Title
PRELIMINARY ENGINEERING MEMORANDUM ON THE THIRTY-SIX INCH ELECTRON CYCLOTRON

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Preliminary Engineering Memorandum

on the

Thirty-six Inch Electron Cyclotron

M. E. Chun

October 4, 1950

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Preliminary Engineering Memorandum on the Thirty-six Inch Electron Cyclotron

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October 4, 1950

Introduction - This report partially covers the engineering phase of work involved to date with the 36-inch Electron Cyclotron, UCRL code name IRT, Job Order number 212-11.

In order to better understand the problems of design a brief resumé of historical and theoretical background is given for convenient reference.

The purpose of construction of this device is to make a practical application of a theory first published by L. H. Thomas in a paper entitled "The Paths of Ions in the Cyclotron"[1] and amplified by L. I. Schiff in an article entitled "On the Paths of Ions in the Cyclotron."[2] Later, E. M. McMillan reinvestigated the properties of a field in which the magnetic field H is a step-function of θ, related to the above theory, and more recently D. L. Judd has investigated other aspects of the theory and rechecked it.

First, let us consider certain features of the "standard," non-FM cyclotron. We may illustrate the magnetic field and behavior of the particle in the manner shown in Fig. 1.

The Thomas theory shows a means of avoiding the conflict at larger radii (high energy) between relativistic correction (requiring the field to increase with radius) and axial stability (requiring the field to decrease with radius).

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1. Phys. Rev. 54, 580 (1938)
2. Phys. Rev. 54, 1114 (1938)

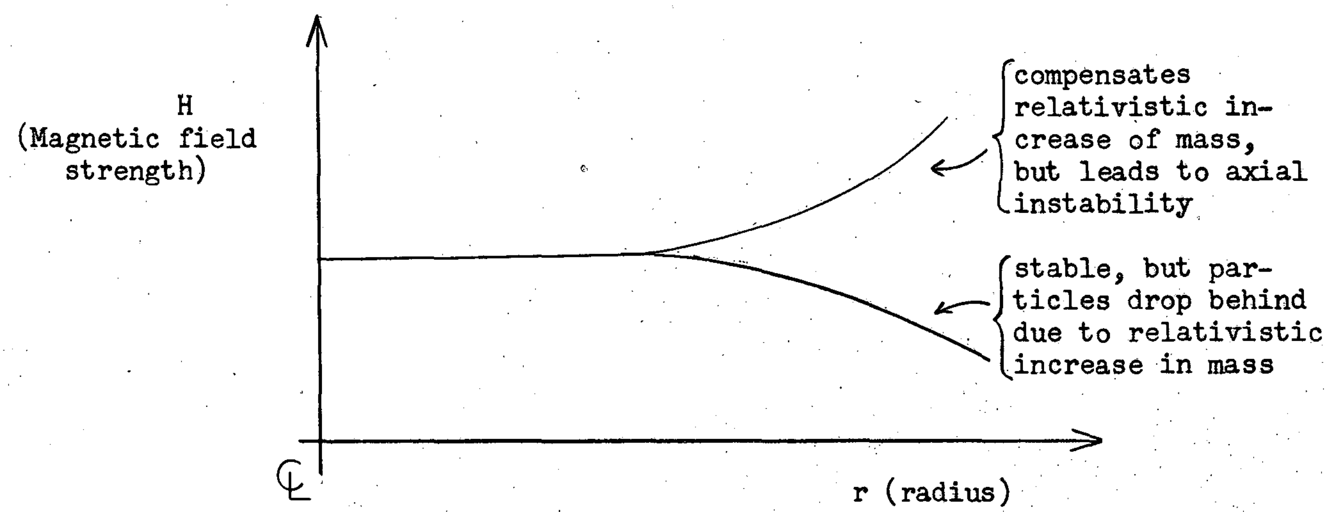


Fig. 1

Magnetic Field - The magnetic field prescribed by Thomas in the plane Z = 0 is given in cylindrical polar coordinates by

$$H_z = \frac{m_o c\omega}{e}\left[1 + A\left(\frac{r\omega}{c}\right)\cos m\Theta + B\left(\frac{r\omega}{c}\right)^2\right]$$

where m_o = rest mass of particle

e = charge (e.s.u.)

c = velocity of light

$\omega = 2\pi f$

f = frequency

r = radius

H = magnetic field

A, B = constants

m = number of magnetic field maxima (m = 3 for 120° segments, the design chosen)

For resonance, with m = 3,

$$B = 1/2 - 1/8\ A^2$$

Thus, we may describe the magnetic field as:

(1) A uniform field,

plus (2) A sinusoidally varying field (amplitude of sine wave αr),

plus (3) A radially increasing component (increasing αr^2).

For axial stability, the constant A must be greater than a certain value A_o. Also, A can be selected so that orbits are radially stable. For the design chosen,

$$A = 1.35 \qquad B = 0.272$$

The A and B terms in the magnetic field formula of Thomas' cyclotron are together responsible for achieving both stability and relativistic correction.

Thomas' theory is developed in power series expansions, in powers of (V/c), and is carried out through 2nd order terms. Judd has investigated magnitude of 3rd order terms and finds that 2nd order theory can be used up to $(V/c) \simeq 1/2$, with only small corrections. Very roughly, this value is 70 kv for electrons.

Axial Stability (Axial Focusing) - Theoretically, axial oscillations are damped so their amplitude is proportional to r - 1/2

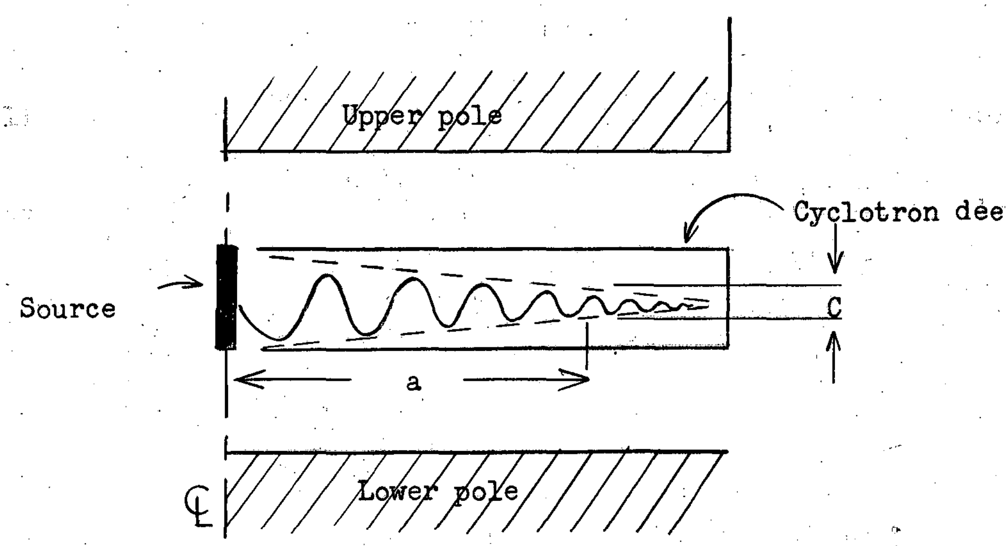


Fig. 2. Cross Section of Beam

If a = average radius of one particular orbit (see Fig. 2), one can write

$$\frac{d^2z}{d\theta^2} + K^2 \left(\frac{a\omega}{c}\right)^2 z = 0$$

$$z = C \cos \left[K \left(\frac{a\omega}{c}\right) z + \delta\right], \quad \text{if } a = \text{constant.}$$

However, a is slowly increasing, so the amplitude C is a function of a. By the adiabatic theorem,

$$C \alpha \left[K \left(\frac{a\omega}{c}\right)^2\right]^{-1/4} \quad \text{or,}$$

$$c \alpha \; a^{-1/2}$$

<u>Orbits</u> - The orbit of the particle is a deformed circle of the general form illustrated in Fig. 3 and is given by the expression

$$r \simeq a \left[1 + \frac{A}{8}\left(\frac{a\omega}{c}\right) \cos 3\,\theta\right],$$

where

$$\frac{a\omega}{c} \simeq \frac{v}{c}$$

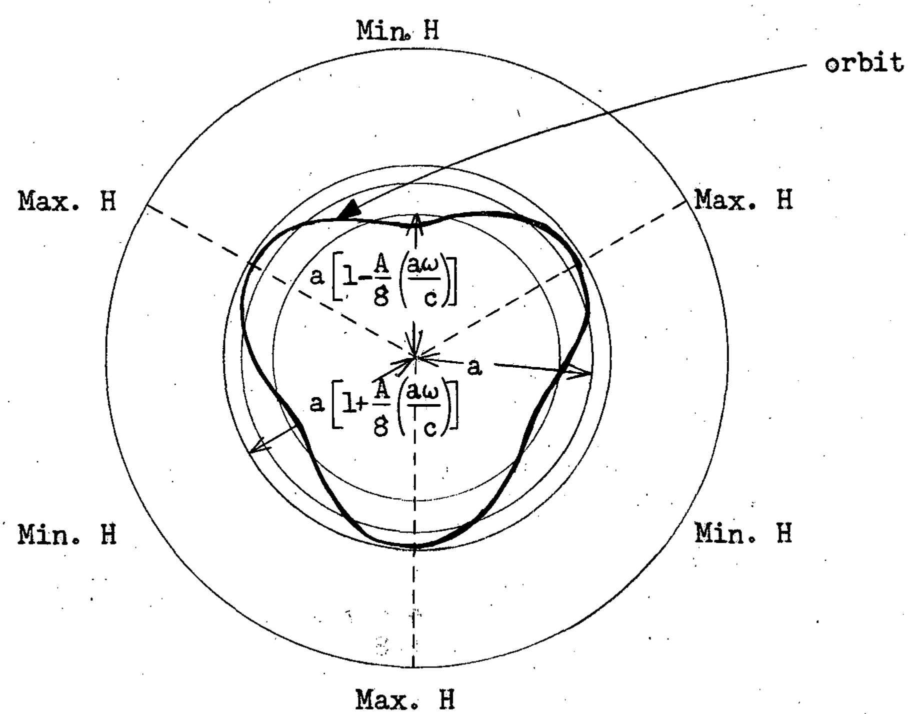


Fig. 3. Plan View of Pole Face

$\frac{A}{8}\left(\frac{a\omega}{c}\right)$ is the relative "modulation" or "ripple" (illustrated in Fig. 4) superimposed on the usual circular cyclotron orbits. It can be seen that at small radii the "ripple" is small and the orbit is a circle, as the radii (energy) are increased the orbits become deformed circles.

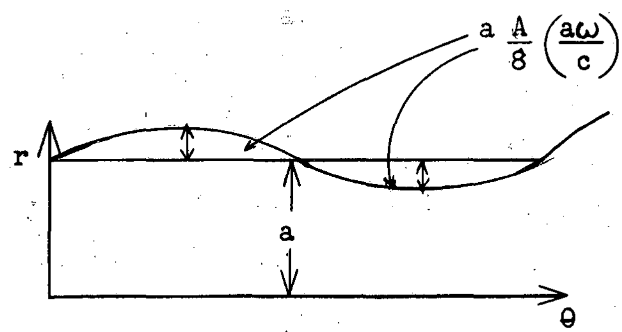


Fig. 4

Magnet Design - The magnetic field is of primary importance. The problem of its design was approached using design factors of a scaled down model. An assumed full scale model deuteron accelerating cyclotron was first considered with these approximate specifications:

Radius: 156 inches

Field Strength: 8000 gauss (center)

Frequency: 6.1 mc

A scale factor of 0.1 pole radius was thought satisfactory for a small electron model, and therefore the design parameters chosen were

Radius = 156 in. x 0.1 = 15.6 inches

Frequency = 6.1 x 10 = 61 mc

$$\text{Ratio of masses} = \frac{\text{deuterons}}{\text{electrons}} = \frac{M_d}{M} = 3671.3$$

$$\text{Field strength} = \frac{8000}{M_d/M} \times 10 = 21.8 \text{ gauss (center)}$$

It is known that the magnetic field between two magnetic poles (below saturation) varies as

$$d \propto 1/H$$

where

H = field strength

d = distance between poles (gap)

It is also known that magnetic lines of force leave the pole at right angles to the pole face at the point being considered. At very small values of d (see Fig. 5), the correction for curvature of the field with respect to curvature of the pole face may be considered to be quite small. As d (gap) is made larger, with sloping pole faces, correction was made by taking small increments of the gap, radially, and determining the H at these points. That is:

$\frac{dH}{dr}$ determines the curvature of the field in the gap.

Thus to determine the order of magnitude of the field two approximations were made.

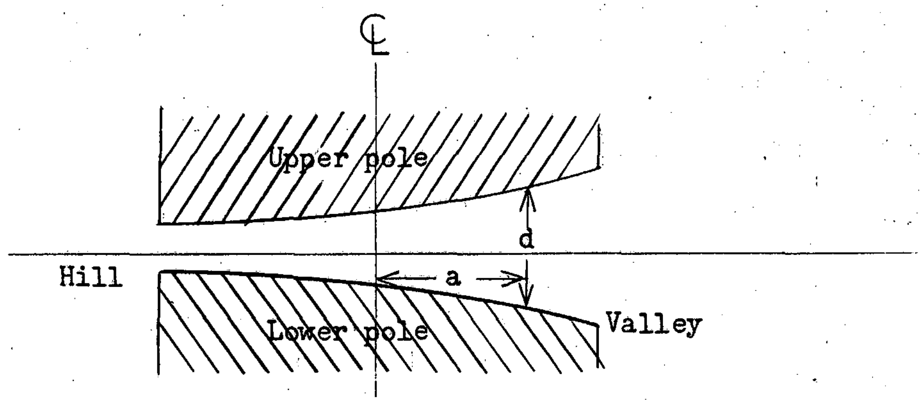


Fig. 5. Plane through Center Line

A minimum gap for rf excitation dee (beam height) was assumed 1.38 inches on the model. The field was assumed perpendicular to each pole face at the points being considered and has constant curvature in the gap. The center of the pole was determined previously to be 21.8 gauss. With this point known the three spaced 120 degree radials which determine maximum and minimum gap were calculated using the Thomas formula. In azimuth, radii were selected and their maximum and minimum values were calculated as a function of θ. At a radius of 15 inches the magnetic field was computed to vary from a maximum of 165 percent to a minimum of 45 percent of its value at the center in each 120° angular sector. (See Fig. 6.)

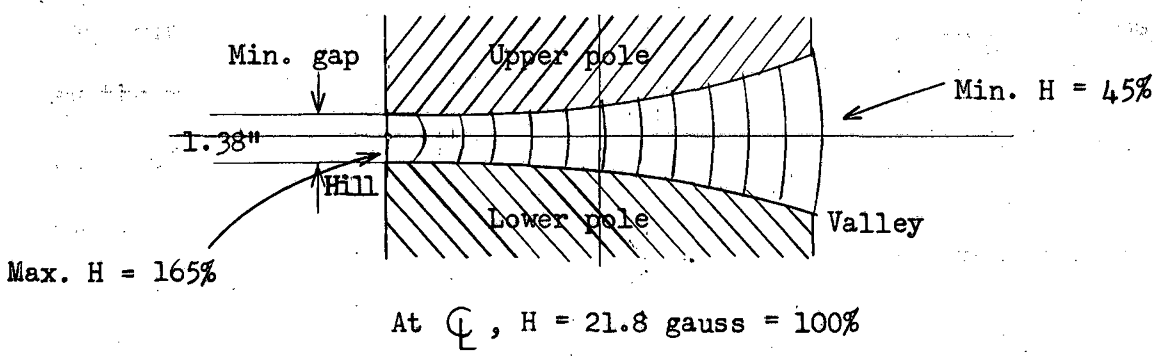
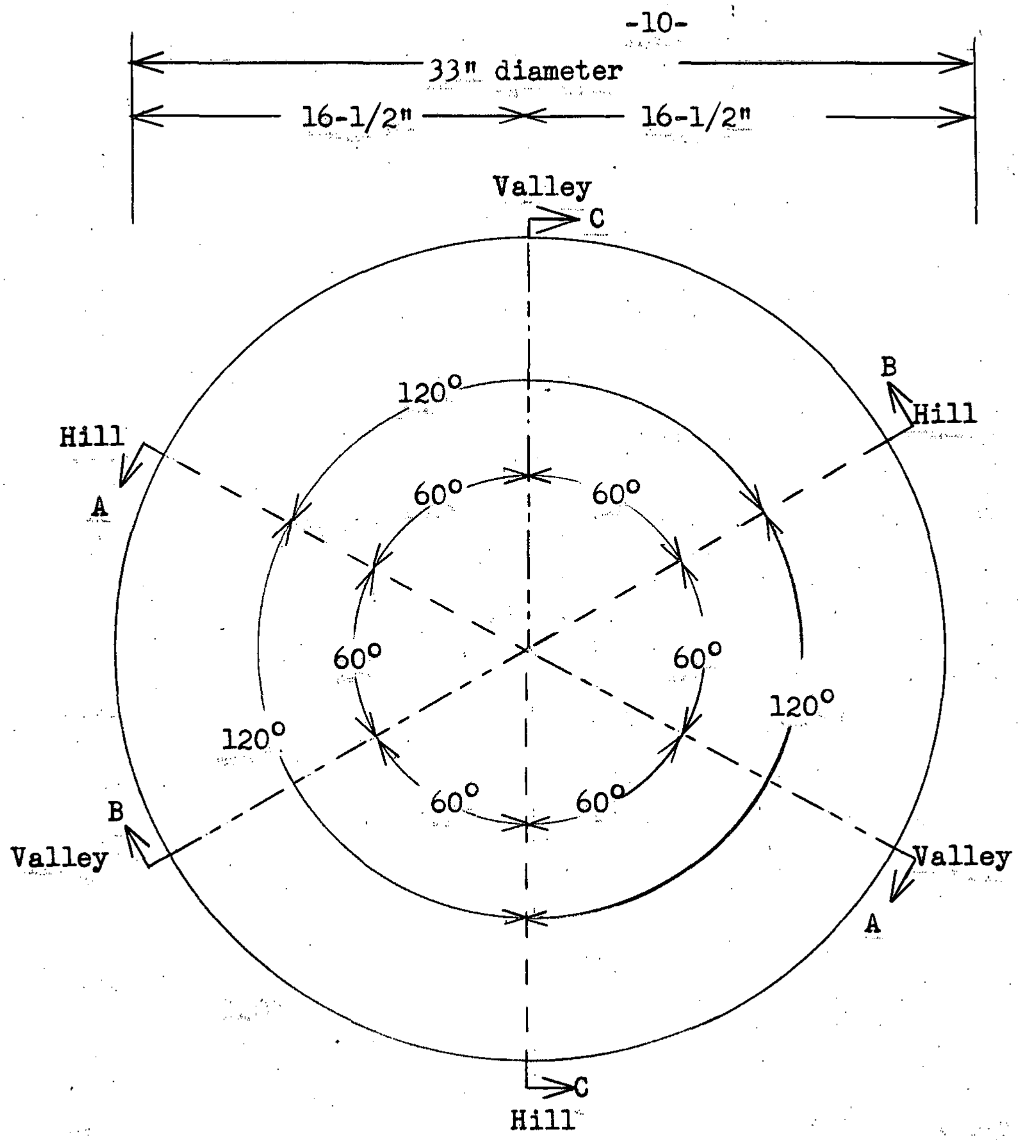


Fig. 6

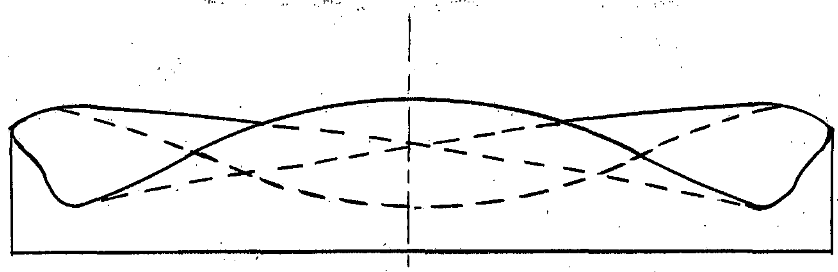
In order to achieve the magnetic field configuration desired, the pole faces were cut by a three-dimensional pantagraph milling machine from a solid iron blank. A plastic model of 120° of the pole face was made as a pattern for the milling machine to follow. It was necessary to demagnetize the pole faces by heat treatment before shaping. Variations as much as ± 4 gauss were found in the blanks before heat treatment. After heat treatment (temperature raise beyond Curie point) variations were found to be less than ± 0.05 gauss over the entire pole face. Figs. 7 and 8 show one of the pole faces.

Magnetic measurements show that the magnetic field in the model conformed to the specifications set forth above within 0.5 percent.

The magnet has no ferro-magnetic return path, air only. Each pole face is excited by a separate external solenoid around it, as shown in Fig. 9.



Plan View of Bottom Magnet Pole



Side View of Bottom Magnet Pole

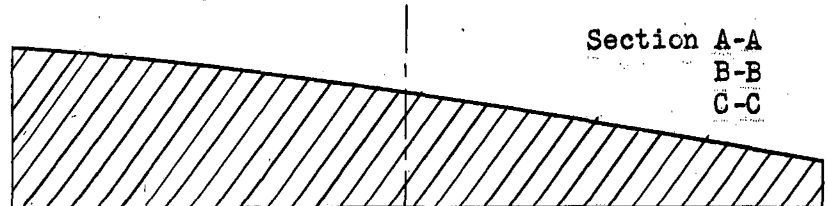


Fig. 7

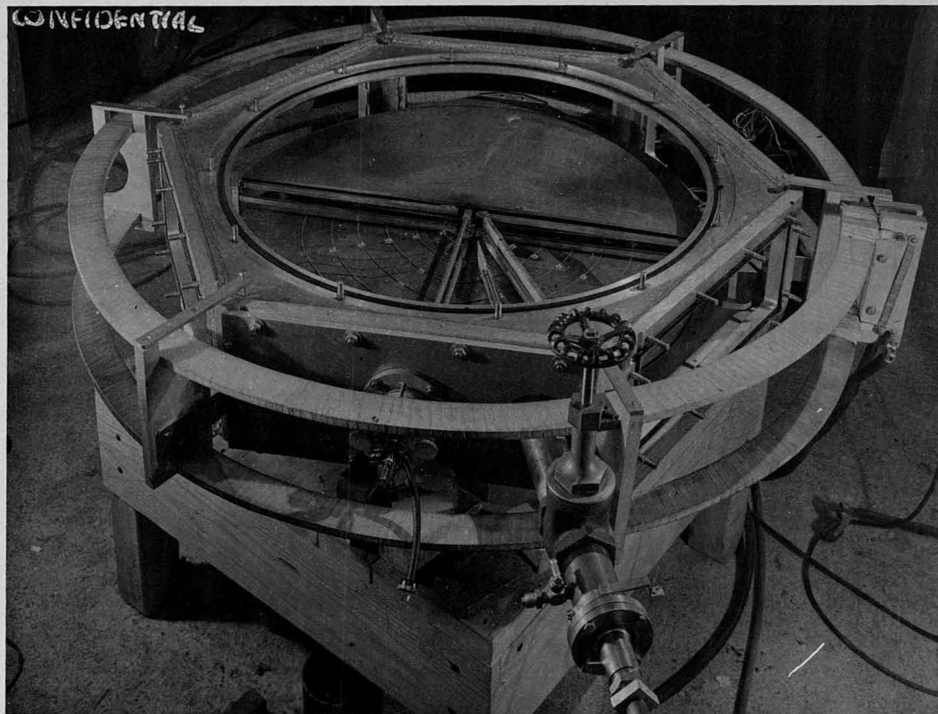


FIG. 8

FIG. 9

Engineering Specifications - During the month of May, 1950, the Electrical Engineering Department was informed of the proposal to build a small scale model cyclotron applying the Thomas theory. The particles selected to be accelerated were electrons and in the preliminary specifications the magnet pole faces were given as 36 inches in diameter. Thus, the name "36-inch Electron Cyclotron." However, later changes and/or modifications have left this as some vague, inconspicuous dimension on the pole mounting flange. The final magnet pole outside diameter was machined to 33 inches (16-1/2 in. max. radius). It was estimated that a machine of this dimension would provide electrons accelerated to approximately 68 Kev.

Since the magnetic field was of first importance work started immediately on pole design and measurements. Byron T. Wright designed the pole face contours to provide the necessary "hills and valleys" conforming with the magnetic field specified by Thomas' theorem, as described above. Space for the equipment was found in a portion of building 43 (a fully stocked warehouse) and modifications were made to the building to provide adequate power, heat, air, gas, water and lights after the contents were moved to another location. Electrical power was secured by installing a 240 volt 3 Ø, 100 amp. line from distribution box 12A in the Synchrotron Building 25, a distance of approximately 150 feet. Water and drain (for vacuum diffusion pump) was secured by running the necessary lines to valves at the fire hose station, (a distance of 75 feet). A telephone was installed and gas and air were tapped from lines running in front of the building. A distribution box, 12A-42, with adequate circuit protection terminates the power line in Bldg. 43.

Bldg. 43 is in a rather isolated section of the Laboratory. This is desirable because it is remote from stray magnetic fields. The magnetic field in the center of the gap of the electron cyclotron is 21.8 gauss. With the earth's magnetic field 0.74 gauss, a varying field of one gauss magnitude would provide large errors.

A list of reports giving the results of magnetic tests on this cyclotron is given below.

U-CLX-1	Azimuthal Uniformity	(no shims added)
U-CLX-2	Radial Uniformity	(no shims added)
U-CLX-12	Radial Unfiromity	(K-CLX-1 added)
U-CLX-4	Radial Uniformity	(K-CLX-2 added)
U-CLX-7	Azimuthal Uniformity	(K-CLX-2 added)
U-CLX-11	Radial Uniformity	(K-CLX-3 added)
U-CLX-8	Azimuthal Uniformity	(K-CLX-3 added)
H-CLX-1	Magnetization	(K-CLX-3 added)
K-CLX-1	Shims added	
K-CLX-2	Shims added	
K-CLX-3	Shims added	
K-CLX-4	% field contour drawing	
K-CLX-5	Gap contour drawing	
K-CLX-6	Earth's magnetic field in Bldg. 43	

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