MAGNETIC FIELD PROPERTIES OF THE INDIANA ISOCHRONOUS CYCLOTRONS*

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ABSTRACT

Some of the measured properties of magnetic fields for the injector stage and final stage cyclotrons under construction at Indiana University are described. The simply geometry and the operation at moderate field strength lead one to expect a predictable magnetic field. A discussion of observed departures from the predicted properties is presented. Data include selected radial and azimuthal profiles as a function of main field excitation; reproducibility from sector to sector and with hysteresis; properties and requirements of current sheet trim coils; and miscellaneous topics.

INTRODUCTION

Adequate isochronism is a prerequisite for obtaining cyclotron beams of high quality. Separated magnet cyclotrons with radial sectors and uniform gap, of which the two cyclotrons at Indiana University will be the first working examples, offer an unusually clean starting geometry which should lend itself to conceptually simpler and more precise isochronization procedures. The orbit dynamical properties of this class of cyclotron have been discussed elsewhere.[1,2] The present discussion is limited to a description of selected magnetic field properties which illustrate the extent to which the real magnetic field has been found to depart from the simplest starting approximation. The data is a necessary part of the input to the design of radial gradient coils or similar isochronizing schemes. The problem of specifying radial gradient coil currents to give an optimal phase history for various particles and final energies must await a full measurement set using the final magnet geometry supplemented by beam diagnostic input.

METHOD

Measurements have been made over the past two years on the assembled four-sector magnet ring of the injector stage cyclotron; on a fifth sector of this machine set aside for mapping purposes, which also acts as a reasonable model (approximately one-third scale) for the final stage sectors; and over the past three months, on the first assembled sector of the final stage cyclotron.

* supported by the National Science Foundation

Most of the measurements have been obtained with a compensated Hall effect sensor known to be linear, reproducible and stable to better than 0.05%. Two dimensional motion is achieved by lathe beds driven by stepping motors. An integrating digital voltmeter is multiplexed to acquire the outputs of a fixed and a movable Hall probe, as well as shunts which monitor magnet current and Hall current. The operation is controlled and data is processed by a digital computer under a variety of control programs. Results are recorded on magnetic tape for input to orbit dynamical programs.

EDGE PROFILES

An effective field boundary (efb) can be determined by linear scans perpendicular to the long straight side face of the pole tip. Far from the region of end effects, the efb is itself straight and determines the machine center by extrapolation to the point of intersection. For the injector stage the efb is found to be located 0.52 magnet gaps beyond the tip face. For the final stage the efb position is influenced by the iron vacuum chamber which acts as field clamp to harden the edge for stronger vertical focussing. The efb moves outward to 0.60 gaps as parts of the clamp saturate. Figure 1a shows the edge profile for the two stages. The logarithmic scale emphasizes the edge profile variations in the tail region as the final stage magnetic field is increased. Note also the harder edge due to the clamp.

The variation in edge profile in a sequence of field scans parallel to the sector boundary of the final stage is shown in Figure 1b. Successive scans are spaced by one gap (7.6 cm) with the curve labelled zero coinciding with the face of the pole tip. The radial variation experienced by the beam in the region between the limits marked inflection and extraction is relatively modest. The contour labelled "V" is the valley cneter line, half way between adjacent magnets. When the field from two adjacent magnets is measured, the highest valley field will be observed just inside the inflection orbit and will be 2.4% of the hill field. In the injector stage this value is 7.2% due to the closer tip spacing of adjacent magnets which is associated with the higher design energy gain of the smaller cyclotron.

The extra field due to superposition of the effect of the adjacent magnet in the central region is more than compensated by two factors which increase particle orbit periods at small radii. One of these is visible in the figure and is a field reduction due to proximity to the inner end of the pole tip. The second is an indirect effect due to orbit curvature in the valley. The combined effects in the injector stage lead to average fields which are too weak by several percent in the central region and this is compensated by shims to reduce the trim coil currents required for isochronism.

The influence of the outer limit of the pole tip in the valley on orbits near extraction is much less pronounced, affecting the average field by about 0.2%, which is well within the limits of trim coil adjustment.

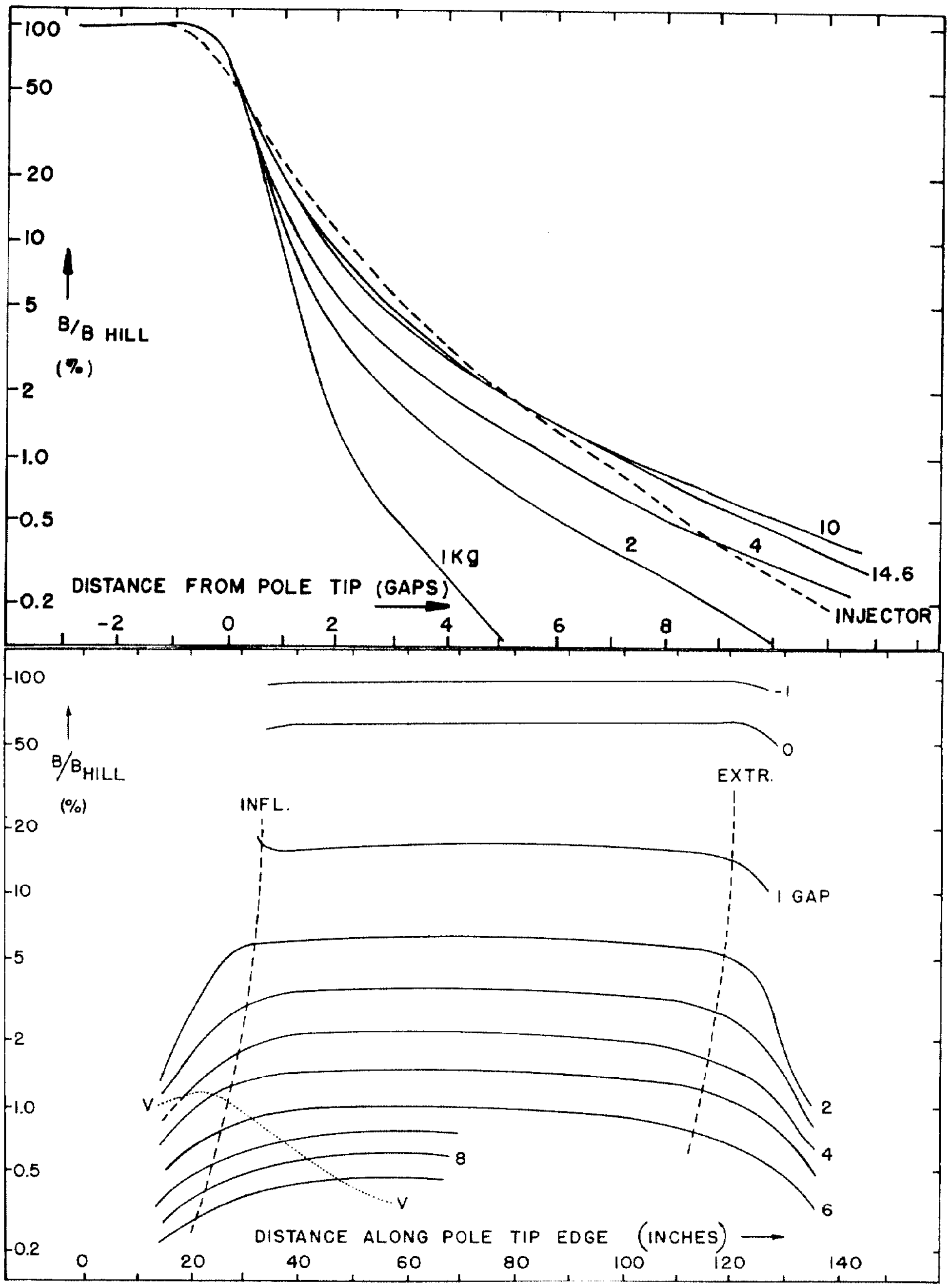

Fig. 1. a. Edge profiles for the injector and for several field values in the final stage. Note logarithmic scale. b. Radial variation in final stage edge profile. See text.

INJECTOR STAGE HILL CENTERLINE PROFILES

To the approximation that the efb is correctly placed as outlined in the previous section and that the field contours within the magnet sector can be shaped to match the orbit curvature, the average field is then correctly determined by a single scan along the sector centerline. The injector stage has remotely operable Hall probes mounted on each sector which are used to verify the setting of radial gradient coils.

The results of several investigations of magnet properties by centerline scans are summarized in Figure 2. Notice the greatly expanded field scale so that small deviations from the nominally flat field are displayed. The end effects are suppressed; pole tip limits lie offscale at 6.6 inches and 42.1 inches. Figure 2a shows the variations among the four sectors in absolute field and field profile. Variations of the order of 0.5% are observed; uncorrected, these variations would result in first and second harmonic errors of amplitude about 20 gauss. Figure 2b shows the observed differential hysteresis of 10 gauss for an extreme case. Any consistent turn-on procedure will reduce the effect to negligible proportions. Figure 2c shows the increasingly convex-upward profile at higher currents. Curves are displaced vertically for clarity. The shape is essentially invarient below 1000 Ampere. The 1800 Ampere case corresponds to the maximum proton energy of 15 MeV from the injector stage, for which the relativistic contribution to isochronism would raise the centerline profile by about 220 gauss; the convex profile for this case affects some of the trim coil currents by comparable amounts. This effect is discussed for the final stage magnet in the next section. Figure 2d shows the field profile change introduced by five current-sheet, single turn trim coils of varying width, excited by a common current of 60 Amperes. Note the break in the curve at each coil boundary, where the linear current density increases abruptly. Coil widths were chosen to give a good fit of the radial derivative to the relativistic requirements as shown in the inset. The largest deviation from the isochronous condition comes from the region inside gradient coil #5 where no coil exists at present. Apart from this region, the observed oscillations about the isochronous condition lead to acceptably small phase excursions.

MAIN STAGE PROPERTIES

At the time of writing, access to one sector of the main stage for mapping purposes has been limited to a few weeks and the prototype radial gradient coil set is still in fabrication. A few of the more important high field properties are summarized in Figures 3 and 4. Figure 3a shows the magnetic field versus main coil current measured up to 1300 Amperes. When four sectors are excited in series, the supply will be power-limited to about 1200 Amperes. With the efb position given in the first section, the measured values give a predicted upper energy limit for heavy ion operation of (220 ± 15) Z^2/A, or about 9 MeV/amu for $Z/A = 1/5$. The derivative of the

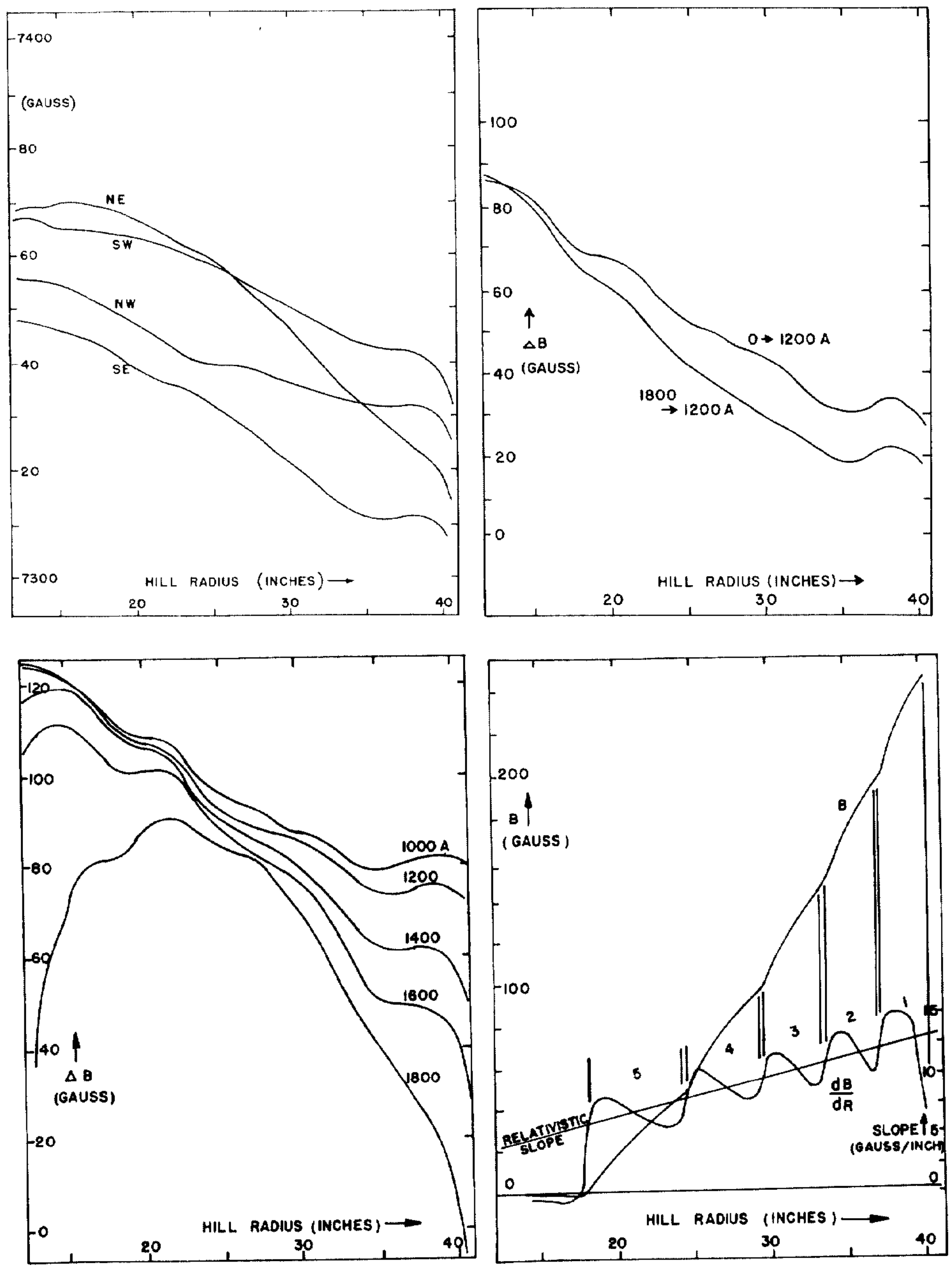

Fig. 2. Injector sector centerline. a. Variation among sectors b. Differential hysteresis. c. Onset of curvature in radial profile. d. Gradient coil field. Inset relates derivative to the relativistic slope.

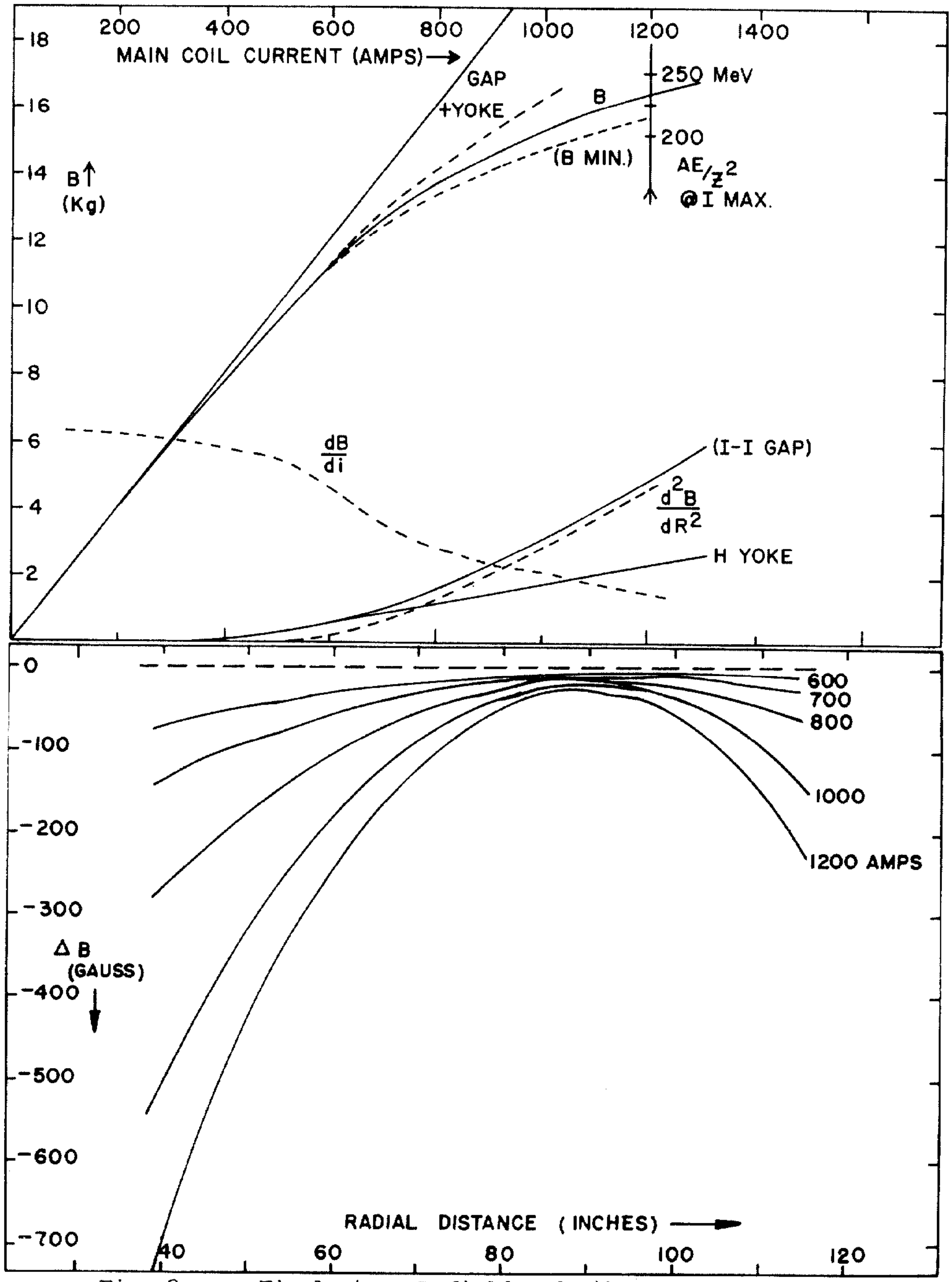

Fig. 3. a. Final stage B field and other parameters versus main coil current. See text. b. Onset of curvature in radial profile. Curves displaced vertically for clarity.

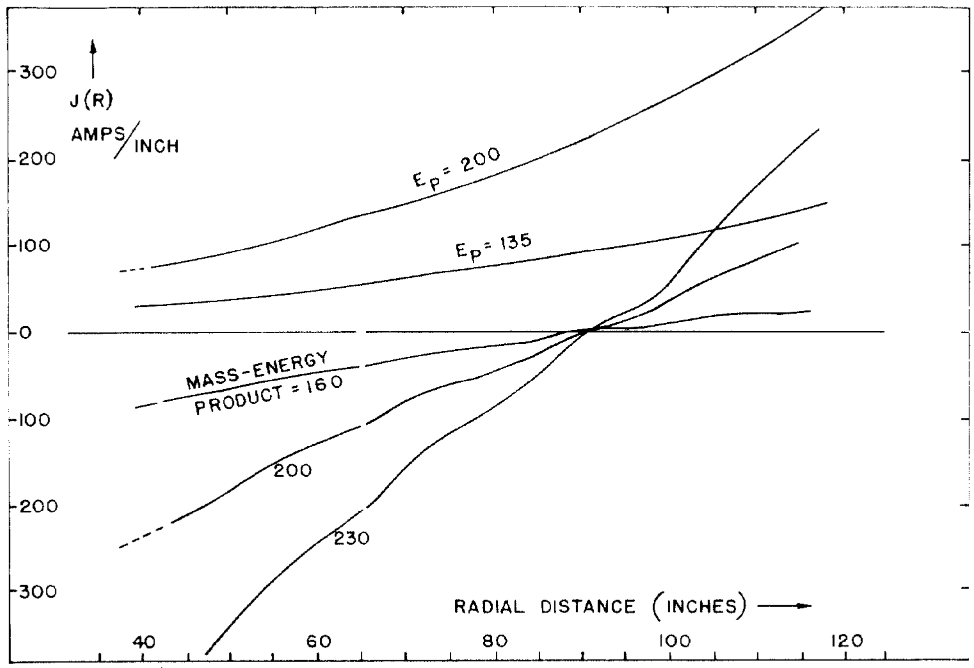

Fig. 4. Final stage. Predicted linear current density in radial gradient coils for relativistic corrections and for flattening of the observed curvature.

excitation curve gives a reasonable estimate for the way in which the trim coil effectiveness will be rediced by the effect of saturation due to the increased reluctance of the return path. The H field of the return yoke was measured as shown, reaching about 30 Oersted at 1300 Amperes. The contributions of the gap and the yoke cannot completely account for the B-i curve because there is an appreciable contribution from pole tip saturation starting at about 600 Amperes. The pole tip field is higher than the gap field by several percent because of the position of the efb. The yoke field is substantially lower due to the large return area.

Figure 3b shows the increasing convex curvature of the radial profile as the pole tip saturation begins. The field is essentially flat at 500 Amperes and below. The data is a good fit to a parabolic shape and the curvature is shown in Figure 3a, increasing almost linearly with current above 600 Amperes. The field near the inflection radius is substantially below the highest point as indicated by the curve labelled Bmin in Figure 3a. The linear current densities predicted from this data are shown in Figure 4 along with the requirements for relativistic isochronization with protons. Measurements will be carried out to determine the radial variations of trim coil effectiveness at several levels of saturation, since different coils return different proportions of their total flux through the yoke. Predictions in Figure 4 are based on equal effectiveness at all coil locations scaling with dB/di and are therefore subject to modification. The data show that coil currents comparable to those required for full energy proton isochronism will be necessary to flatten the convex curvature encountered in the present measurements.

SUMMARY

Some of the measured properties of the magnetic fields of the separated magnet, radial sector, constant gap geometry of the Indiana University Cyclotron Facility have been described. The intent has been to demonstrate the magnitude of some of the more important deviations from the simple invarient geometry. Reproducibility from magnet to magnet and differential hysteresis are found to give measurable effects which are easily corrected. Current-sheet, single turn trim coils give acceptably smooth radial profiles provided their widths are selected to give small enough phase excursions at the discontinuities in current density. At the higher fields, pole tip saturation gives a substantial convex curvature which requires gradient correcations comparable to the relativistic correction for protons. Field clamps on the final stage produce a field with a somewhat harder edge at the expense of a field-dependent position for the effective field boundary. Proximity to the pole tip extremities causes departures from the desired straight, radial sector boundary of a fraction of a percent at large radii but several percent at small radii.

ACKNOWLEDGMENTS

Many of my colleagues at the IUCF contributed a substantial amount of time and effort to help make these measurements possible. Space precludes recognition of all their individual contributions.

REFERENCES

1. M. M. Gordon, Ann. Phys. 50, 571 (1968).

2. B. M. Bardin et al., IEEE Trans. Nuclear Sci. NS-18, 311 (1971).

DISCUSSION

BLOSSER: I want to ask two things. You showed a dB/dr that went jogging up and down and I couldn't see the scale. Could you say how much ν_z variation that makes?

POLLOCK: No, I cannot quote the variation in ν_z. In general, the requirements for isochronism are the most severe and the jogging that I showed you is acceptable. The phase history determines how many coils are required to have an acceptably smooth field. In the case of the injector stage the oscillation is acceptable.

BLOSSER: Acceptable on isochronism but -

POLLOCK: Perhaps someone who has been working on the orbit dynamics would like to speak about the effect on ν_z? It is quite a small effect.

BLOSSER: The other thing I want to ask is I think you said that there were like 10 or 20 G differences between the sectors at the same excitation.

POLLOCK: Yes.

BLOSSER: You would then have differently-excited correcting winding on each sector?

POLLOCK: Yes. Now, again you don't want to get confused by the scale. There was a very large zero offset on that curve. For a 1000A excitation of the magnet you require one or two amps difference between the sectors in order to make them have the same field. That means, in general, a slight current correction in the main coils from one magnet to the next.

BLOSSER: You do that with different power supplies?

POLLOCK: There are two ways to do it. One is to bypass each coil with a small transistor shunt circuit, and the other is to add an additional turn around the magnet and excite that with a few amps.