R.F. SYSTEMS*

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Summary

A brief history of rf systems for cyclotrons will be presented, followed by some general remarks about typical problems. Finally, the rf system for the M.S.U. 500 MeV superconducting cyclotron will be described.

Early R.F. Systems

The 37 inch cyclotron which ran just before the 2nd World War was the first machine with a fairly large r.f. structure. Initially the engineering of this r.f. system was done by people with expertise in high power broadcast transmitters, employing the standard methods used to feed antennas. However, it soon became apparent that a high energy storage, high Q dee which frequently sparked did not look like an antenna load, and different methods had to be found to drive it. So, very quickly a nuclear physicist (K. Mackenzie) had to learn how to be a cyclotron r.f. engineer. He reasoned that the dee structure had to be the boss, so he tightly coupled a grounded grid self-excited triode oscillator to it in such a way that the correct drive would exist only for the fundamental mode. This worked well in air, but because a self-excited oscillator can only deliver power proportional to the square of the r.f. plate voltage, this system could not break through the various glow discharge and multipactoring thresholds which exist at a few hundred volts on the dee. This problem was solved by insulating the dee so that it could have a dc bias superimposed on the r.f. Until the day when r.f. systems would again be fed by a driven transmitter nearly all cyclotron r.f. systems employed this biasing technique.

After the success of the 37 inch cyclotron, a 60 inch machine was built at the Crocker (Berkeley) Laboratory employing a geometry as in Fig. 1B. It worked so well that it was used as a model for many cyclotrons that were constructed around the world before 1940, and E.O. Lawrence started building the 184 incher, but the war intervened before it could be completed.

184" Cyclotron

I joined the cyclotron community in 1946 to work on the 184" cyclotron at Berkeley under Dr. MacKenzie and E.O. Lawrence. Things were very confused. To accelerate protons to the 92" radius would require one million volts on the dees, and everyone really knew that would be impossible. Then Ed McMillan and Veksler came up, independently, with the invention of phase focusing. By causing the frequency to decrease during acceleration the ions could be accelerated to arbitrarily large radii with very modest

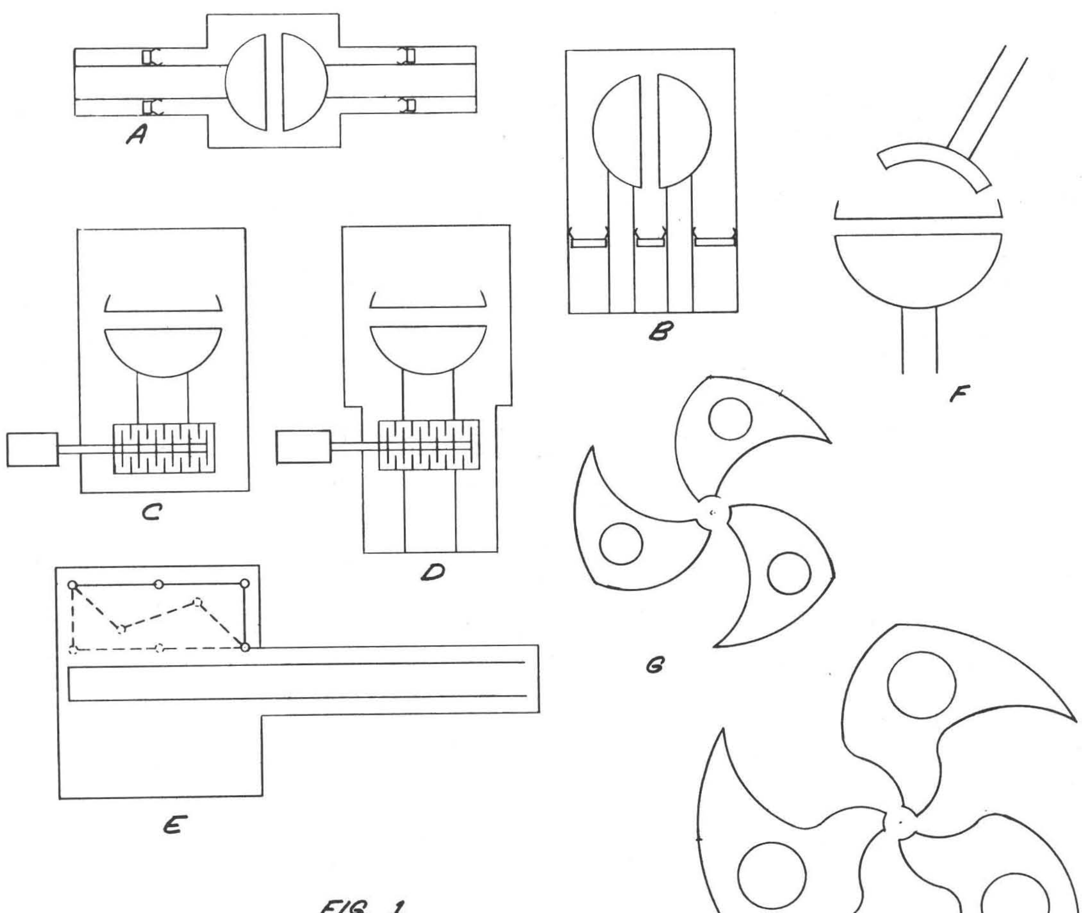

FIG. 1
VARIOUS DEES

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dee voltages. To test this invention the 37" cyclotron was immediately converted to an FM (frequency modulated) machine with a rotating condenser and a self-excited transmitter intimately connected to the dee stems by loops after a design by Mackenzie. It worked (after considerable hassle) and we proceeded forthwith to built the 184" FM cyclotron.

The 37" FM cyclotron was a $\lambda/4$ system capable of a maximum of 2 to 1 frequency modulation, but in practice only about 20%. Ken Mackenzie came up with the brilliant design of a $3/4\lambda$ system for the 184" cyclotron that in theory could achieve a 3 to 1 frequency range and in practice a 2 to 1 range. There were, however, three problems that live with us to this day: possible parasitic oscillations, sparking at the rotating blades or dee to ion source, and excitation of other modes in the r.f. structures that robbed power from the transmitter. Since the transmitter was very strongly coupled to the dee, the harmonics generated by the transmitter could excite these parasitic harmonic modes when the frequencies matched. So all the early FM machines had dips and drastic phase modulation in the dee voltage at the several places where the tube harmonics matched these modes. The most bothersome modes were the $5/4\lambda$ and $7/4\lambda$ modes of the main resonator, the $\lambda/2$ mode due to the width of the dee, and a $\lambda/2$ transverse mode in the variable condenser.

The tubes were triodes. In about 1952, RCA developed the shielded grid triode and a 100 kW model of this was used on the first USA operating isochronous cyclotron, the Berkeley 88 inch. Fortunately, about the time more sophistication was essential, Eimac came out (1961) with the first of their family of high power tetrodes, which made driven systems popular again.

Isochronous Cyclotrons

By 1965 there were a number of isochronous cyclotrons and the MSU 50 MeV cyclotron exemplified the need for considerably more sophistication in the control of the rf system than was necessary with FM cyclotrons. By closing down the energy slits and thus achieving an arbitrarily small phase acceptance angle the energy spread in the external beam could be quite small. However, to utilize this feature, the amplitude of the rf accelerating voltage must be stable and free of noise and ripple. The theorists specifying the requirements for the Princeton machine, whose magnet was a copy of the MSU machine, asked for stability and purity of 1 part in 10^5.

Fortunately, by this time considerable advances had been made in control of rf systems due to the even more demanding requirements of proton synchrotrons. In fast cycling proton accelerators, such as the PPA and the Fermilab booster, any servo loops had to be fast, or, where frequency coherent errors existed, self correctors had to be used. Now to reduce the probable uncorrected 60 Hz rf amplitude ripple of, say 5%, to .001% requires an open loop gain in the amplitude servo of 5000 at 60 Hz. If one employs a well behaved servo, whose gain fall off linearly with frequency, this means that the unity gain frequency for the amplitude servo must be 300 KHz. This is very difficult to achieve because the break frequency of the resonator is somewhere 10 to 50 KHz and thus contributes 6 db. per octave and 90^o phase lag above that frequency, meaning that the operational amplifier and the amplitude detectors must be flat up to about 1 MHz. To my knowledge the best that has been done was at Princeton where the unity gain frequency was 50 KHz and 0.01% purity was achieved.

Tidbits

If there is one thing that experience teaches us it is that, however well conceived the design of the rf system initially is, various problems will manifest themselves when it is required to perform, and modifications to the initial design will have to be made. The best that one can hope for is that the rf system will not self destruct on first turn on! Assuming it can be turned on at all, then one improvises. The first thing one does is to remove some of the cute little "improvements over previous designs" that one had installed, and go back to proven methods. And prayer is probably helpful too: pray that each time one turns on after a modification that some large and expensive component doesn't blow up, burn up, or melt down.

It is ever amazing to me, though, that even with rf systems which have serious flaws in their conception, after toil and trouble, midnight hours, and strenuous efforts, the systems are finally <u>made</u> to work. The ingenuity of man knows no bounds!

On the "Q" of resonators

Q. Kerns of Fermilab informs me that the measured Q of his resonators is consistently 15% to 20% lower than his calculated values. At M.S.U. we have made careful measurements on the Q of a $\lambda/4$ 9 inch OD line at 40 MHz and can report that, using the $\Delta F/F$ and the $\tau = Q/\pi F$ seconds method, and reducing the drive and the measuring coupling to the point where neither were affecting the results, the measured Q agreed to within 1% of the calculated value. Using yet a third method, namely direct measurement of Rs, substantiated this result. Moral: never believe the first measurement of anything.

On Fast Phase Control

The standard rf system usually employs a fine tuner which has a response limited to about 5 Hz. However, mechanical vibrations of the structures driven by reciprocating motors (vacuum pumps) or trucks passing by on an adjacent highway, or by water pressure variations in the cooling system can result in phase modulation of up to 100 Hz. Also, especially at turn on, and if the water temperature is not regulated, the thermally induced expansions and contractions of the structures can, and usually do, result in a dF/dt of the resonator at faster rates than the fine tuner can compensate for. What to do? For typical systems, $\pm 10^o$ phase modulation can result from only 1 PPM frequency modulation. So the solution seems simple: provide for fast servo phase modulation correction of 10 PPM. Now this typical rf system has a circulating energy of about 10^8 VA, so that 10 PPM means that one must provide for only 1 KVA of reactance modulation. Some people have actually installed a separate reactance modulator tube to accomplish this. However, this is never necessary. The transmitter tube itself can do its own reactance modulating by suitably varying the phase of its drive. Thus, for really fine tuning, or as some would say, for precision phase control, a "fast" phase servo involving a fast electronic phase shifter must be included.

In electron storage rings this scheme is absolutely essential to avoid beam blowup problems at the synchrotron frequency. And for systems where water pressure modulations cause phase modulation of $\pm 10^o$, installation of this fast phase servo will completely wipe out the problem. Such fast phase shifters have been used at PPA, Fermilab, SPEAR, and DCI and are included in the design for the MSU 500 MeV superconducting cyclotron, and for GANIL.

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The M.S.U. R.F. System

With the advent of superconducting heavy ion cyclotrons new challenges are presented to the r.f. engineer: very high dee voltages, very high frequencies (up to 90 MHz perhaps), a large frequency range (3 to 1), great precision of voltage and phase regulation (10^{-5} and $.2^{o}$), no median plane access, and, because of the large external magnetic fields, the requirement that the transmitter be remote from the dees. Because of the severe spiralling, the dees hardly look like dees. Fig. 1G shows their shape, the circles showing where top and bottom stems support and tune the three dees. Originally, it had been proposed to excite the dees on the third, sixth, or ninth harmonic of the particle frequencies, so that all dees could be in phase. But this meant a frequency range of 30 to 90 MHz and since a dee was $\lambda/2$ long at 100 MHz there would be a large (3 to 1) radial variation of dee voltage.

A classic paper by MacKenzie and B.H. Smith[1] described their efforts in 1952 to excite the three dees of a model of the first isochronous cyclotron 120^{o} out of phase so that acceleration could ensue on the fundamental. They stated that unless the dee to dee capacities were neutralized (by loops connecting the stems) three phase operation was impossible, and since then no one has tried three phase operation. However, we now not only believe it to be possible, but our design will use this mode as the preferred mode. Thus, with a frequency range of 9 to 32 MHz, and utilizing the harmonic members 1, 2, 3, 4, 5, and 7, sometimes changing the sense of rotation, and for 3 and 9 working in phase, we propose to capture and accelerate almost any ion.

We have built a full scale high Q model to prove that 3ϕ operation with partial independence of control of each dee voltage and phase is feasible and with an ECAP program calculated it as well, with agreeing results. So we proceed with confidence.

Fig. 2 shows in cross section one dee driven by a transmitter. An additional complication for the r.f. engineer is that now he is also the pumper. Cryogenic panels in the lower dees will do the pumping. The dees are supported on 99.5% purity alumina insulators which have a Q of 20,000 and, by extrapolating from FNAL experience, are believed to be capable of supporting the 100 kV r.f. voltage that will exist across them at 9 MHz. The dees will be tuned coarsely by movable finger stock shorts spanning a length of 12 ft. The current flowing through these fingers will be 2400 amps at 32 MHz, resulting in a linear current density of 200 amps per inch, about 3 times what anyone else has successfully achieved. We have made tests to indicate that this is possible, but still keep our fingers crossed.

In any case we never plan to move the fingers while the r.f. is on. Fine tuning of ±.3% (±2 p.f.) will be accomplished by hydraulically driven capacitors.

Each dee will be driven by a tuned transmitter whose output transmission line (75 ohms, 4 inch OD) is loop coupled to the transmitter (1/5 voltage point) in such a manner that, as the transmitter short is moved for tuning, no adjustment of the loop is necessary. The transmitter moving short is a duplicate of the

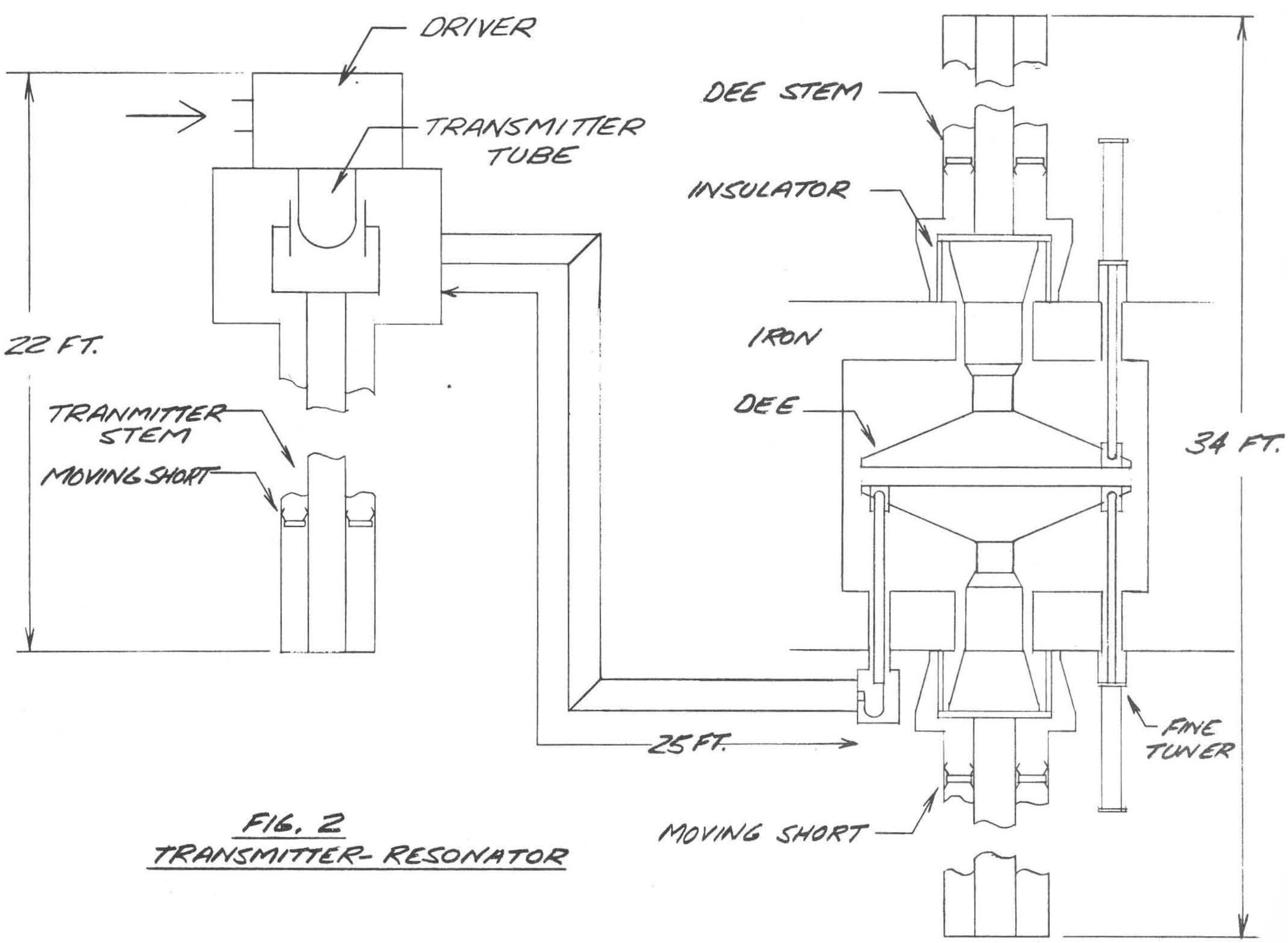

FIG. 2
TRANSMITTER- RESONATOR

stem moving short, except for the finger stock which shorts the loop at the short carriage. The transmission line drives the dee via a coupling capacitor (which must be accurately set to terminate the line, requiring an adjustment range of 1 to 5 p.f.) The criterion for proper adjustment is that there be no reflected power in the line, as measured by a directional coupler. The criterion for tuning the dee by the fine tuner is that the phase difference across the coupling capacitor be 90^{o}. The criterion for tuning the transmitter is that the plate and grid r.f. votages be different by 180^{o}.

The transmitter tube (4CW100000E) is driven by a tuned circuit of proven reliability as used on the Princeton cyclotron (Fig. 3). A phase servo drives the commercially available variable inductor (30 amps) and the 1 kW 50 ohm resistor on the grid reduces the Q to about 10 and discourages parasitics. The grid of the 4CW2000 driver is tuned by a similar servo and in turn is driven by a commercially available 25 watt solid state broad band amplifier. The complication of using this tuned driver is done to save the money required to buy a 1 kW broad band driver for the final (bear in mind, we have three transmitters of 75 kW each). Because of the 180^{o} phase difference between the driver anode and the final grid, a small capacitor from the final anode can neutralize the 1 pf feedback capacity of the final tube by connecting it to the driver anode. This is the main reason for employing this circuit.

Low Level

However well designed the high power part of the r.f. system is, its performance often is determined by how well the detailed and sophisticated low level electronics for control and regulation are done. Fig. 4 shows how we propose to do the low level. We freely borrow the lore of fast cycling proton accelerators in providing F1, F2, F3 (120^{o} phase shifted r.f. sig- $\overline{F1}$, $\overline{F2}$, $\overline{F3}$ (their 90^{o} shifted signals) and F+ and $\overline{F+}$ (single side band, F=2 MHz, signals) for use in phase detectors and otherwise so that when moving from one frequency to another only the synthesizer (here from 135 to 210 MHz) need be adjusted. We employ rather special amplitude detectors and phase detectors which are linear over a 10000/1 amplitude range, thus permitting the various servos to "lock on" for dee voltages of 100 volts, well below multipactoring thresholds.

Turn On and Turn Off Problem

We will now describe a problem which, to my knowledge, has not been previously discussed. With a transmitter strongly coupled to a long transmission line, but loosely coupled to a resonator which has 100 times the circulating energy of the transmitter plus transmission line, we must talk about the transient situation at turn on and at turn off, and what happens when the dee sparks. When the transmission line is a multiple of $\lambda/2$ long everything seems OK except that the middle of the line will rise to a very large voltage at fast turn on and turn off and spark. If the line is an odd multiple of $\lambda/4$ long, the end will spark down, etc. All this is easy to analyze, so we will turn on with a limited rate (still greater than 10^{6} V/sec) and turn off slowly. Also, we must provide spark gaps in the line. Perhaps we will have to install an r.f. crowbar.

In addition, we will have photo-transistors and light pipes looking at possible spark locations (including the moving dee stem fingers) to inform us of when and where sparks occur and, hopefully, to permit us to turn off before various things become molten globs.

For what interest it may be, Fig. 1H shows our DUCK DEE geometry for the proposed 800 MeV superconducting cyclotron for which the 500 MeV machine will be an injector. The main problem foreseen for this system is that the designers now call for 200 KV dee voltage!

References

1. Smith, B.H. and MacKenzie, K.R.: "Three Phase Radiofrequency System for Thomas Cyclotrons". R.S.I. 27 7, 485 July (1956).

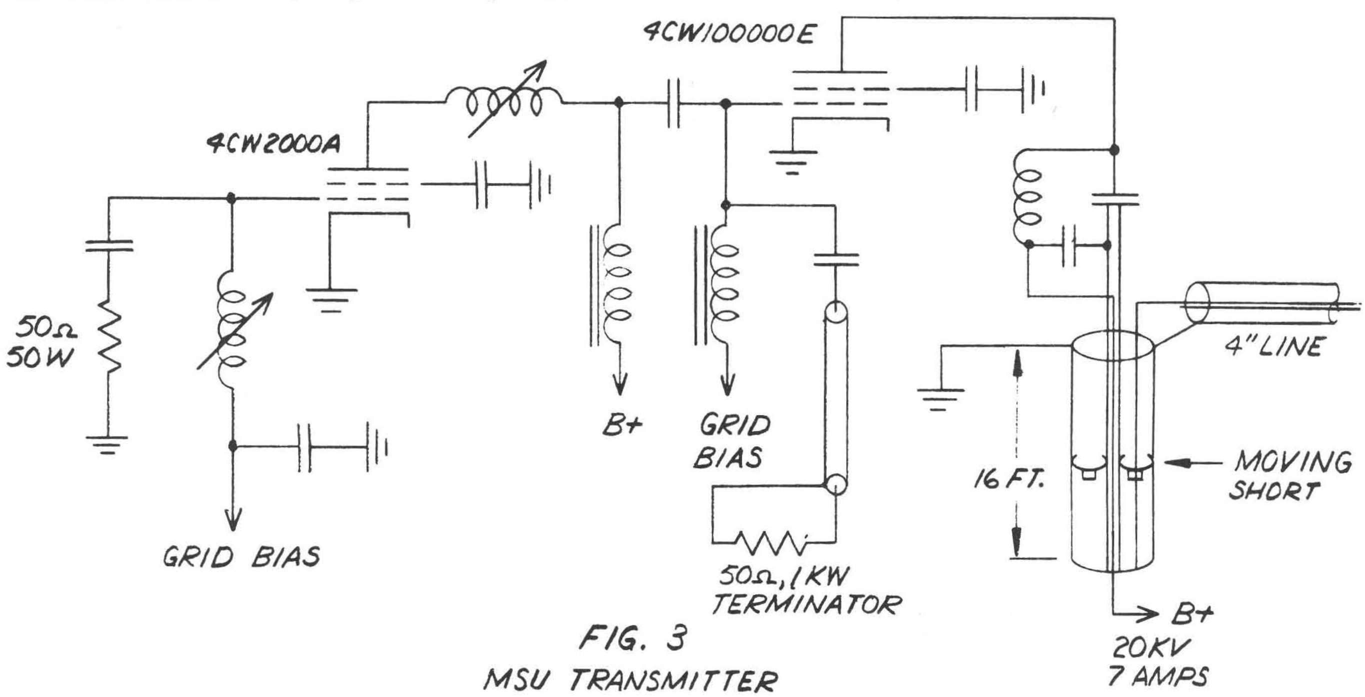

FIG. 3
MSU TRANSMITTER

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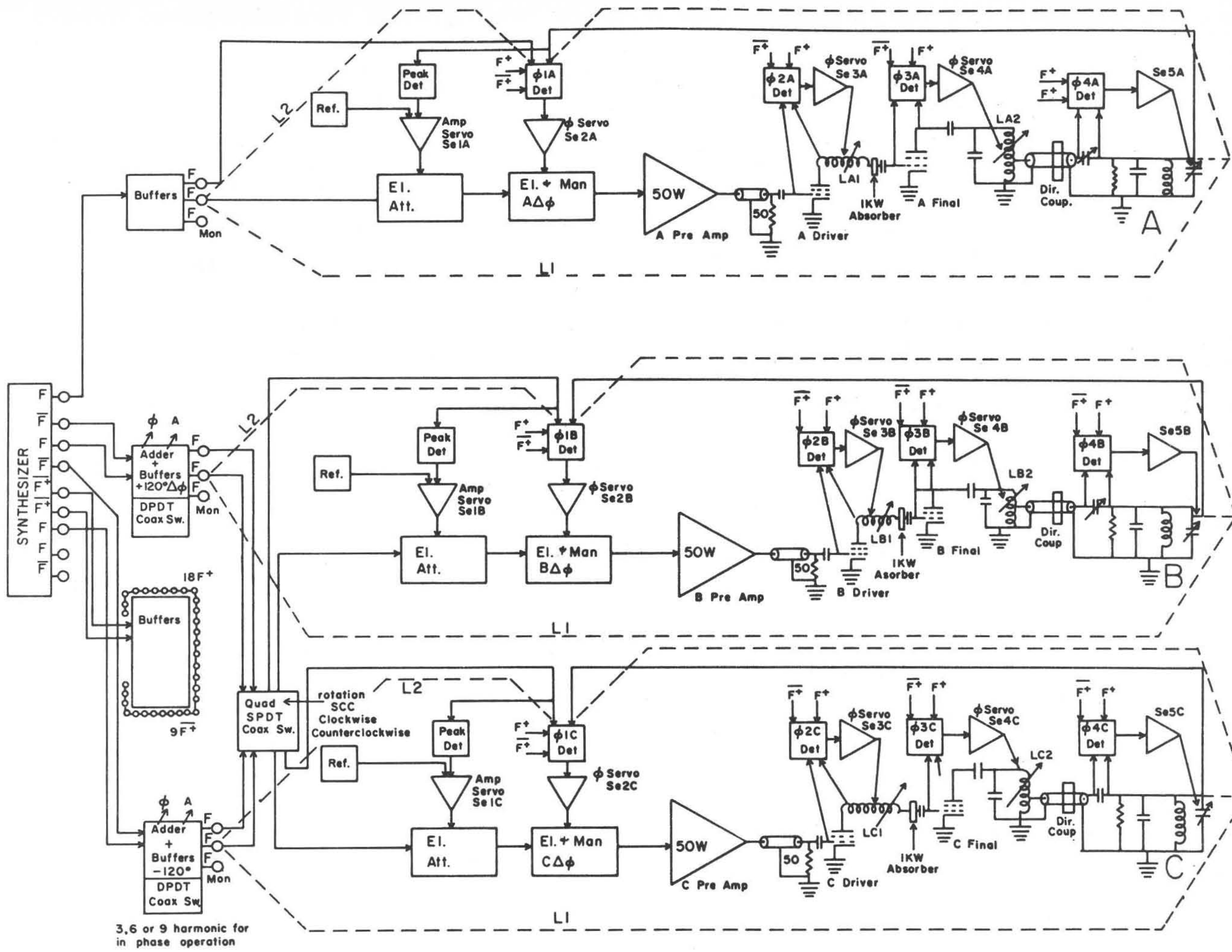

FIG. 4

BLOCK DIAGRAM
MSU SUPERCONDUCTING CYCLOTRON
R.F. SYSTEM JUNE 30,1977