# FAST HARMONIC FIELD MAPPER*

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The K500 cyclotron field of MSU was mapped by P. Miller et al., in 1978[1-3] using a configuration of 55 flip coils spaced at 1/2 inch radial increments that could traverse the 360 degrees of azimuth and pause at specified azimuths to record the magnetic field. The voltage from the coils was integrated with chopper stabilized op amps and a multiplexer +16 bit ADC read these B values into a computer file for later analysis. These measurements were well done. But then an operator error occured and the position of the coil relative to the magnet was indeterminate.

When beams were circulated it became obvious that there were first and second harmonic components in the field that could not be accounted for, and corrections should be made either by moving the coil within the cryostat, moving the cryostat, or shimming the magnet.

In early 1983 it was decided that we would mount coils on arms separated by 120 degrees and buck them out so that the third harmonic $d\phi/dt$ component would be cancelled and thus we could measure the first and second field harmonics very accurately. The original intention was to do as others had done, namely, use fast ADC's to read the voltages, and computer process the result to get the Fourier components. However, because of the 100 to 1 dynamic range of the fast ADC's and the likelihood that noise would be a problem, we decided to do things differently.

Using a fast Fourier transform analyzer was considered, but this instrument is very expensive, so we decided to use a completely electronic analog approach: we decided to use active bandpass filters to render the harmonic components.

## Overall Scheme

The MSU Cyclotron magnet is a spiral ridged three sector magnet producing a third harmonic flutter field of about 1 Tesla in a 4 Tesla average field. To measure the 1st and 2nd harmonic field components with an accuracy of ±1 gauss and ±2 degrees in phase, 25 coils were mounted on each of six azimuths of a 5/8" thick G10 disk in such a manner that, equivalently, we had three sets of 50 coils at 1/2 inch radial increments, spanning from 2 inches to 26.5 inches. Sets were 120 degrees apart in azimuth.

A 150 twisted pair cable was threaded down the 5/4 inch shaft to a switch box. In this rotating box we had the option of connecting any wires to a 100 position slip ring assembly. The normal connection was to connect pairs of coils at a given radius in such a way that the 3rd harmonic $d\phi/dt$ cancelled. However, we could also connect the coils at a given azimuth directly to the slip ring assy.

Figure 1 shows the arrangement. The disc is rotated at 60 rev/min and the raw signals are fed to a 64 position reed switch multiplexer, thence to three bandpass filters which can be switched to have gains from 1 to $10^4$ in decade increments. Following these are digital phase detectors and sample and hold peak detectors. Finally, the digital signals are multiplexed and ADC's sends everything to the VAX-750 computer for data storage, analysis, and print out on a terminal.

## Coils

We ordered 200 coils wound by a commercial coil winder. These are honeycomb type coils using #38 wire. The coil dimensions were .25 inch ID, .5 inch OD, .5 inch high which is the correct set of values to achieve cancellation of the second order error in a nonuniform field. The coils were each calibrated in a known 1 tesla field by rotating them at precisely 60 RPM. The mean value of NA was .033$m^2$ turns, and it was possible to select 150 of them in sets of three such that within each set the variation in NA was less than 0.1%.

## Speed Control

The filters had a bandwith of .001 Hz and a resultant phase shift of 1 degree/$2\times10^{-5}$ Hz, so precise control of the rev/min was essential. This was accomplished by starting with a 1 PPM stable 10 MHz temperature regulated crystal oscillator. This was scaled down to 5 KHz, and a 5000 pulse per revolution optical encoder permitted an analog phase detector plus servo amplifier plus printed circuit dc motor to phase lock the rotating disc to the oscillator.

## Filters

The filters consist of three cascaded second order active band pass filters, each employing three resistors, two identical condensers and an OP27 op amp having a gain of $3\sqrt{100}$. To get the possible gain of $10^4$ mentioned earlier, an op amp preceded the filters. The rejection ratio of the 3 Hz signal by the 1 Hz filter was 38000 to 1. The settling time was 10 seconds.

Electronics has come a long way since 20 years ago. The condensers were reputed to have a zero temperature coefficient at room temperature and the resistors (made in Isreal) had a 10PPM/°C temperature coefficient. The final result was a temperature coefficient of phase of 4 degrees per degree Kelvin, very satisfactory since we thermally isolated the filters and measured gain and phase error every 5 minutes during a run, and the computer compensated for any errors. The maximum phase compensation needed during a day was 10 degrees, the amplitude compensation was negligible, as only 1% accuracy was needed. The input noise for the 1 Hz filter was .1


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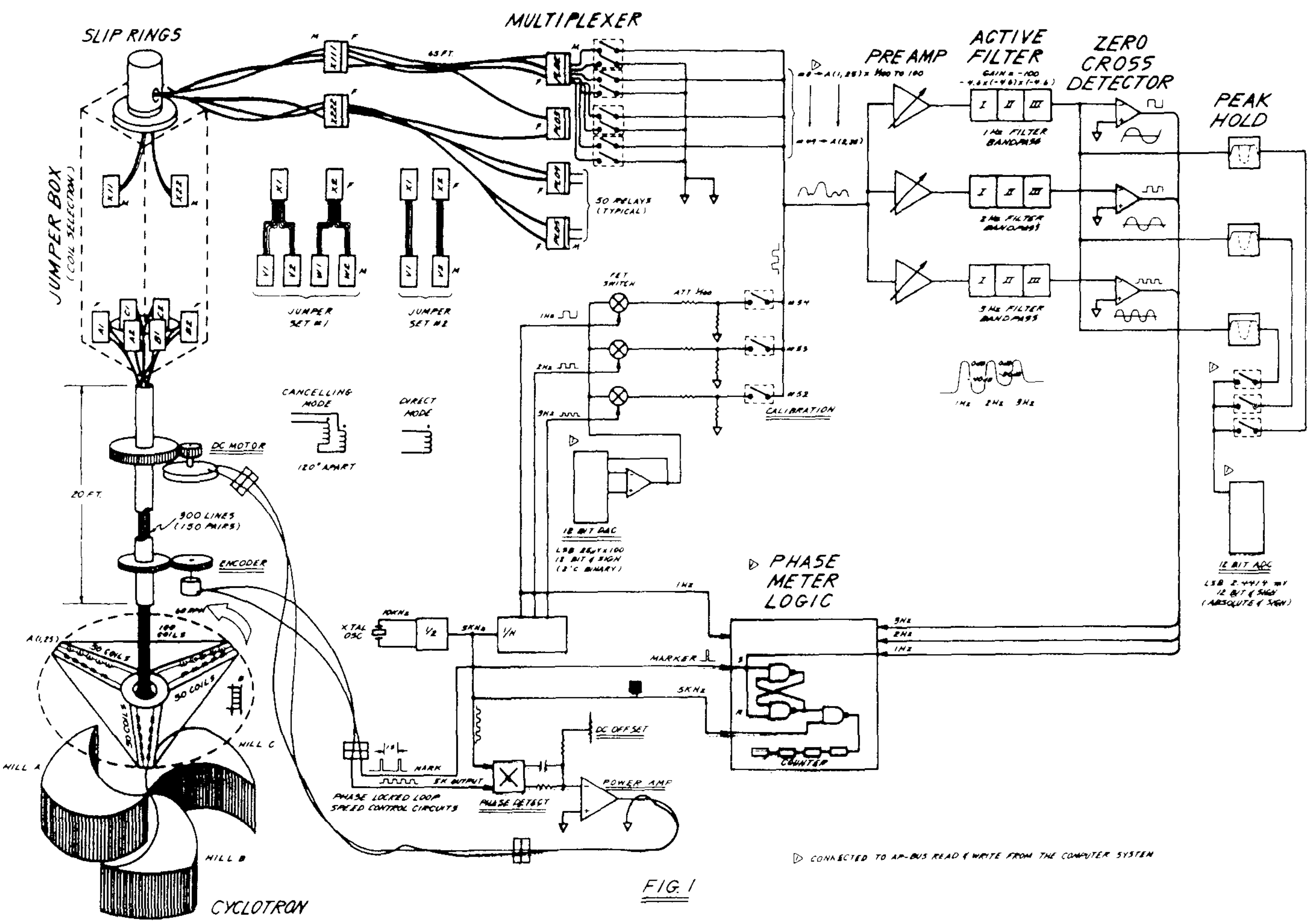
SLIP RINGS
MULTIPLEXER
PREAMP
ACTIVE FILTER
ZERO CROSS DETECTOR
PEAK HOLD
JUMPER BOX
(COIL SELECTION)
50 RELAYS (TYPICAL)
JUMPER SET #1
JUMPER SET #2
CANCELLING MODE
DIRECT MODE
120° APART
DC MOTOR
20 FT.
900 LINES (150 PAIRS)
ENCODER
1 Hz FILTER BANDPASS
2 Hz FILTER BANDPASS
3 Hz FILTER BANDPASS
FET SWITCH
CALIBRATION
12 BIT DAC
12 BIT ADC
PHASE METER LOGIC
MARKER
COUNTER
XTAL OSC
DC OFFSET
POWER AMP
PHASE DETECT
PHASE LOCKED LOOP SPEED CONTROL CIRCUITS
HILL A
HILL B
HILL C
30 COILS
CYCLOTRON
CONNECTED TO AP-BUS READ & WRITE FROM THE COMPUTER SYSTEM

FIG. 1

microvolts, and a 1 gauss 1st harmonic produced 20 microvolts, so the signal to noise ratio was 200 to 1 for a 1 gauss signal.

### Phase Detectors

In addition to the 5000 pulses per second from the optical encoder on the rotating shaft, the encoder produced one pulse per revolution at a reference azimuth. This pulse was used to gate on a counter counting the 5 KHz pulses until the filter outputs went through a positive going zero crossing. The computer read these counts as a measure of phase.

### Peak Detectors

A second set of counters were gated on at these zero crossings and at a preset number of counts later, corresponding to 90 degrees for that harmonic, a MOSFET sample and hold switch was gated on into a condenser for 1 ms to give an analog output of the peak voltage.

### Operation

On instruction from the terminal the computer program controlled the operation. At the beginning of a run, at the middle, and at the end, calibrations for amplitude and phase were made by switching 1, 2, and 3 Hz square waves into the filters and recording and printing out the results. Both for these calibrations, and for the actual coil signals the program read the outputs every three seconds, compared the new values with the previous values and when these amplitude differences were less than 1% and the phase differences less than 2 degrees, the program stepped the multiplexers along to the next set of inputs and outputs.

For the calibrations this could take as much as 50 seconds per step, but for the coils, since there was only a small difference in amplitude and phase between adjacent radii, only 20 seconds was required. Thus the total time for a map was about 20 minutes.

Figure 2 shows an oscilloscope picture of the raw $d\phi/dt$ signal for a coil at 26 inch radius and the $d\phi/dt$ outputs of the three filters. At this time the 3rd harmonic is leaking thru the 2nd harmonic filter. Figure 3 also shows the bucked out signal from a pair of coils at 12 inch radius and the filter outputs. Now all filters have gains of 1000, and the outputs are nice clean sine waves. The first and second harmonics were 2 gauss and 9.6g respectively.

Over 100 maps were made in one week of mapping. Repeatability was good to better than 1 gauss and 2 degrees. The total time to install the equipment, do the mapping and remove the equipment was one week.

### Conclusion

This method of mapping the harmonic fields worked very satisfactorily. Another paper presented at this conference will describe the results obtained from these maps,[4].

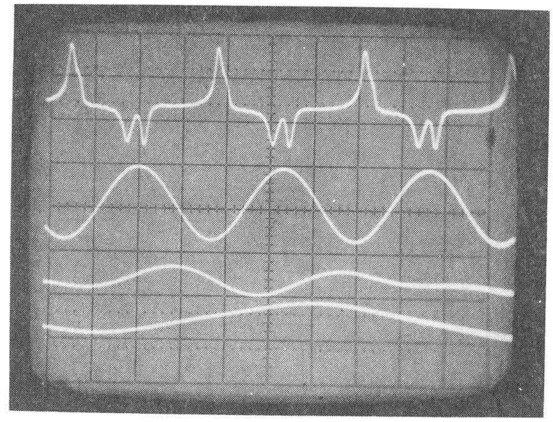

Fig. 2.

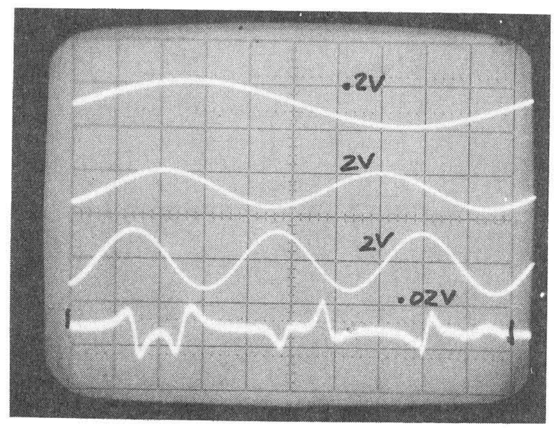


Fig. 3.

### REFERENCES

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