AN ABSTRACT OF THE THESIS OF

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Title BEAM PARAMETERS OF THE OSU CYCLOTRON

Abstract approved ________________________________________________________________________

In order to anticipate needed changes in the cyclotron and for maximum operating efficiency several beam parameters for the OSU cyclotron were investigated. These parameters were (1) the energy of the internal beam, (2) the internal beam profile and (3) the dee-to-dee voltage.

The energy of the internal beam was calibrated by the use of a nuclear reaction threshold. The reaction chosen for the final energy calibration was Cu$^{65}$ (p,n)Zn$^{65}$ which has a threshold energy of 2.166 + 0.010 Mev (15). Copper foils were bombarded at varying radii with protons and the 1.12 Mev gamma rays associated with the decay of the induced Zn$^{65}$ activity were identified in the complete decay spectrum which was analyzed using a multi-channel analyzer. The yield of induced Zn$^{65}$ activity was determined as a function of the energy of the incident protons and
compared with the data of Shoupp (15). It is shown that the expression \( E = \frac{1}{2} m \omega^2 r^2 \) describes the energy of the internal beam to at least 2% accuracy where \( \frac{\omega}{2\pi} \) is the oscillator frequency and \( r \) is the distance from the center of the ion source cone.

A cross section of the beam profile was obtained by bombarding thin stainless steel foils in forked probes placed horizontally midway between the dees. It was expected that the vertical amplitude of the beam might be related to the radius and the magnetic field gradient by the following

\[
A = \frac{\text{Const.}}{\left( r \frac{\partial B}{\partial r} \right)^{\frac{1}{4}}}
\]

The experimental results were not in complete agreement with this expression although they suggest a linear relation between the amplitude \( A \) and the quantity \( (r \frac{\partial B}{\partial r})^{-\frac{1}{4}} \).

A measurement of the dee-to-dee voltage was made at several relatively low frequencies and voltages. A relationship is derived which shows that the voltage with respect to ground of the dees may be expressed as some
constant, $K$, times the voltage across suitably chosen capacitors in the dee voltmeter circuit provided that the frequency of the oscillator is greater than 50 Kc/sec. This constant $K$ was determined for each dee. The dee-to-dee voltage was then computed as a function of the oscillator plate current and at the operating frequency of 9.8Mc/sec. The calculated dee-to-dee voltage is about 50 Kv at the oscillator plate current of 3 amps.
BEAM PARAMETERS OF THE OSU CYCLOTRON

by

JOHN ROBERT PRINCE

A THESIS

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BEAM PARAMETERS OF THE OSU CYCLOTRON

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INTRODUCTION

Construction of the Oregon State University (OSU) cyclotron was started in June 1950 (3, p. 1). Although the original design called for separate oscillator frequencies for the acceleration of protons and deuterons (2, p. 1) the final design utilizes a fixed frequency oscillator.

In the fixed frequency cyclotron, ions of mass m and charge e are introduced near the center of the cyclotron dees through the exit slit of the ion source cone. These ions are accelerated by an r.f. voltage applied to the dees. Due to their interaction with the magnetic field, the ions spiral outward as they gain energy with the angular frequency, $\omega = eB/m$. This relation between $\omega$ and B, the magnetic flux density, is called the resonant condition. When the r.f. voltage is applied to the dees with this same frequency, $\omega$, the ions which are in proper phase will be accelerated each time they cross the dee gap. The accelerated ions will travel a spiral path until they impinge on a target or are lost from the beam by
either hitting the dees or being scattered by residual gas in the dee tank.

Some of the pertinent physical parameters of the OSU cyclotron which can be measured directly are as follows:

\[ r = \text{orbital radius of the accelerated particle. Targets have been bombarded out to a radius of 15 inches.} \]

\[ f = \frac{\omega}{2\pi} = \text{the resonant frequency which has been measured as 9.80 Mc/sec} \]

\[ B = \text{magnetic flux density and is about 13,000 gauss (3, p. 61)} \]

Protons, deuterons and alpha particles have been successfully accelerated in the OSU cyclotron. The protons are not accelerated directly but are obtained by accelerating singly charged molecular hydrogen ions. The maximum energies expected for these particles (at about 15 in. radius) are 7.5 Mev for deuterons, 3.7 Mev for protons and 1.5 Mev for alphas.

In order to anticipate needed changes in the cyclotron and for maximum operating efficiency it is important to have detailed knowledge concerning the characteristics of the beam. Examples where this information is important is in the placement of small targets for bombardment and in the design of beam deflectors. The purpose of this
thesis is to discuss various beam parameters of the OSU cyclotron. These investigations include (1) energy calibration of the internal beam, (2) the internal beam profile, and (3) the dee-to-dee voltage.
ENERGY CALIBRATION OF THE INTERNAL BEAM

A generalized theory of fixed frequency cyclotrons, such as the one at OSU, has been worked out by Cohen (5). If the variations in B, the magnetic flux density, are small, one may assume that the resonant r.f. frequency \( \omega = eB/m \) is constant and equal to the angular frequency of the accelerated ions. Furthermore, if the energies are low enough so that relativistic changes in mass are negligible, the energy of the accelerated ions may be expressed by

\[
E = \left(\frac{1}{2}\right)m\omega^2 r^2
\]  

(1)

when \( r > 3d \) (5, p. 11). At small values of r, the trajectories of the particles are complex.

In the above:

- \( E \) = energy of the accelerated ion
- \( m \) = mass of the ion
- \( \omega \) = resonant r.f. angular frequency
- \( r \) = orbital radius of accelerated ion
- \( d \) = distance between the dees

At the energies considered (up to 3 Mev for protons) the relativistic mass increase of the proton is less than about 0.3%. In the region where the accelerated ion spends most of its time (out to 12 inches) the magnetic
flux density $B$ decreases less than 1% and out to a radius of 14 inches $B$ is constant within 1.5% (3, p. 61). Thus, equation (1) describes the energy of an accelerated proton to about 2% for the conditions of this experiment.

The radial distance has been assumed to be the distance measured from the center of the ion source cone. This distance can be readily measured and for this reason the justification for an additional calibration of the energy of an internal beam may be questioned. It should be pointed out that the center of the orbits may not coincide with the geometrical center of the dees (14). Even though the exit slit in the ion source cone is well centered, the initial motion of the ions may effectively offset this center. The effect of the initial motion and the fact that the orbits are quasicircular means that the center of curvature of these orbits is not well defined. The center of these orbits can also shift as a result of asymmetries in the magnetic field.

For these reasons it was felt worthwhile to measure the energy of the internal beam at different radii and to determine how well equation (1) might hold. It was not expected that significant departures from equation (1)
would be found. However, an experimental verification of this equation for the conditions prevailing at the OSU cyclotron gives confidence in the operation of the machine and provides necessary background information on which to base future modifications.

There are a variety of methods available for determining the energy of high energy particles. In general, charged particle energies can be measured by deflection with either magnetic or electrical fields. Such methods are commonly used for determining the energy of an external cyclotron beam.

Absorption techniques have been used for determining the energy of an internal cyclotron beam (6). This technique requires accurate knowledge of absorption coefficients or a calibration with particles of a known energy.

After considering other available techniques for determining the energy of the internal beam of the OSU cyclotron, it was decided that a nuclear reaction threshold would be used. A number of these reactions can be used for accelerator energy calibrations (1, 10, 11) and the most useful ones have been reviewed by Marion (12). The choice of a suitable reaction depends upon finding a
well-defined threshold in the energy range of interest and one which would yield an easily identified product.

The range of particle energies of interest is dictated by the possible range of positions of the water-cooled target probe. At present this probe can operate only at target radii from about 10 inches to 15 inches, the distances being measured from the ion source cone. This corresponds to proton energies from 1.28 Mev to 2.88 Mev.

The threshold energy for the Li\(^7\) (p, n) Be\(^7\) reaction has been determined by a number of investigators (8, 11) and is perhaps the nuclear reaction most widely used for a secondary energy calibration in this range (11, 12). The threshold for this reaction is 1.8814±0.0011 Mev (8) and falls within the capabilities of the OSU cyclotron. Therefore the initial calibration was attempted with this reaction.

The experimental procedure was to bombard lithium targets at varying radii and then to analyze the target for the product Be\(^7\). This isotope is unstable and decays to Li\(^7\) by electron capture with a half-life of 54 days. Associated with this decay is a 0.48 Mev gamma ray. The
decay scheme for Be$^7$ is given in fig. 1. As evidence for
the presence of Be$^7$ the 0.48 Mev gamma ray was detected
by means of a NaI (Tl) crystal and analyzed with a single
channel differential pulse-height analyzer.

Due to the fact that copper was used as the backing
material for all of the lithium targets, there was also
the possibility of the reaction Cu$^{63}$ (p, n) Zn$^{63}$. The
isotope Zn$^{63}$ is unstable and decays either by electron
capture or positron emission to Cu$^{63}$ with a half-life of
38 minutes. Therefore discrimination between the 0.48 Mev
gamma ray associated with the decay of Be$^7$ and the 0.511
Mev gamma rays associated with the annihilation of the
positron from Zn$^{63}$ was attempted by allowing the Zn$^{63}$
activity to decay before analyzing the bombarded target.

Two series of experiments were conducted with differ-
ent types of lithium targets. The first series employed
LiCO$_3$ fused onto a water-cooled copper target. Because of
the heating caused by the bombardment, the LiCO$_3$ tended
to crack and spew out into the vacuum system resulting in
high-voltage breakdowns with subsequent loss of a good
vacuum. These instabilities made it necessary to design
new targets.
Figure 1
Decay scheme for Be\(^7\)

Figure 2
Decay scheme for Zn\(^{65}\)
A second series of lithium bombardments was initiated using pure lithium metal evaporated onto copper "buttons." In some cases these targets were strongly oxidized and poorly bonded to the copper backing. Under bombardment these targets also resulted in instabilities of the type already described.

In order to reach the threshold energy of this reaction it was necessary to place the target very close to the dees. Under these conditions, the oscillator became loaded in such a way that the oscillator frequency would shift. Additional difficulties (and embarrassments) developed when it was pointed out that the fourth harmonic of the cyclotron oscillator was approaching the communication band of the local police. In all subsequent runs, the oscillator frequency was monitored periodically to avoid interference with police communication.

Complete energy spectra were not obtained for all of the targets because of the technical difficulties with the cyclotron that have already been mentioned and because of drift problems with the single channel differential pulse-height analyzer. For some of the targets the output of the crystal detector was displayed on an oscilloscope.
screen and the presence of Be$^7$ was determined only visually. Because of these techniques, the confidence limits were low for those targets placed near the threshold region since a positive result may have been due to the presence of long lived induced contamination in the copper targets.

The results of these preliminary experiments with lithium are given in TABLE 1. In order to compare the experimental results with theory we solve equation (1) for $r$ when $E = 1.88$ Mev, $\omega = 6.17 \times 10^7$ radians/sec and $m = 1.67 \times 10^{-27}$ kg, and obtain a value of 12.1 inches for the threshold radius. Although the value for $r$ implied in TABLE 1 (i.e. 11.5 in.) does not agree with that calculated from equation 1, the qualitative trend in the results indicated that the method would be useful for further investigation.

The technical difficulties encountered in our search for the Li(p, n) threshold resulted in our abandoning this reaction and looking for a new one. After successful trials, the reaction chosen for the final energy calibration was Cu$^{65}$ (p, n) Zn$^{65}$ which has a threshold energy of $2.166 \pm 0.010$ Mev (15). The product of this reaction Zn$^{65}$
TABLE 1

The Presence of Be-7 Activity after Bombardment of LiCO₃ with Protons

<table>
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<tr>
<th>No. of Targets</th>
<th>Radial Position of Targets, in.</th>
<th>Results</th>
</tr>
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| 2              | 11 1/8                         | Negative
| 1              | 11 2/8                         | Negative
| 1              | 11 4/8                         | Negative
| 3              | 11 5/8                         | Positive 2 |
| 1              | 11 6/8                         | Positive 2 |
| 2              | 12                             | Positive 1 |
| 3              | 12 4/8                         | Positive 1 |

1Confidence in these results is high
2Confidence in these results is low

Assigned confidence limits are based upon the number of bombarded targets at each position, whether or not a complete gamma spectrum was obtained for each target and available calibration data at the time each target was analyzed.
is unstable and decays by either electron capture or positron emission to Cu\(^{65}\) with a half-life of 250 days. Associated with this decay is a 1.12 Mev gamma ray so that the targets can be analyzed for the product conveniently. The decay scheme for Zn\(^{65}\) is given in fig. 2. For comparisons, figs. 5 and 6 show a typical spectrum obtained from one of the bombarded targets and a calibration spectrum from a standard Zn\(^{65}\) source.

A preliminary series of copper foil targets was bombarded with protons at radial distances from 12.5 inches to 13.75 inches in 1/4 inch steps, all measurements being referred to the center of the ion source cone. The foils were then analyzed for induced Zn\(^{65}\) activity utilizing a 3 inch NaI (Tl) crystal and a Nuclear Data 512 channel differential pulse-height analyzer. A background count was taken for the same length of time and electronically subtracted from the gross data. Therefore, all spectra presented are corrected to net counts. The results of this preliminary series are given in fig. 3 in which the photopeaks of the induced Zn\(^{65}\) activity are plotted at different radii.

The results of these copper bombardments showed that
Figure 3

Photopeak of induced Zn\textsuperscript{65} activity on Cu targets bombarded with protons preliminary series.

Target position in inches
the gamma rays associated with the decay of $^{65}$Zn were readily detectable and furthermore suggested the possibility that relative yields of $^{65}$Zn could also be determined at different radii provided that bombardment times and beam currents could be determined.

At the OSU cyclotron the beam current is not measured directly but can be calculated in terms of the beam power. The temperature difference between the water going in and out of the water cooled probe is measured with thermisters in a simple bridge circuit. Since the water is kept flowing at a constant rate, as determined by a flow meter, the imbalance current in the bridge circuit which is designated by $I_B$, is a measure of the relative beam power. For protons the beam power is related to $I_B$ and the true beam current by the following relation.

$$ P = C I_B = i E = i k r^2 $$

(2)

where

$P = $ beam power

$C = $ constant

$i = $ beam current (particles per second)

$E = $ particle energy
\[ k = \text{constant} \]
\[ r = \text{radius of target position} \]

At a given radius, E is calculated by equation (1) and the absolute beam current is then determined using a calibration of the thermister circuit with an electric heater of known input power. In this manner relative beam currents were obtained by monitoring the beam power throughout each bombardment.

There were some difficulties in holding the beam current constant. During the long bombardments, heating occurs in various parts of the cyclotron which directly or indirectly affects the beam current through changes in the arc characteristics, changes in oscillator frequency and changes in the quality of the tank vacuum. In general the beam fluctuations were observed to be about 25%. These fluctuations, however, were generally slow and by recording the beam power at intervals of from three to five minutes during a bombardment of about one hour, average beam currents could be determined to about 5%.

Another series of copper foil bombardments was made with targets placed at radial distances from 12.5 inches
to 13.5 inches in 1/4 inch steps, all measurements being referred to the center of the ion source cone. The foils were analyzed, as before and the results are given in fig. 4 in which the photopeaks of the induced Zn$^{65}$ activity are plotted at different radii.

The complete spectra for the second series of copper targets bombarded from 13.0 to 13.5 inches are shown in figs. 6-8. For reference fig. 5 shows the spectrum for a known Zn$^{65}$ source. As the radius at which the foil is bombarded is increased, the induced activity also increases. This is associated with the fact that as the energy of the bombarding proton increases above the threshold energy, the cross-section for the Cu$^{65}$ (p, n) Zn$^{65}$ reaction also increases.

The yield of Zn$^{65}$ was determined for each target in arbitrary units. The yield is proportional to the area of the photopeak of the gamma spectrum and can be normalized for unit beam current and unit time by taking into account the length of bombardment, the bombarding beam power and the radial distances at which the target was bombarded. An equation which describes the yield in arbitrary units is the following:
FIGURE 4

PHOTOPEAKS OF INDUCED Zn$^{65}$
ACTIVITY ON Cu TARGETS BOMBARDED
WITH PROTONS. FINAL SERIES.
Figure 5

Spectrum of Zn$^{65}$ reference source.
FIGURE 6
SPECTRUM OF INDUCED Zn$^{65}$ ACTIVITY ON Cu TARGET BOMBARDED WITH PROTONS AT 13.5 INCHES
Figure 7

Spectrum of induced Zn$^{65}$ activity on Cu target bombarded with protons at 13.25 inches.
Figure 8

Spectrum of induced $^{65}$Zn activity on Cu targets bombarded with protons at 13.0 inches.
and from equation (2) this becomes

\[ Y = \frac{A}{tTt} \]

(3)

\[ Y = \frac{A}{tT} \frac{kr^2}{\overline{P}} \]

(4)

where

- \( Y \) = yield of Zn\(^{65} \)
- \( A \) = area of the Zn\(^{65} \) photopeak
- \( T \) = count time on analyzer
- \( t \) = length of bombardment
- \( \overline{P} \) = average beam power

The results of this normalization are given in fig. 9.

It is obvious from an analysis of figs. 3 and 4 that the threshold for the Cu\(^{65} \) (p, n) Zn\(^{65} \) reaction is between 12.75 and 13.0 inches. An examination of fig. 9 gives a threshold radius of 12.95\( \pm \) 0.05 inches for this reaction. From equation (1) this corresponds to a threshold energy of 2.152\( \pm \) 0.034 Mev. Comparing this value with that given by Shouppe, 2.166\( \pm \) 0.010 Mev, (15) it can be seen that the agreement is good within the experimental error.

In fig. 10 the obtained yields for induced Zn\(^{65} \) activity have been plotted against the energy of the
bombarding ions as determined by equation (1). For comparison, the yields reported by Shoupp have also been plotted in the same figure. No significant difference is observed between the two experimental curves.
\[ \text{Cu}^{65} (p, n) \text{Zn}^{65} \]
\[ E_T = 2.152 \pm 0.034 \text{ MeV} \]

Target position in inches
Figure 9

Proton energy in MeV
Figure 10

\[ \text{Cu}^{65} (p, n) \text{Zn}^{65} \]
\[ E_T = 2.166 \pm 0.010 \text{ MeV} \]

\( x-x-x \) Shoupp (15)
BEAM PROFILE MEASUREMENT

The shape and intensity of the magnetic field of the OSU cyclotron was investigated by Bates (3) for a variety of field shims. The field profiles were then compared with those of other fixed frequency cyclotrons (7). Based on this comparison together with some consideration of the way in which the field changed at the largest bombardment radii, a shim was selected which was thought to be adequate. Before considering a future modification of the shim arrangement in order to obtain larger beams at large radii, it is important to investigate the focusing properties of the beam through beam profile measurements. Previous qualitative information was based on the size of discoloration spots on bombarded targets.

A cursory review of the literature revealed various methods for determining the beam profile. At North American Aviation, Inc. (13) a profile indicator was developed which consists of tantalum probes geometrically positioned in such a way that signals from these probes indicate both the horizontal and the vertical distribution of the beam. In addition, profile information was obtained
from copper foils irradiated in the beam. These foils were cut into horizontal and vertical strips and their radioactivity counted subsequent to their bombardment.

At the Radiation Laboratory of the University of California (14), stainless steel foils were bombarded in forked probes placed horizontally midway between the dees. The foil was found to burn forming a cross section of the beam profile. These burned foils were then radioautographed to determine the amount of beam spreading. By this method, it was possible to determine the beam focusing and also a beam blow up.

Kimura, et al. (9) used copper mesh screens with frames of quartz bars to study the deflected ion beam trajectory in a cyclotron. With this technique he was able to obtain cross-sectional data and the angular divergence of the beam.

In measuring the beam profile for the OSU cyclotron it was decided to use the technique described by Rossi (14). Stainless steel foils, either 1 or 2 mil in thickness were mounted in copper forked probes and bombarded with deuterons. The foils were placed so that the cyclotron beam was intercepted at radial distances from 12-15
inches. These foils were then radioautographed in order to estimate the amount of spreading of the beam beyond the burned portion.

Two things became immediately obvious during these first experiments. The first was that under seemingly identical bombardment conditions the pattern in the burned foils could not always be reproduced well. This failure was thought to be due to the edges of the burned area peeling back in an irregular fashion as a result of the heat developed from the bombarding ions. This interpretation was supported by the presence of randomly spaced beads of melted metal along the edge of the burned area. The second item noticed, from the radioautographs, was that there was no appreciable spreading of the beam beyond the burned portion of the foil. For these reasons, no more radiographs were made since they yielded no reliable information.

In order to investigate the beam profile further, additional stainless steel foils were bombarded with alpha particles. Alpha bombardments had the advantage that while the cyclotron was in operation an observer could watch the foils through a port in the cyclotron dee tank
because of the very low radiation fields during the experiment. Observing these foils during bombardment did reveal marked variations in the amount of peeling back from foil to foil. Fig. 11 shows two of these foils bombarded with alpha particles under conditions as identical as possible. Fig. 12 shows additional foils bombarded with deuterons which show better reproducibility.

Although the foil studies are preliminary and only qualitative in nature, figs. 11 and 12 show that there is some degree of focusing of the beam and further that there is no evidence of beam blow up. The results obtained are in general agreement with previous observations that the beam intensity falls off at larger radii. However our failure to observe a blow up may be due to a weak beam rather than good focusing.

For an attempted comparison between experiment and theory, it is instructive to develop a relationship between the beam amplitude and the radius. Consider accelerated ions only at radii greater than about 10 cm.

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1 The author is indebted to Dr. Larry Schecter, Dept. of Physics, OSU, for assistance in the development of the theory in this section.
Beyond this radius electrostatic focusing is much less important than magnetic focusing and to a first approximation may be neglected. This condition arises principally from the fact that at larger radii the ion spends an extremely small fraction of its time in the dee gap but spends all of its time in the magnetic field (16).

The vertical magnetic focusing force on the ion is

\[ f_z = e (\vec{\nu} \times \vec{B})_z = e v_t B_r \]  

(5)

where

- \( f_z \) = vertical focusing force
- \( e \) = charge on the ion
- \( v_t \) = horizontal tangential velocity of the ion
- \( B_r \) = radial component of the magnetic flux density

Since near the median plane, the radial field component is small and slowly changing we can make the following approximation:

\[ B_r = \frac{\partial B_r}{\partial z} z \]  

(6)

Because the ion is essentially in free space,
\[ \nabla \times \vec{B} = 0, \text{ or} \]
\[ \frac{\partial B_r}{\partial z} = \frac{\partial B_z}{\partial r} \tag{7} \]

Since \( B_z \approx B \) and \( v_t = r \omega \) we have
\[ f_z = e r \omega \frac{\partial B}{\partial r} z \tag{8} \]

From a radial plot of the field (3, p. 61), we know that the field gradient is negative in the acceleration region; therefore the vertical motion depends on
\[ f_z = -k_z z \tag{9} \]

where
\[ k_z = \left| e \omega r \frac{\partial B}{\partial r} \right| \tag{10} \]

The above conditions show that if the radius remained constant, the ions would execute vertical harmonic motion with constant amplitude \( A \). The energy of this motion, \( W \), and its period \( T_z \), are
\[ W = \frac{1}{2} k_z A^2 \tag{11} \]

and
\[ T_z = 2\pi \sqrt{\frac{m}{k_z}} \tag{12} \]
The radius of the ion path does change, however, and so does $\partial B/\partial r$, but only slowly during one period of vertical oscillation. Because of these conditions, we are dealing with the case of the adiabatically invariant harmonic oscillator (4, p. 104) for which the total "action" remains constant.

Therefore we have

$$WT_z = \text{Const.} \quad (13)$$

or

$$\left( \frac{1}{2} k_z A^2 \right) \left( 2\pi \sqrt{\frac{m}{k_z}} \right) = \text{const.} \quad (14)$$

Combining equations 10 and 14 gives

$$A = \frac{\text{Const.}}{\left( r \frac{\partial B}{\partial r} \right)^{1/4}} \quad (15)$$

While reproducibility was difficult, useful information can be obtained by plotting the average beam amplitude, as determined by a number of foils, as a function of $(r \frac{\partial B}{\partial r})^{-1/4}$. Such a plot shows that the experimental points lie fairly well along a straight line as predicted by equation 15 although the line does not pass through the origin. The results are shown in fig. 13 and demonstrate
that the cyclotron beam is focusing at least very roughly in the manner expected. This condition is also confirmed qualitatively by an inspection of the beam profiles shown in figs. 11 and 12.
FIGURE 11

Two Stainless Steel Foils Bombarded with Alpha Particles under as Identical Conditions as Possible. Note Non-reproducibility.
FIGURE 12
Two Stainless Steel Foils Bombarded with Deuterons.
Correlation of beam amplitude with orbital radius.
DEE-TO-DEE VOLTAGE MEASUREMENT

In the design and operation of a cyclotron it is important to know the dee-to-dee voltage. Not only is there a minimum dee-to-dee voltage necessary to get the beam to a given energy or radius (5, p. 5), but also the beam current increases as the accelerating voltage is increased and as adjacent beam orbits become more widely separated. Since the dee voltage had never been measured reliably for the OSU cyclotron, it was decided to attempt a measurement of this parameter. Since a direct measurement of the dee-to-dee voltage is complicated by the relatively large voltages and the high frequencies involved, only indirect measurements were undertaken.

Fig. 14 shows the complete circuit diagram for the r-f voltmeters which monitor a fraction of the dee voltage through coupling capacitors. In our experiments the 6AL5 voltmeter tube was taken out and the Jones plug removed. A schematic of this simplified circuit is given in fig. 15. These modifications were felt necessary in order to simplify the circuit as much as possible.

In fig. 15, $v_2$ is the voltage between the dees and
Figure 14

Circuit diagram of the north dee R-F voltmeter. The south dee R-F voltmeter is the same, although not shown.
Figure 15

Simplified schematic of the R-F voltmeter circuit. The constant voltage impressed on the dees at varying frequencies is $v_2$ and $v_1$ is the measured output voltage at the point shown.
ground, and \( v_1 \), the voltage-to-ground at a point between the coupling capacitor and the dee voltmeter. Although under normal cyclotron operating conditions \( v_2 \) cannot be determined readily because of the high operating voltages and frequencies, \( v_1 \) can be. However, if the relationship between \( v_2 \) and \( v_1 \) could be established, i.e., \( v_2 = K v_1 \), at lower frequencies, then \( v_1 \) could be measured under normal conditions and by the use of this relation \( v_2 \) could be calculated. In general \( K \) is expected to vary with the frequency, but it is possible to calculate the range in which \( K \) is to a good approximation frequency independent.

Referring to fig. 15 and by applying Kirchhoff's rules, the following relations hold for the instantaneous currents and voltages.

\[
i_1 = i_2 + i_3 \quad (16)
\]

Making use of the approximation that \( R \gg 1/\omega C_5 \),

\[
i_1 = i_2 + v_1/R \quad (17)
\]

At 25kc/sec, \( R \omega C_5 \approx 7 \)

Also in the idealized circuit where we neglect other stray
capacitances and inductances in the dee system, we may set

\[ v_2 = -\left( \frac{j i_1}{\omega C_1} + \frac{j i_2}{\omega C_2} \right) \]  

(18)

where \( C_2 = C_3 + C_4 \) and \( j = \sqrt{-1} \)

Combining (17) and (18) we have

\[ v_2 = -\frac{j i_1}{\omega C_1} - \frac{j}{\omega C_2} \left( i_1 - \frac{v_1}{R} \right). \]  

(19)

Therefore

\[ v_2 = -j i_1 \left( \frac{1}{\omega C_1} + \frac{1}{\omega C_2} \right) + \frac{jv_1}{\omega C_2} \]  

(20)

From the circuit components and (16) we have

\[ i_1 = v_1 \left( \frac{1}{R} - \frac{\omega C_2}{j} \right) \]  

(21)

Combining (20) and (21) we have

\[ v_2 = v_1 \left( \frac{1}{R} - \frac{\omega C_2}{j} \right) \left( \frac{-j}{\omega C_1} - \frac{j}{\omega C_2} \right) \]  

\[ + j \frac{v_1}{R} \frac{1}{\omega C_2} \]  

(22)

Multiplying out the above terms

\[ v_2 = -\frac{v_1}{R} \frac{j}{\omega C_1} - \frac{v_1}{R \omega C_2} + \frac{v_1 C_2}{C_1} + v_1 \]
(23) continued.

\[(23)\]

\[+ j \frac{v_1}{R} \frac{1}{\omega C_2}\]

Collecting terms gives the following

\[v_2 = v_1 \left(1 + \frac{C_2}{C_1} - \frac{j}{R \omega C_1}\right)\]  \hspace{1cm} (24)

To an approximation (24) is independent of \(\omega\) if

\[\frac{1}{R \omega C_1} \ll \frac{C_2}{C_1}\]  \hspace{1cm} (25)

since \(C_2/C_1 \gg 1\).

Equation (25) holds when \(\omega \gg 50\) Kc/sec. At 50 Kc/sec.,

\[1/R \omega C_1 \approx 70\] and \(C_2/C_1 \approx 500\).

Therefore, to a first approximation we can write

\[v_2 = v_1 \frac{C_2}{C_1} = K v_1\]  \hspace{1cm} (26)

where \(K\) is constant. Within the frequency range stated
above \(K\) will also be the ratio of the rms value of \(v_2\) and
\(v_1\) as well as the instantaneous values.

With the oscillator power off and the dees discon-
nected, a signal generator was used to apply an a-c
voltage between one of the dees and ground. Both \( v_2 \) and \( v_1 \) were determined using a Tektronix 541 oscilloscope. The determination of \( v_1 \) at a number of frequencies with a constant \( v_2 \) was made and their ratios calculated.

The results indicate that up to 400 Kc, \( K \) is relatively constant. Measurements were attempted at higher frequencies, however instabilities occurred in the measuring equipment, presumably due to resonances in the dee circuit, and the results were confusing. While the present measurements may not be entirely satisfactory, better measurements are difficult. The results of these measurements are given in TABLES 2 and 3.

The trace of the voltage signal of \( v_1 \) appearing on the oscilloscope was somewhat blurred due to noise and background which was not easily removed. The magnitude of the voltage \( v_1 \) was measured by comparing the average amplitude of the signal with a calibration signal. The experimental error in \( v_1 \) was assumed to be the amplitude or width of the oscilloscope trace.

After the ratios of \( v_2/v_1 \) were calculated for both dees an average \( K \) was determined. This turned out to be: for the north dee, \( K_n = 2,200 \pm 400 \); and for the south
Following these measurements the cyclotron was placed in operating condition and \( v_1 \) was measured for both the north and south dees at a number of oscillator plate currents. From these data the dee-to-ground voltage was determined utilizing the relations \( v_2 = \bar{K} v_1 \). These results are tabulated in TABLES 4 and 5.

In order to obtain the dee-to-dee voltage at any given oscillator plate current it is simply necessary to add the appropriate numbers from TABLES 4 and 5. When this is done fig. 16 results. Since the cyclotron normally operates at an oscillator plate current of about 3 amperes, these measurements indicate a dee-to-dee voltage of about 50 kilovolts.

These measurements indicate that \( K \) is relatively constant and does not vary appreciably with frequency. It is interesting to calculate an expected \( K \) at varying frequencies and to compare this value with the observed \( K \). From equation 26, \( C_1 \) was calculated for each dee using the experimentally determined \( K \). The value of \( K \) was then calculated for frequencies varying from \( 2.5 \times 10^4 \) cps to \( 1.0 \times 10^7 \) cps using the simplified circuit shown in
fig. 15. The calculated values are given in TABLE 6.
The values of $K$ shown in TABLE 6 compare favorably with the values determined experimentally.
TABLE 2

SOUTH Dee VOLTAGE MEASUREMENTS AS A FUNCTION OF INPUT FREQUENCY

<table>
<thead>
<tr>
<th>$f$ (Kcps)</th>
<th>$v_2$ (v)</th>
<th>$v_1$ (v)</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>20</td>
<td>0.011 ± 0.0040</td>
<td>1800 ± 600</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>0.011 ± 0.0048</td>
<td>1800 ± 800</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>0.011 ± 0.0048</td>
<td>1800 ± 800</td>
</tr>
<tr>
<td>200</td>
<td>20</td>
<td>0.011 ± 0.0050</td>
<td>1800 ± 800</td>
</tr>
<tr>
<td>300</td>
<td>20</td>
<td>0.012 ± 0.0050</td>
<td>1700 ± 700</td>
</tr>
<tr>
<td>400</td>
<td>20</td>
<td>0.012 ± 0.0050</td>
<td>1700 ± 800</td>
</tr>
</tbody>
</table>

$\frac{K}{K_s} = 1800 ± 300$
TABLE 3

NORTH DEE VOLTAGE MEASUREMENTS AS A FUNCTION OF INPUT FREQUENCY

<table>
<thead>
<tr>
<th>f (Kcps)</th>
<th>$v_2$ (v)</th>
<th>$v_1$ (v)</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>20</td>
<td>0.0085 ± 0.0035</td>
<td>2400 ± 1000</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>0.0088 ± 0.0032</td>
<td>2300 ± 800</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>0.0085 ± 0.0035</td>
<td>2300 ± 1000</td>
</tr>
<tr>
<td>200</td>
<td>20</td>
<td>0.0095 ± 0.0025</td>
<td>2100 ± 600</td>
</tr>
<tr>
<td>300</td>
<td>20</td>
<td>0.0095 ± 0.0035</td>
<td>2100 ± 800</td>
</tr>
<tr>
<td>400</td>
<td>20</td>
<td>0.0095 ± 0.0045</td>
<td>2100 ± 1000</td>
</tr>
</tbody>
</table>

$\bar{K}_n = 2200 ± 400$
TABLE 4

CORRELATION OF SOUTH DEE VOLTAGE-GROUND
WITH OSCILLATOR PLATE CURRENT

<table>
<thead>
<tr>
<th>Oscillator Plate Current (amp)</th>
<th>$V_1$ (v)</th>
<th>South Dee Voltage-Ground (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>$2.35 \pm 0.15$</td>
<td>$4000 \pm 800$</td>
</tr>
<tr>
<td>1.0</td>
<td>$6.05 \pm 0.15$</td>
<td>$11000 \pm 2000$</td>
</tr>
<tr>
<td>1.5</td>
<td>$8.10 \pm 0.10$</td>
<td>$14000 \pm 3000$</td>
</tr>
<tr>
<td>2.0</td>
<td>$12.35 \pm 0.15$</td>
<td>$22000 \pm 4000$</td>
</tr>
<tr>
<td>2.5</td>
<td>$16.20 \pm 0.00$</td>
<td>$28000 \pm 5000$</td>
</tr>
<tr>
<td>3.0</td>
<td>$16.10 \pm 0.20$</td>
<td>$28000 \pm 5000$</td>
</tr>
</tbody>
</table>


TABLE 5

CORRELATION OF NORTH DEE VOLTAGE-GROUND WITH OSCILLATOR PLATE CURRENT

<table>
<thead>
<tr>
<th>Oscillator Plate Current (amp)</th>
<th>$v_1$ (v)</th>
<th>North Dee Voltage-to-Ground (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>$0.85 \pm 0.10$</td>
<td>$1900 \pm 400$</td>
</tr>
<tr>
<td>1.0</td>
<td>$2.25 \pm 0.25$</td>
<td>$5000 \pm 1000$</td>
</tr>
<tr>
<td>1.5</td>
<td>$4.63 \pm 0.13$</td>
<td>$10000 \pm 1600$</td>
</tr>
<tr>
<td>2.0</td>
<td>$7.60 \pm 0.35$</td>
<td>$17000 \pm 2800$</td>
</tr>
<tr>
<td>2.5</td>
<td>$10.25 \pm 0.25$</td>
<td>$23000 \pm 3600$</td>
</tr>
<tr>
<td>3.0</td>
<td>$10.7 \pm 0.10$</td>
<td>$24000 \pm 3800$</td>
</tr>
</tbody>
</table>
### TABLE 6

**CALCULATED K VALUES FOR VARYING FREQUENCIES**

<table>
<thead>
<tr>
<th>$f$ (cps)</th>
<th>$K_N = \frac{v_2}{v_{1N}}$</th>
<th>$K_S = \frac{v_2}{v_{1S}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.5 \times 10^4$</td>
<td>2800</td>
<td>2300</td>
</tr>
<tr>
<td>$5.0 \times 10^4$</td>
<td>2500</td>
<td>2000</td>
</tr>
<tr>
<td>$1.0 \times 10^5$</td>
<td>2400</td>
<td>2000</td>
</tr>
<tr>
<td>$2.0 \times 10^5$</td>
<td>2300</td>
<td>1800</td>
</tr>
<tr>
<td>$3.0 \times 10^5$</td>
<td>2300</td>
<td>1800</td>
</tr>
<tr>
<td>$4.0 \times 10^5$</td>
<td>2200</td>
<td>1800</td>
</tr>
<tr>
<td>$1.0 \times 10^6$</td>
<td>2200</td>
<td>1800</td>
</tr>
<tr>
<td>$1.0 \times 10^7$</td>
<td>2200</td>
<td>1800</td>
</tr>
</tbody>
</table>
Correlation between dee-to-dee voltage and the oscillator plate current.


11. Marion, J. B., T. W. Bonner and C. F. Cook. Study of the reactions $^3\text{He}$, $^7\text{Li}$, $^9\text{Be}$, $^9\text{Be}$, $^9\text{B}$, and $^{19}\text{F}$ (p,n). Physical Review 100:91-96. 1955.


