The University of Illinois Spiral-Ridge Cyclotron*

J. S. Allen

Several years ago we were greatly impressed by the successful operation of the Los Alamos, Thomas-shim cyclotron. Since our cyclotron was almost identical with the Los Alamos machine before its rejuvenation, we decided to add spiral shims and field coils to it. I certainly will be pleased if our beam current is as high as that from the present Los Alamos cyclotron. Unfortunately, ours is a very complicated machine and there will be many problems which must be solved before we obtain large beam currents.

Much of the early design work on the magnetic field of this machine was done by Dr. P. Stahelin[1]. Model measurements were made, the parts were built, and for the last nine months or so we have been studying the field configuration.

So far, I believe that there has been no discussion in this meeting of the problems that are involved if one desires to make a variable-energy cyclotron. We have found that the difficulties in doing this are very great if the magnetic field is to vary, say, by a factor of two or more. Our machine certainly would have been operating about six months ago if we had designed it to operate at just one value of the magnetic field.

The University of Illinois cyclotron has pole pieces 43 in. in diameter. According to our initial design specifications the maximum proton energy was to be 16 Mev with a central field of about 12 kilogauss and an extraction radius of 18.5 inches. For perfect r-f isochronism the increase in the field from the center to the extraction radius was to be about 200 gauss. The design called for an axial frequency ω_z = 0.2 and the first estimates were made in terms of the smooth approximation for the focusing frequencies. According to our calculations, we required a RMS flutter of about 8% at the extraction radius. Our most recent measurements show that the flutter is about 7%. The axial focusing frequency computed by means of the MURA WT-V program predicted ω_z = 0.35 at the extraction radius. Apparently, the frequency computed by means of digital computers usually is larger than the value estimated by the smooth approximation formulas.

The field measurements in the cyclotron were made with bismuth wire coils held at liquid nitrogen temperature. The accuracy of the measurements is about ±1 gauss. The precision of the measurements seemed to be limited mainly by noise which appeared when a coil was placed in the magnetic field. These bismuth coils were placed in small Dewar flasks containing liquid nitrogen. The noise is very small when the field is off, but increases when the field is turned on. There are various types of noise which can be reduced. The most serious source of noise is caused by gas bubbling up through the liquid nitrogen. Every time a bubble appears the resistance changes, resulting in a fluctuation at the recorder. This is a very troublesome effect, but we have been able to reduce it by winding thread and cheesecloth around each coil. Apparently, the size of the bubbles is reduced by the porous cloth.

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Another disadvantage of this method is the changing composition of the liquid nitrogen. Since the nitrogen contains a small amount of oxygen, the ratio of the two components changes as the liquid evaporates. Since the temperature of the bath changes slightly as the ratio varies, a gradual drift of the resistance of the coil occurs. Despite these disadvantages the bismuth coil method has the advantage of simple circuitry. The work of converting the resistance readings to field values can be reduced by programming the output for a digital computer.

There are four shims on each pole piece. Each shim is in the form of an Archimedean spiral with $\tan\gamma = 0.05R(\mathrm{cm})$ and is 0.875 in. thick. The earliest measurements were made with the spirals extending as close to the center as possible. The shims were terminated at the center by an iron disk 2 in. in diameter. With this arrangement the flutter extended almost to the center. However, we discovered that, as the main magnetic field was varied, the field profile at the center assumed shapes which were almost impossible to correct by means of coils. In general, the field either decreased or increased rather sharply at the center, depending on the value of the average magnetic field. We were not able to eliminate this effect by changing the thickness of the shims near the center. Our final measurements were made on a shim configuration in which the shims were terminated at the center in an iron disk 7.25 in. in diameter. The thickness of the central disk was adjusted so that there was a smooth joining of the fields at the junction with the spiral shims.

The general arrangement of the magnetic shims is shown in Figure 69. The shims terminate in a disk at the center of each pole piece. A vertical section through one of the pole pieces shows how the five field coils cross over the shims.

The field coils are shown in Figure 70. These coils are made of hollow copper tubing 1/4-in. sq. The coils are held in place on the inner side of each copper dee liner by 4 aluminum blocks which lie in the valleys between the iron shims. The square copper tubing is insulated by a layer of fiber glass insulation impregnated with a silicone-containing varnish. Additional insulation is provided by two layers of Teflon tape wound around each coil. The Teflon tape is an excellent insulating material but has a tendency to tear if the surface is scratched.

We discovered that the coils will vibrate in the magnetic field with rapid abrasion of the insulation if the current through the coils has an appreciable ripple. Our present power supplies have a ripple of $\pm 1\%$ and appear to be satisfactory.

A plot of the flutter factor against the radius of a pole piece is shown in Figure 71. The maximum flutter of about 7% should provide a positive axial focusing frequency for 16-Mev protons. Since the flutter factor is very small inside a radius of 3 in., we may need to provide a negative field gradient in this region to obtain positive axial focusing.

Plots of the average axial magnetic field as a function of the radius are shown in Figure 72 and 73. In each case the shim configuration is that shown in Figure 69. The field contours have a hump at the center which begins to appear at about 12 kilogauss and increases with increasing field values. This hump can be almost entirely eliminated by the central field coil. The rapid decrease of the field near the extraction radius of 18.5 in. makes the field correction very difficult. Isochronous fields up to 14.4 kilogauss can be realized with the 5 field coils presently in use.

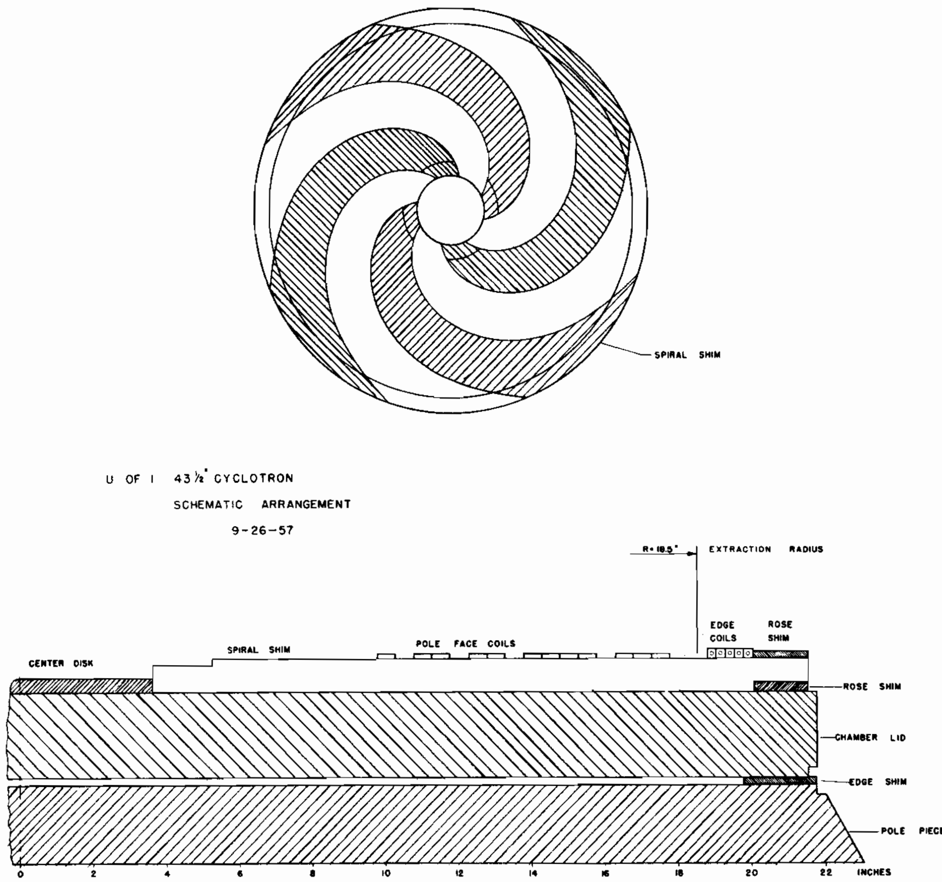

Fig. 69. The shim arrangement used in the University of Illinois 43-inch cyclotron. The shim thickness is 7/8-in. Five sets of field correction coils are required.

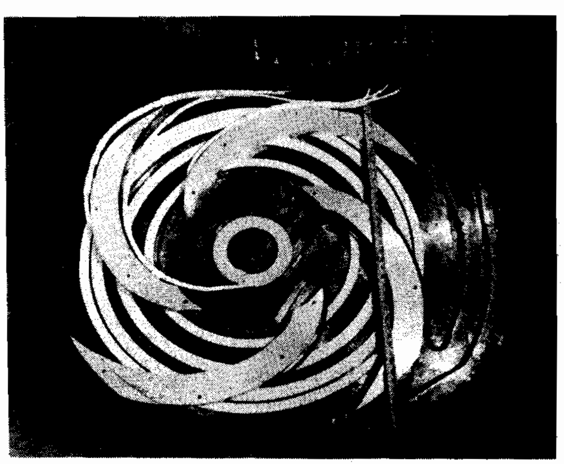

Fig. 70. The five sets of water-cooled field coils are clamped to the inner surface of each copper dee liner with four aluminum clamps.

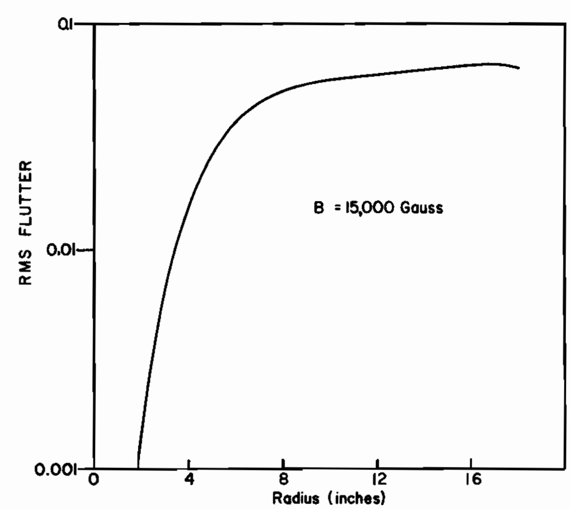

Fig. 71. A plot of the flutter against radius. The spiral shims terminate at the center in a 7-1/4-in. dia. iron disk.

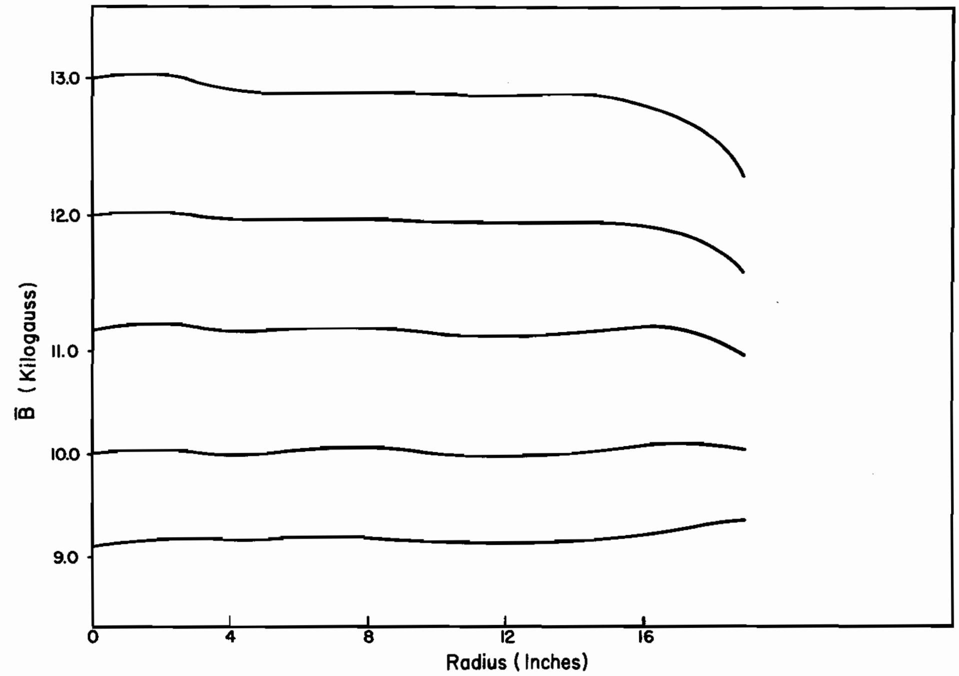

Fig. 72. The azimuthally averaged magnetic field as a function of the radius of a pole piece.

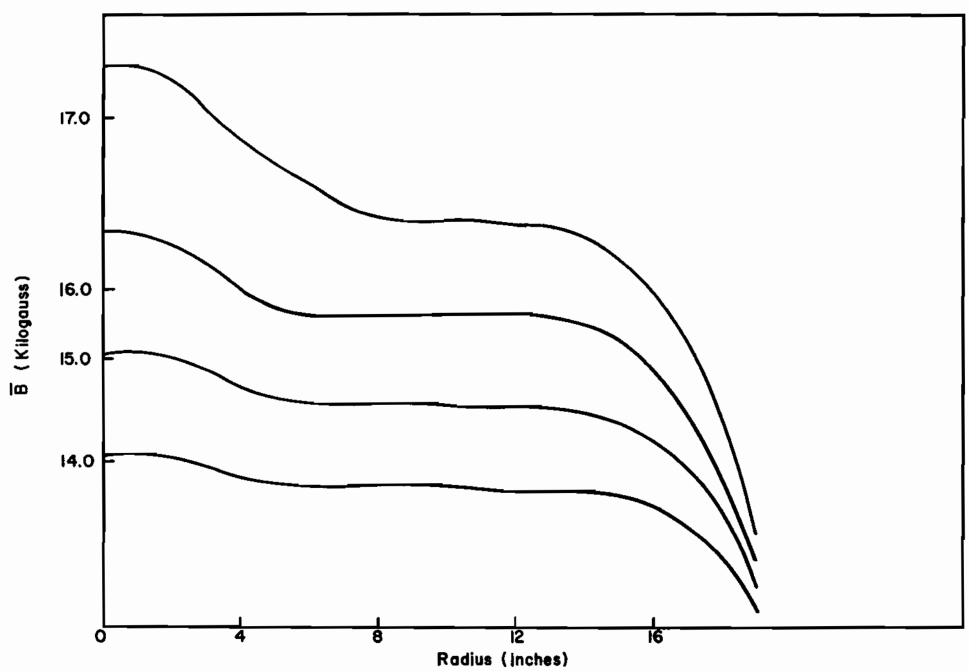

Fig. 73. The azimuthally averaged magnetic field.

A composite of the corrections produced by the individual field coils is shown in Figure 74. The uppermost curve represents what we call the base field, which is 13 kilogauss in this example. The current through each coil is 200 amp in a direction such that the field contribution opposes the main field. The field contribution from the innermost coil extends out to about 6 in. from the center and has the right shape to compensate for the bump which appears at the center.

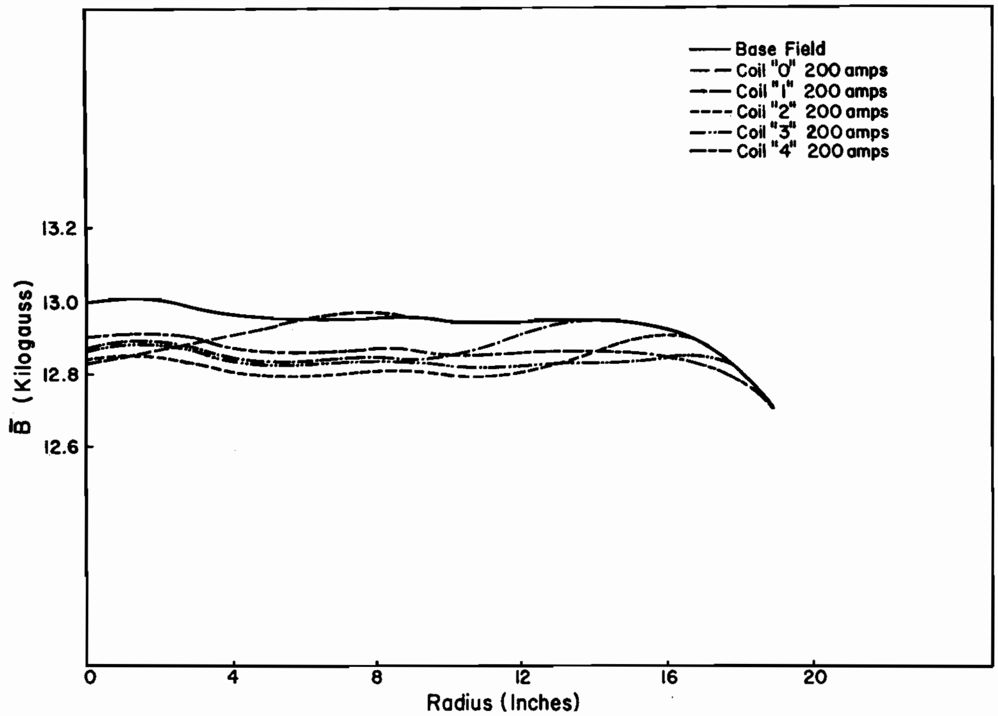

Fig. 74. A composite of the corrections produced by the five field coils. The current is 200 amperes or about 2000 amp-turns for each pair of coils. The corrections oppose the base field.

Each of the outer coils produces a contribution which is approximately constant out to a given radius. The outermost coil has no effect on the base field beyond 19 in., but provides an almost constant reduction of the field inside 15 inches. By adjusting the relative magnitudes of the currents in the five coils one can produce quite a large change in the slope of the average magnetic field.

The problem of selecting the correct combination of currents in these coils is quite difficult. So far, we have made the computation by hand and, in general, have not found unique solutions. Usually several combinations of currents through the coils will produce acceptable solutions. We now are coding this problem for a digital computer. The optimum set of currents will be selected by a least-squares method, in which the degree of isochronism of the field contour is an important factor. The whole problem is complicated by the fact that the contribution from the correction coils is a function of the value of the base field and, consequently, a large number of correction curves are required.

An attempt to produce a truly isochronous field for 15-Mev protons is shown in Figure 75. The total increase in the field from the center to the extraction radius should be 180 gauss. The fit between the corrected curve and the resonance curve is good except at a radius of about 9 inches. A better fit for some other combination of currents through the field coils may be possible.

An attempt to realize the desired field for 11-Mev deuterons is also shown in Figure 75. The radial increase of the resonant field should be about 100 gauss. In this case large corrections are required for the bump at the center and the drop near the exit radius. The fit between the resonant and the corrected curve is excellent near the extraction radius. The fit near the center probably could be improved by increasing the current through the central correction coil.

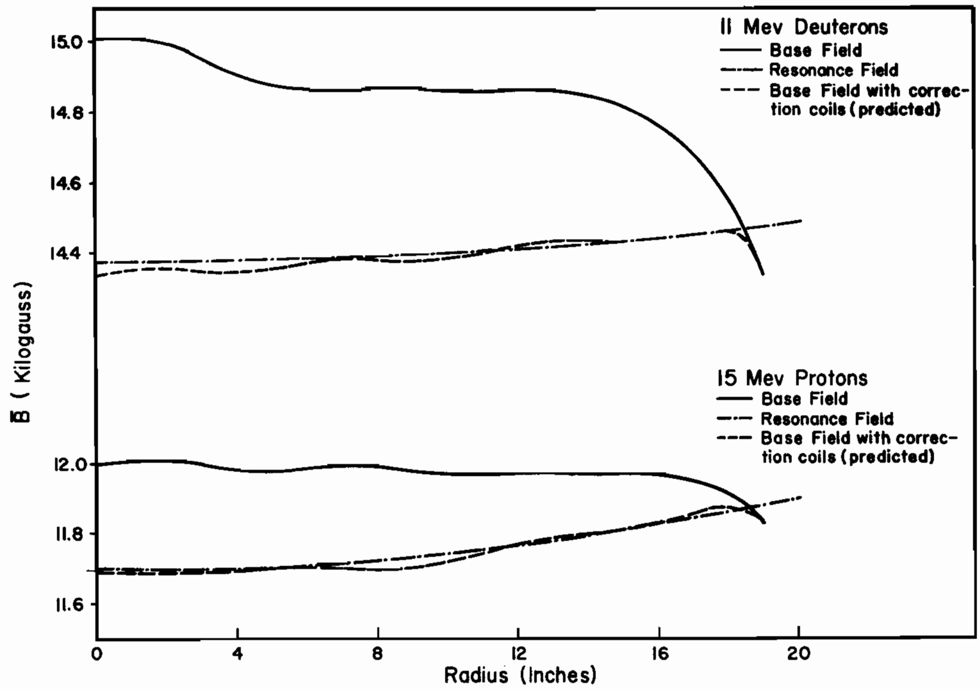

Fig. 75. Corrected field configurations for 15-Mev protons and 11-Mev deuterons.

I might say that we have had some difficulty in obtaining the power supplies for the field coils. The best solution would be to have five separate power supplies current-regulated and adjustable, say, from zero to 600 amperes. However, these are not commercially available with the desired current range.

Unfortunately, the resistance of these coils is very low. For instance the resistance of the innermost coil is only 0.01 ohm. Since the current range is to be from nearly zero to 500 amp, we need a power supply with a maximum output of 5 volts. In the case of the larger coils, the resistance is greater and we need about 15 volts.

At present, we have two regulated supplies with outputs adjustable from 18 to 30 volts. The larger supply has a maximum rating of 500 amp and the smaller a rating of 250 amperes. Consequently, we have the problem of supplying the current in the five coils by means of these supplies. The most convenient rheostat we have found consists of a water-cooled Invar tube with a diameter of 1/4 in. and wall thickness of 10 mils. These tubes will dissipate about 12 kilowatts per linear foot. However, the resistance cannot be conveniently adjusted by remote control. The availability of power transistors with a maximum current rating of 13 amp and a power rating of 50 watts suggests that the current control can be accomplished by this method.

The problem of making this cyclotron into a flexible, variable-energy machine has not been entirely solved. At present we are investigating various schemes for remote control of the currents in the correction coils, and the frequency of the oscillator.

CHAIRMAN KELLY: Do you have some measurements of the difficulty of getting the first and second harmonics out, particularly the second harmonic?

ALLEN: Yes, the measured harmonic content is given in Table 4, where the field at the center is 11 kilogauss. The field is represented by the expansion

$$B = \frac{\alpha_o}{2} + \sum_{n=1}^{\infty} (\alpha_n \cos n\theta + \beta_n \sin n\theta).$$

The maximum amplitude of the nth harmonic is $\varepsilon_n = \sqrt{\alpha_n^2 + \beta_n^2}$.

Table 4. Harmonic Content in Illinois Machine.

n	ε_n (gauss) No. poleface coils	ε_n (gauss) Coil No. 1 250 amp.
1	2.0	2.0
2	2.0	2.0
3	6.0	3.0
4	1.2×10^3	1.2×10^3
5	6.0	2.0
6	2.0	2.0
7	2.0	2.0
8	1.3×10^3	1.3×10^3
9	2.0	2.0
10	2.0	2.0
11	2.0	2.0
12	20.0	20.0

The error in the measurements is ±2.0 gauss and the entries in the table represent upper limits of the measured harmonics.

LIVINGOOD: Are there any difficulties in the leads that go into the central coil? Do you find any significant measurable field to your leads?

ALLEN: We worried about this quite a bit. We scanned back and forth over the leads to the coils, and we feared that we might see some definite pattern in our harmonics. The data for the harmonics were collected by measurements at a given radius 15° apart. From these data we extracted the harmonic content and other bits of information. Consequently, this should have shown a definite bump, let us say, along the line going from the innermost coil which is the most serious. We found no indication whatsoever of a contribution. That is, when we made measurements with this central coil on and with it off there was no difference in the field within a couple of gauss.

JUNGERMAN: Did you mention the average gap?

ALLEN: The median iron-free gap is 6-3/8 inches. The valley-to-valley gap is 7-1/4 inches.

DOLS: Will you describe the shape of the pole tip in the center of the gap, at zero radius?

ALLEN: The spiral shims go in toward the center with an angle of 45° and terminate at a 7-1/4 in. disk. To prevent an increase of the field near the center, the profile of the shim which terminates at the circular part has a step cut in it.

VERSTER: Are these other oscillations of the realized field in comparison with the actual field not serious for axial and radial stability because the K-value differs quite largely?

ALLEN: Yes, the small oscillations or fluctuations of the realized field from the resonance field may prove to be serious for both radial and axial stability. We plan to study the stability of the orbits theoretically and also by actual measurements.

GREEN: If I may make a quick report, the highly regulated low voltage power supply until recently has been extremely difficult, but we have now extensive experience with using transistors for 100 amperes at a few volts with very high-speed response. With a few precautions it is extremely easy. If anyone is interested in the high current transistor recipe, speak to me and I will refer him to our engineers who have licked it. It turns out to be extremely simple.

We simply throw 1,000 amperes directly through the transistors -- they are a rheostat -- and we have response up to kilocycles. The only thing I was afraid of when we started was if someone sneezed in the next room 500 bucks worth of transistors would go up in smoke. It turned out that this little objection is readily overcome with a couple of tricks.

CHAIRMAN KELLY: Perhaps we can have a short discussion of these power supplies at another session, or perhaps in the overflow session. It is more an engineering problem and not directly related to how to get these field shapes.

All references are to technical reports of the Department of Physics, University of Illinois

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(3) Precision Magnetic Flux Density Measurements with Bismuth Wire. J. B. Carroll and J. A. McKee.
(4) Field Harmonics in the Cyclotron Magnet. J. A. McKee.
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(6) Multi-Purpose Magnetic Particle Analyzer. R. L. Burman and A. I. Yavin.
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(8) Orbit Stability Studies for the University of Illinois Spiral Ridge Cyclotron. P. G. Kruger.