reduction in aperture, and the final high field aperture can be quite small.

The non-linearity in the running quadrupole field is adjusted to be the same as in standard AG machines by the design of the surface windings, and the non-linearity in the d.c. guide field is also corrected by a small running correction similar to the scanning field.

The change of the orbit with time is approximately the same in SFAG and FFAG, but the instantaneous ion optical behavior is similar to that of the standard AG machines, and any of the operation points in the necktie diagram can be chosen.

By splitting the RF modulation range into two sets of drift tubes, or cavities, adequate recycling time can be left to permit more than a 100% duty cycle of acceleration. The radial velocity of the scanning field, which determines the required RF accelerating voltage, can be adjusted to minimize RF problems, and also to permit the output beam to last over a considerable portion of each cycle. It is believed that

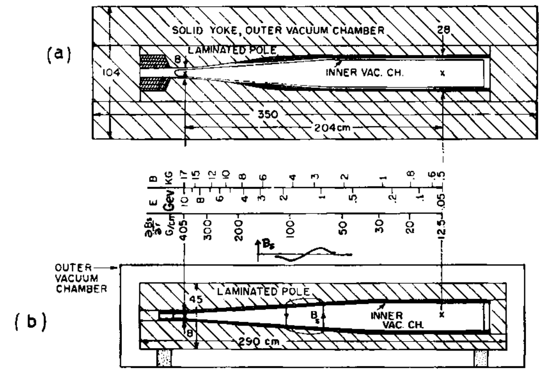

Fig. 4 Magnets in a 10 GeV separate type SFAG.
a) d.c. magnet;
b) scanning magnet.

there should be no practical difficulties in achieving scanning fields with a repetition rate up to several tens of cps, and, altogether, very high average beam intensities should be achievable with a SFAG.

To illustrate the possibilities of SFAG, the parameters for a 10 GeV separate type SFAG protron synchrotron are presented in Table I.

A 450 keV EIGHT-SECTOR FIXED-FREQUENCY ELECTRON CYCLOTRON

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Soon after the invention of the cyclotron by E. O. Lawrence in 1930, it was realized that for axially symmetric magnetic fields, axial focusing and isochronous orbits are basically incompatible. Constant frequency machines using classical (conventional) cyclotron principles are limited to rather low energies, typically about 25 MeV for protons, at reasonable energy gain per turn. Efforts to go to higher energies have generally centered about the use of the principle of frequency-modulation. Machines of this type have been built in which accelerated protons approach the 1 GeV energy range, but they are limited to a pulsed beam averaging at most a fraction of a microampere.

The present day requirements for higher intensities at high energy have resulted in a renewed interest in a type of machine originally suggested in 1938

(*) Operated for USAEC by Union Carbide Corporation.

by L. H. Thomas [1] in which axial focusing and isochronism are made compatible by incorporating carefully controlled azimuthal variations in the magnetic field. The original analysis by Thomas was extended by Judd [2], and in the period 1950-1956 two three-sector electron models using azimuthally-varying-field (AVF) principles were built and successfully operated at the Lawrence Radiation Laboratory [3]. During 1951-1952 studies were made for the conversion of the presently operating ORNL 86 inch cyclotron (22 MeV protons) to a three-sector machine, but for reasons of convenience this was never completed. The suggestion by Symon, Kerst, Jones, Laslett, and Terwilliger [4] in 1956 that added focusing may be achieved by spiraling the magnetic field has made the AVF-type machine more attractive at high energies.

Sector-focused machines now in operation include a four-sector straight-pole machine at Delft [5] (12 MeV protons) and a six-sector spiral-pole machine at Dubna [6] (12 MeV deuterons). At Los Alamos Scientific Laboratory three-sector Thomas shims have been used for some time to improve the axial focusing in an otherwise conventional cyclotron. A four-sector spiral-pole cyclotron (14 MeV protons) at the University of Illinois is in the testing stage. Other four-sector cyclotrons are nearly complete at UCLA (50 MeV protons) and at the University of Colorado (30 MeV protons). A flexible three-sector variable-energy machine is under construction at Oak Ridge National Laboratory. This cyclotron will accelerate a variety of particles; typical maximum energies are: protons, 75 MeV; deuterons, 40 MeV; and heavy particles, 100 MeV. A three-sector cyclotron at LRL (60 MeV deuterons) is also under construction. All of the above machines, except the one at Dubna, were described at the Conference on Sector-Focused Cyclotrons at Sea Island, Georgia [7]. Several other machines, also described at the Conference, are in various stages of study, design, or construction.

Since 1954 a program has been in progress at Oak Ridge National Laboratory to develop fixed-frequency AVF cyclotrons, both as medium-energy (< 100 MeV) and as high-energy machines, > 500 MeV. Central to the ORNL approach has been a departure from dependence on analytical theory for the determination of the dynamic properties of a given field configuration. Computer programs developed by M. M. Gordon and T. A. Welton [8] have enabled rapid determination of the dynamic properties in magnetic fields measured or calculated in polar coordinate mesh. Analytical methods are used primarily to design the original field and subsequently to gauge corrections to the field to achieve the required dynamic properties such as axial focusing frequency, radial focusing frequency, and orbit time. The recent improvements in the analytical theory by Parzen at MURA [9], Smith and Garren at LRL [10], and Bassel at ORNL [7] have been of considerable value in the design of machines of low sector number and in the understanding of second order effects.

To gain some understanding of the problems involved in going to kinetic energies approaching the rest energy of the particle, and also to verify the accuracy of the computational methods, a four-sector electron model was built at ORNL in 1957 [11]. This was a radial-sector machine which accelerated electrons to 190 keV. It was designed entirely by means of Welton's computer programs augmented by other computer programs to determine the magnetic field of the air-cored coils which produce the magnetic field. Measurements of the axial-focusing frequency, radial-focusing frequency, and location of radial resonances, and axial-radial coupling resonances completely verified the machine calculations. Also, the isochronism condition was so well satisfied that the threshold energy gain per turn to accelerate electrons to full energy was only 90 eV indicating that over 2000 turns were being achieved.

The subject of the present discussion is the new electron analogue now being built at Oak Ridge National Laboratory to model a proposed 850 MeV proton accelerator.

The analogue is being built primarily to study the problem arising in the extraction of a high-quality beam from such a machine using the properties of the 8/4 resonance [12,13]. It will also be used to investigate any new or unforeseen problems in the design of the full-scale machine.

The device will have an eight-sector spiraled magnetic field. The spiral of the magnetic field is $\theta = r^2$ with r expressed in units of c/ω. The properties of the machine are summarized in Table I.

TABLE I

Cyclotron analogue II — Design specifications

Cyclotron unit (c/ω)	16.000 in.
Central field (B_0)	41.926 G
Orbit frequency	117.399 Mc/sec
Axial focusing frequency, ν_z	0.2
Energy for $\nu_r = 8/4$	470 keV
Maximum energy	510 keV

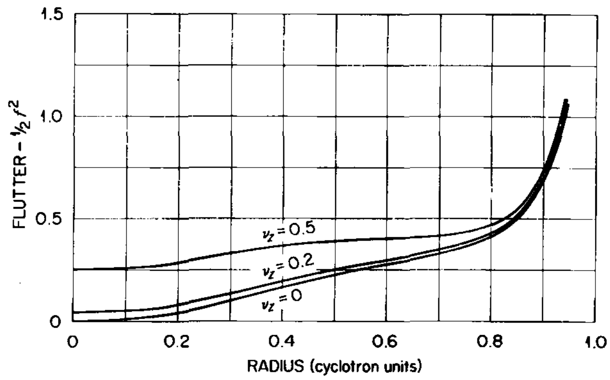

Fig. 2 Required azimuthal variation for $\nu_z = 0$, 0.2, 0.5 for a $\theta = r^2$ spiral.

MAGNETIC FIELD DESIGN

As in the four-sector model, the magnetic field for the eight-sector model is produced entirely by air-cored coils. This has the distinct advantage in that with high-speed computers the magnetic field of a configuration can be determined to any desired accuracy; secondly, at the low magnetic fields used, the magnetic properties of iron are entirely too variable, and in a given piece, too inhomogeneous, to permit achieving the desired accuracy of $\sim 1/10^4$ by construction accuracy alone. Thus, the use of air-cored coils permits not only an exact calculation of the magnetic field, but it also eliminates a considerable amount of experimental trimming which would otherwise be necessary.

The system used in the eight-sector analogue, to achieve the desired azimuthal variation of the magnetic field as a function of radius, is to vary the angular width of the sector coils, see Fig. 1. Figure 2 shows the required azimuthal variation for a field with $\theta = r^2$ spiral $(2\tan^2\gamma = 8r^4)$. The ordinate is $f^2/2 = 1/2 \sum_n (a_n{}^2 + b_n{}^2)$, commonly referred to as " flutter. " Although the spiral is moderate, the reduction of required flutter is substantial. At the deflection radius, for example, $8r^4$ is approximately 4. With the system of flaring the coil angularly as a function of radius, only a few turns are used and hence, high currents are required. In the present design, Fig. 3, with three-turn coils located 2.7 cm above and below the median plane, about 530 A is required. The coils consist of a series of tangent circular arcs, the magnetic fields of which are machine computed.

Obtaining the desired focusing with this geometry is somewhat more difficult than it would first appear.

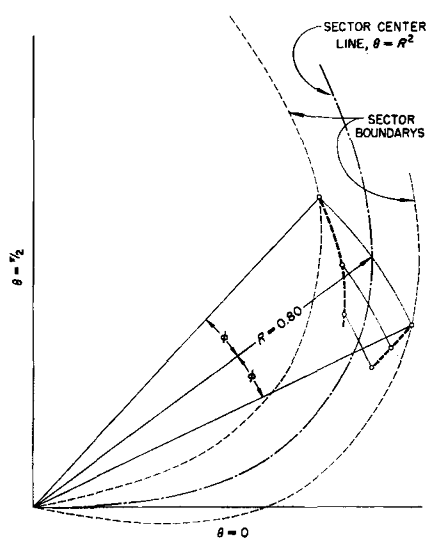

Fig. 1 Method of flaring coils to adjust flutter.

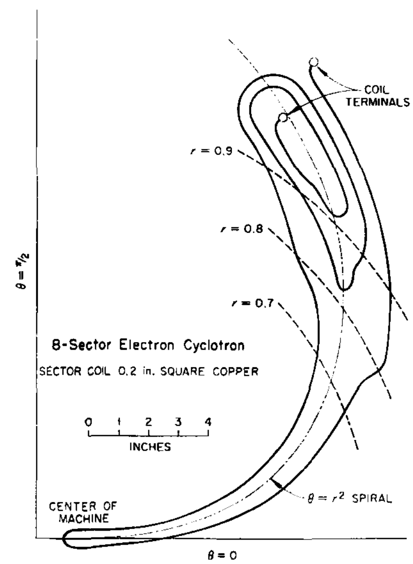

Fig. 3 Configuration of three-turn sector coil.

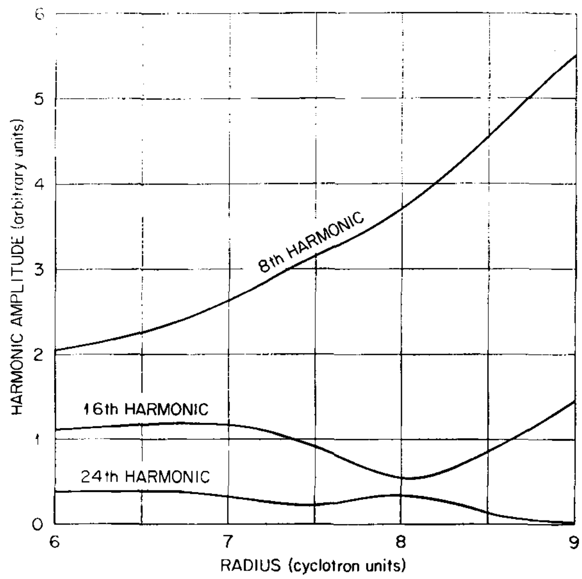

Fig. 4 Amplitude of harmonics in 8-sector magnetic field.

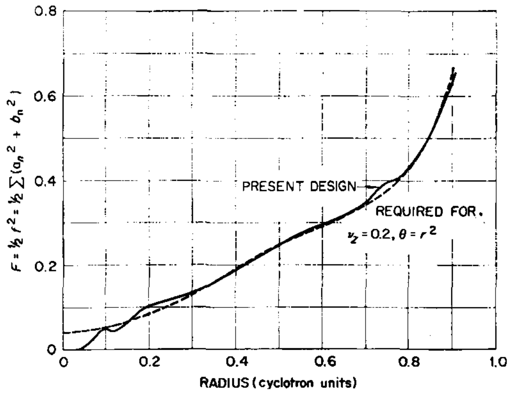

Fig. 6 Flutter of 8-sector field.

First, the harmonic content of the field varies considerably as a function of radius; second, even though the coil is symmetrical about the desired spiral angle, the harmonics do not exactly follow this function, and, moreover, the angles of the various harmonics differ. What is done to achieve proper focusing is to adjust the coil angularly, point by point, about the desired spiral to minimize the deviations of the first harmonic. The focusing perturbations caused by the deviations in spiral of the second and higher harmonics is taken care of by varying the flutter. This is best typified by Figs. 4 and 5, which show the amplitude and angular dependence of the 8th, 16th, and 24 th harmonics after successive corrections of the 8th harmonic angle, and in Fig. 6 by the flutter of the same field which does in fact produce good focusing. The irregularity in the flutter in the region $r = 0.70 \rightarrow r = 0.85$ is required by deviations of the 8th and 16th harmonic spiral angles.

The equilibrium orbit properties of the magnetic field just described are shown in Fig. 7. Isochronism and good axial focusing are maintained to well beyond $r = 0.84$ ($\nu_r = 8/4$), the intended deflection radius. It may be necessary to make some changes in just that region to enhance deflection.

The central magnetic field configuration deserves mention. At the center of the machine the azimuthal variation is, of course, zero and increases radially at a rate depending upon the magnet gap and pole number. To obtain better focusing near the center, the tips of the coils are arranged so that at small radii the geometry is predominantly four-sector, and a rather abrupt transition is made to eight-sector as soon as adequate axial focusing is obtained.

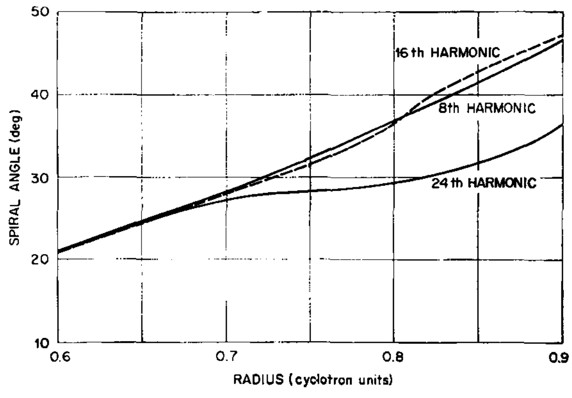

Fig. 5 Angular variation of harmonics in 8-sector magnetic field.

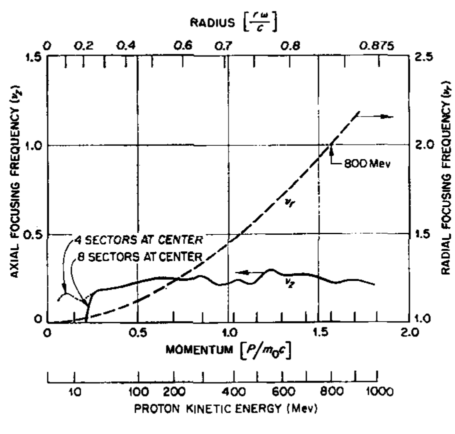

Fig. 7 Equilibrium orbit properties.

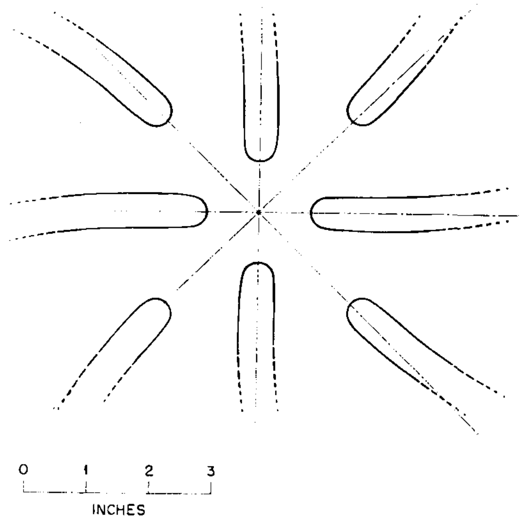

Fig. 8 Transition from four to eight sectors in central region.

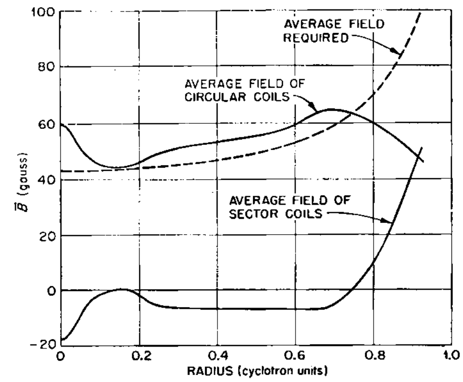

Fig. 10 Average field requirements.

This is shown in Figs. 8 and 9 which show the coil geometry at the center, and the harmonic content of the fields thus produced. The question of the orbit stability in the transition region has been examined with Gordon's non-equilibrium orbit computer program; the orbit stability appears to be excellent.

AVERAGE FIELD

The sector coils previously discussed provided only a small fraction of the required average field, see Fig. 10. The difference between the average field produced by the sector windings and the isochronous average field must be provided by circular windings. By judicious choice of coil location, the average field is fitted to within 1 %, except near the center, by four windings located about 6.5 cm from the median plane. Final fitting is provided by 36 uniformly spaced windings located 2.1 cm from the median plane. The degree of fit obtained is about 5 parts in 10^5 throughout most of the machine. The location of the various coils within the machine is shown in Fig. 11.

FABRICATION SYSTEMS

In the design of magnetic systems, it has been the intent to achieve the desired field accuracy of 1 part in 10^4 by construction accuracy wherever possible. This is to minimize, or perhaps eliminate, the field trimming required after construction of the machine. No suitable means has been devised to wind satisfactory sector coils with many turns of relatively small gauge wire to achieve the required number of ampere turns. The system finally devised makes maximum use of the most modern automatic machining techniques and also of newly developed

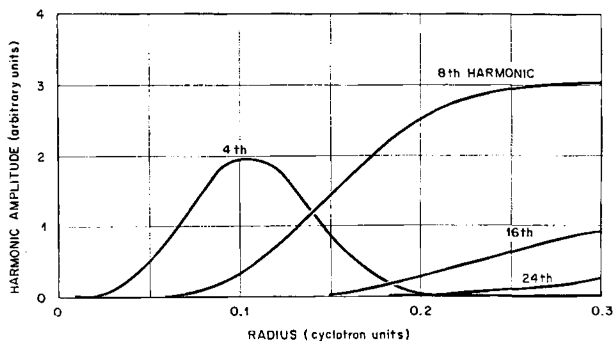

Fig. 9 Magnetic field harmonics in the central region.

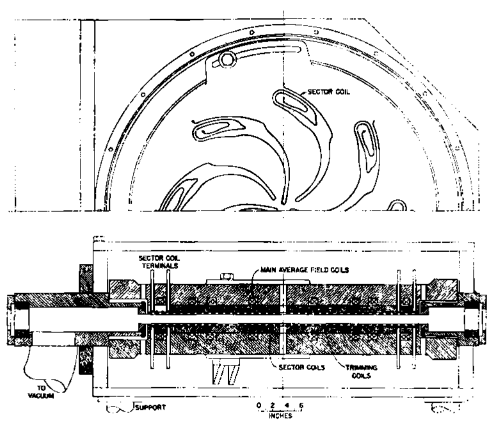

Fig. 11 Cross-section of machine showing location of coils.

resin adhesives. The choice of fabrication methods has generally been dictated by the desire to achieve a constructional accuracy of ± 0.001 in. wherever feasible.

The sector-coil assembly drawing, Fig. 12, illustrates the fabrication method. Water passages exactly the shape of the conductor are machined in an aluminium plate approximately 5/8 in. thick. The plate is then resin-bonded to a plate of identical shape, but without grooves; this provides water passages of the required shape. After the assembly is machined to the required flatness. A groove to match exactly the required conductor shape is machined in the reverse side of the first plate. The grooved aluminum plate is then anodized to a thickness of 0.0002 in. to provide electrical insulation. A copper plate, machined to produce ridges the exact shape of the conductor, is bonded into the matching grooves in the aluminum. After curing, the back of the copper is machined away, leaving the required depth of conductor accurately located and bonded in the aluminum plate.

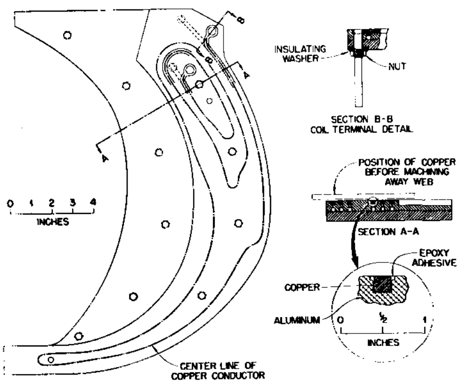

Fig. 12 Sector-coil assembly.

Tests of this system have shown that, with ordinary water pressures of ~ 80 psi, a temperature rise of only 5° C will be experienced at 550 A current. Fig. 13 is a photograph of a test section

MECHANICAL ARRANGEMENT AND VACUUM SYSTEM

The main coil support system consists of two large aluminium disks to locate accurately the various coils in precise parallel planes, Fig. 11. The main average-field coils are located in grooves in the disks. The average-field trimming coils are to be supported against the surface of the sector coils.

The whole magnet system is mounted within the vacuum chamber to simplify the support of atmospheric pressure loads. A double vacuum system is used to avoid difficulty from any out-gassing of the various bonding agents. The beam space is maintained at a pressure of 10^{-6} mm Hg while the regions containing the coils are maintained at a pressure of about 10^{-2} mm Hg. The two regions are separated by thin aluminum plates located against the average field trimming coils. A 4 in. mercury diffusion pump is used for the high vacuum system.

RADIO-FREQUENCY SYSTEM

The accelerating system is designed to ensure the efficient extraction of a high quality beam. A single-dee resonant system, similar to that used in the four-sector electron cyclotron [11], is driven by a regulated master-oscillator power-amplifier system which includes the dee as part of the regulating loop. The voltage on the dee will be regulated to about 0.05%. The addition of a third harmonic to approximate a square wave form is planned.

LIST OF REFERENCES

1. Thomas, L. H. The paths of ions in the cyclotron. Phys. Rev., *54*, p. 580-98, 1938.
2. Judd, D. L. Theoretical study of relativistic constant frequency cyclotrons. Phys. Rev., *100*, p. 1804, 1955.
3. Kelly, E. L., Pyle, R. V. and Thornton, R. L. Two electron models of a constant-frequency relativistic cyclotron. Rev. sci. Instrum., *27*, p. 493-503, 1956.
4. Symon, K. R., Kerst, D. W., Jones, L. W., Laslett, L. J. and Terwilliger, K. M. Fixed-field alternating-gradient particle accelerators. Phys. Rev., *103*, p. 1837-59, 1956.
5. Heyn, F. A. and Tat, K. K. Operation of a radial sector fixed-frequency proton cyclotron. Rev. sci. Instrum., *29*, p. 662, 1958.
6. Vasilevskaya, D. P., Glazov, A. A., Danilov, V. I., Denisov, Yu. N., Dzhelepov, V. P., Dmitrievskij, V. P., Zamolodchikov, B. I., Zaplatin, N. L., Kol'ga, V. V., Kropin, A. A., Lyu Ne-chuan, Rybalko, V. S., Sabenkov, A. L. and Sarkisyan, L. A. Zapusk tsiklotrona s prostranstvennoj variatsiej napryazhennosti magnitnogo polya. (Start-up of a cyclotron with a spatially varying magnetic field.) Atomnaya Energiya, *6*, p. 657-8, 1959. (in Russian.)

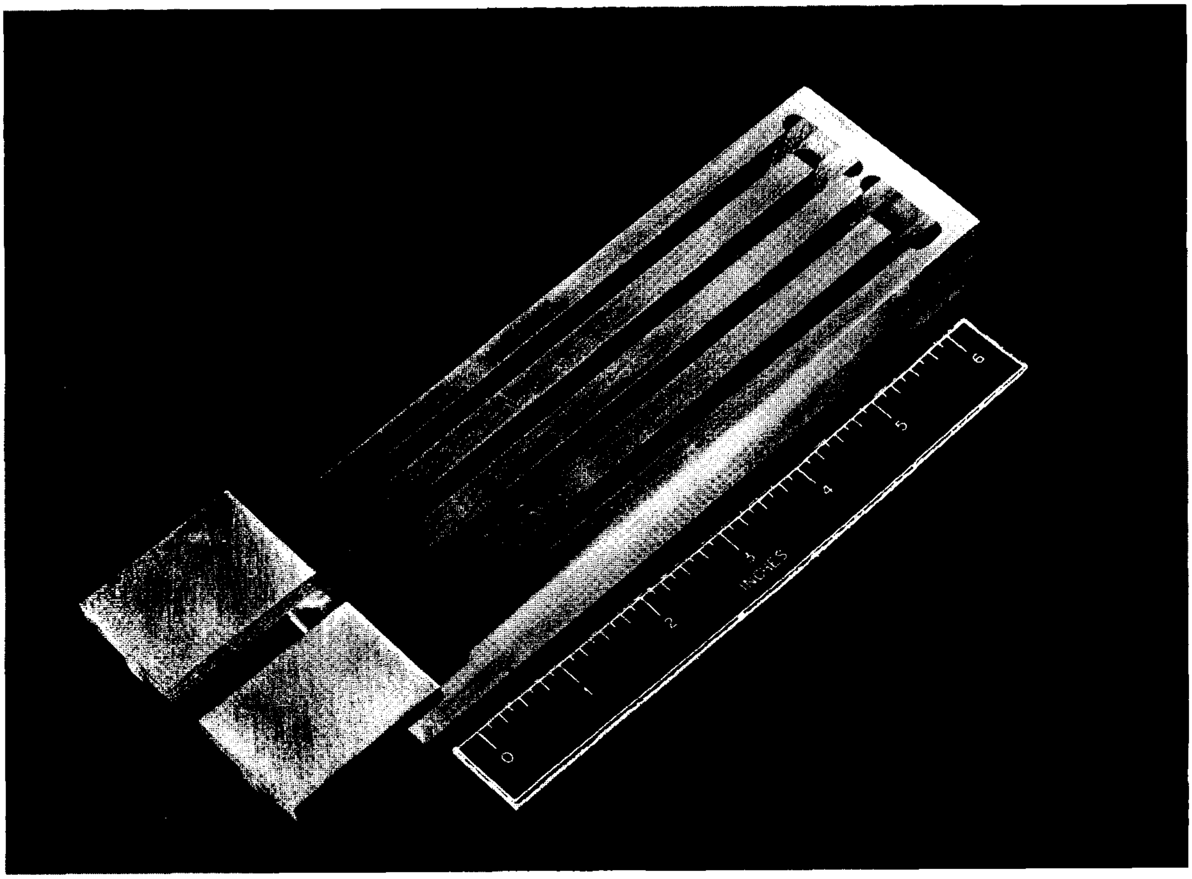

Fig. 13 Sector-coil test specimen.

7. Conference on sector-focused cyclotrons. Proceedings. *ed.* F. T. Howard. Sea Island, Georgia, February 2-4, 1959. Nuclear Science Series Report Number 26; and National Academy of Sciences. National Research Council Publication 656. (in press).
8. Gordon, M. M. and Welton, T. A. Computational methods for AVF cyclotron design studies. ORNL (*) 2765, 1959.
9. Parzen, G. Theory of accelerators with a general magnetic field. MURA (*) 397, April 16, 1958.
10. Smith, L. and Garren, A. A. Orbit dynamics in the spiral ridged cyclotron. UCRL (*) 8598, January 12, 1959.
11. Blosser, H. G., Worsham, R. E., Goodman, C. D., Livingston, R. S., Mann, J. E., Moseley, H. M., Trammel, G. T. and Welton, T. A. Four-sector azimuthally varying field cyclotron. Rev. sci. Instrum., *29*, p. 819-34, 1958.
12. Gordon, M. M. and Welton, T. A. The 8/4 resonance and beam extraction from the AVF cyclotron. Bull. Amer. Phys. Soc., *3*, p. 57, 1958.
13. Gordon, M. M. In : Conference on sector-focused cyclotrons. Proceedings. *ed.* F. T. Howard. Sea Island. Georgia, February 2-4, 1959. Nuclear Science Series Report Number 26; and National Academy of Sciences. National Research Council Publication 656. (in press).

DISCUSSION

O'NEILL : Have you had any trouble maintaining these fairly tight tolerances off the median plane of the machine?

MARTIN : Maintaining the median plane (spacing) tolerances is the most difficult part of constructing the machine. Much of that work will be done by hand fitting. We hope to get the field accurate enough to get a beam through the machine even if at somewhat higher accelerating voltage then the lowest we plan to use. Then, by measuring the phase of the electron we will be able to make appropriate changes in the trimming coil currents to achieve the desired degree of isochronism. The tolerance requirements are considerably less stringent with respect to the azimuthal variations in the magnetic field.

CYCLOTRON WITH SPACE VARIATION OF THE MAGNETIC FIELD (**)

V. I. Danilov, Yu. N. Denisov, V. P. Dmitrievskij, V. P. Dzhelepov, A. A. Glazov, V. V. Kol'ga, A. A. Kropin, Lu Ne-chuan, V. S. Rybalko, L. A. Sarkisyan, A. L. Savenkov, B. I. Zamolodchikov, N. L. Zaplatin and D. P. Vasilevskaya

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(presented by V. P. Dmitrievskij)

I. INTRODUCTION

The first ideas of the application, in circular accelerators, of the magnetic field space variation date back to 1938 when L. Thomas suggested a variation of the field with azimuth in a cyclotron [1]. At that time these ideas were not properly developed due to the fact that the restriction on energy for a cyclotron was caused by the ion phase motion, and this restriction was removed by the suggested method only in a narrow energy region of accelerated ions. No less an essential obstacle to the development of this problem was the relatively low level of both measuring and calculating techniques. The principle of phase-stable acceleration suggested in 1944-1945 by V. I. Veksler [2] and McMillan [3] made it possible to

(*) See note on reports, p. 696.

(**) Mention of the starting up of this accelerator has been made by Vasilevskaya et al. See the reference [6] to their paper on p. 210.