieces with two exciting coils. The hatched part between the magnet and the concrete foundation, is the iron bed machined accurately. And the bonded magnet yoke blocks

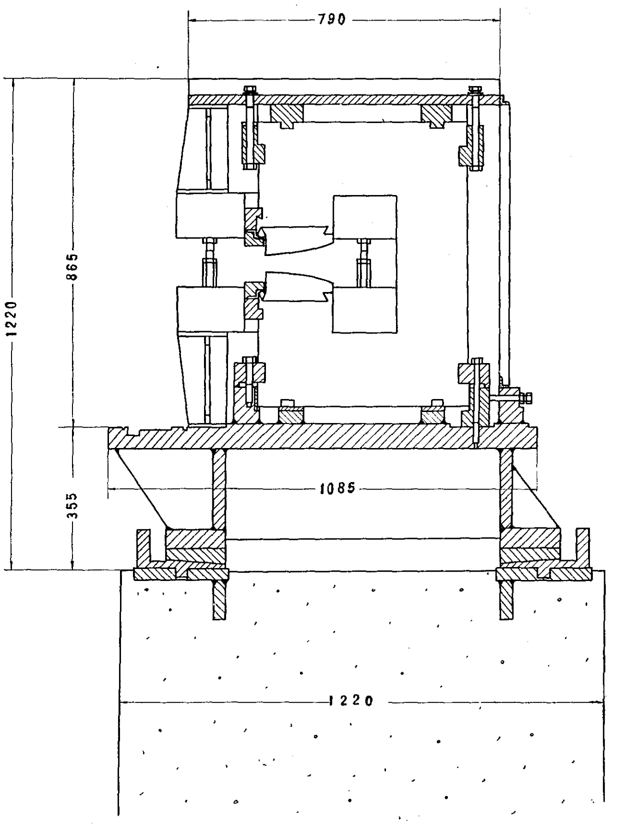

Fig. 18. Sectional view of magnet

have to achieve their dimensional accuracy required for alignment only by stacking on the bed side by side.

Beside machining each bed accurately, it is also important to keep the relative positions of 8 individual beds in their right positions both radially and vertically within the allowance ±0.2 mm.

Using special measuring devices such as a long range micrometer and an optical instrument named "Alignment Telescope" as well as specially designed levelling devices attached to each bed at the bottom, we achieved the final installation of these 8 beds within the range ±0.05 mm to the design value for the both radial and vertical directions.

Fig. 19 shows a scene of examining the right positions of these 8 beds by means of the above mentioned optical instrument. In Fig. 19, we can see a centering device for 8 beds at the center of the building. This device is most important, because it determines the positioning accuracy of 8 beds on which the magnet blocks are installed. Therefore, we adopted a deeply examined and specially desined device for it.

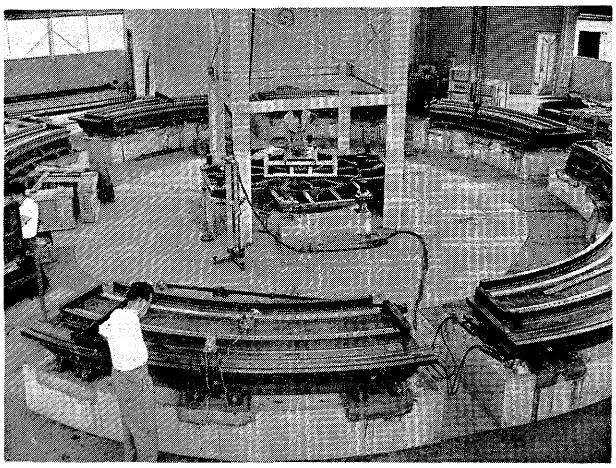

Fig. 19. Scene of examining right positions of 8 unit magnets beds

VII. CONCLUSION

As the alternating gradient synchrotron is the newly appeared accelerator and has been built only one in Cornell University, U.S.A. up to now, there were many technically unknown problems or difficulties in both design side and manufacturing side of the 1,000 MeV alternating gradient synchrotron. We overcame those matters step by step by conducting proper experiments and necessary examinings in cooperation with Institute of Nuclear Study of Tokyo University. Particularly, the complicated and advanced technologies were required for bonding hundreds of silicon steel plates of this size into one block accurately.

We have also conducted our own study on the control problem of the electric supply to the resonance circuit. Finally we achieved the automatic adjusting system of the both frequency and voltage of the electric supply to the exciting coils within the fluctuation $\pm 0.1\%$ to a fixed value.

Since this apparatus is the largest one in Japan as well as one of a few higher energy accelerators in the world, it is expected to make the another great strides and to obtain the fruitful results in the field of experimental nuclear physics in the near future.

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