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THE RADIO FREQUENCY SYSTEM FOR THE INDIANA UNIVERSITY ISOCHRONOUS SEPARATED SECTOR CYCLOTRON*

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The Indiana University Cyclotron design includes seven resonators excited at radio frequencies between 25 Mhz and 36 Mhz. Three of these resonators are associated with the chopper, buncher and pulse selector. Two are in the injector accelerator and two in the main accelerator. A common reference frequency drives independent amplifier chains for each resonator. All systems may be adjusted for any phase relationship and power level up to design maximums. Once established phase and power levels are maintained by closed loop control circuits. An auto-tune feature is incorporated in the control circuits to keep resonators at exact resonance and to automatically retune when the operating frequency is changed. Multipactoring break-thru is enhanced by pulsing the amplifier drive and by over-coupling amplifiers to the resonators until normal field is attained. A block diagram of the system is shown in Figure 1.

FREQUENCY REFERENCE

The frequency reference for the system is a General Radio Frequency synthesizer Model 1165. This unit has a stability of 5×10^{-11} for 1 second averaging and is adjustable in 100 Hz intervals. Frequency adjustments can be made remotely and are normally made from the operating console. All resonant circuits in the seven amplifier chain automatically retune and track reference frequency changes.

The synthesizer is followed by a leveled distribution amplifier. This item is a broad band solid state amplifier with output power sensors and a double balanced diode mixer as a current controlled drive attenuator. The amplifier itself has a gain of 46 Db and maximum power output of 10 watts. The feedback loop

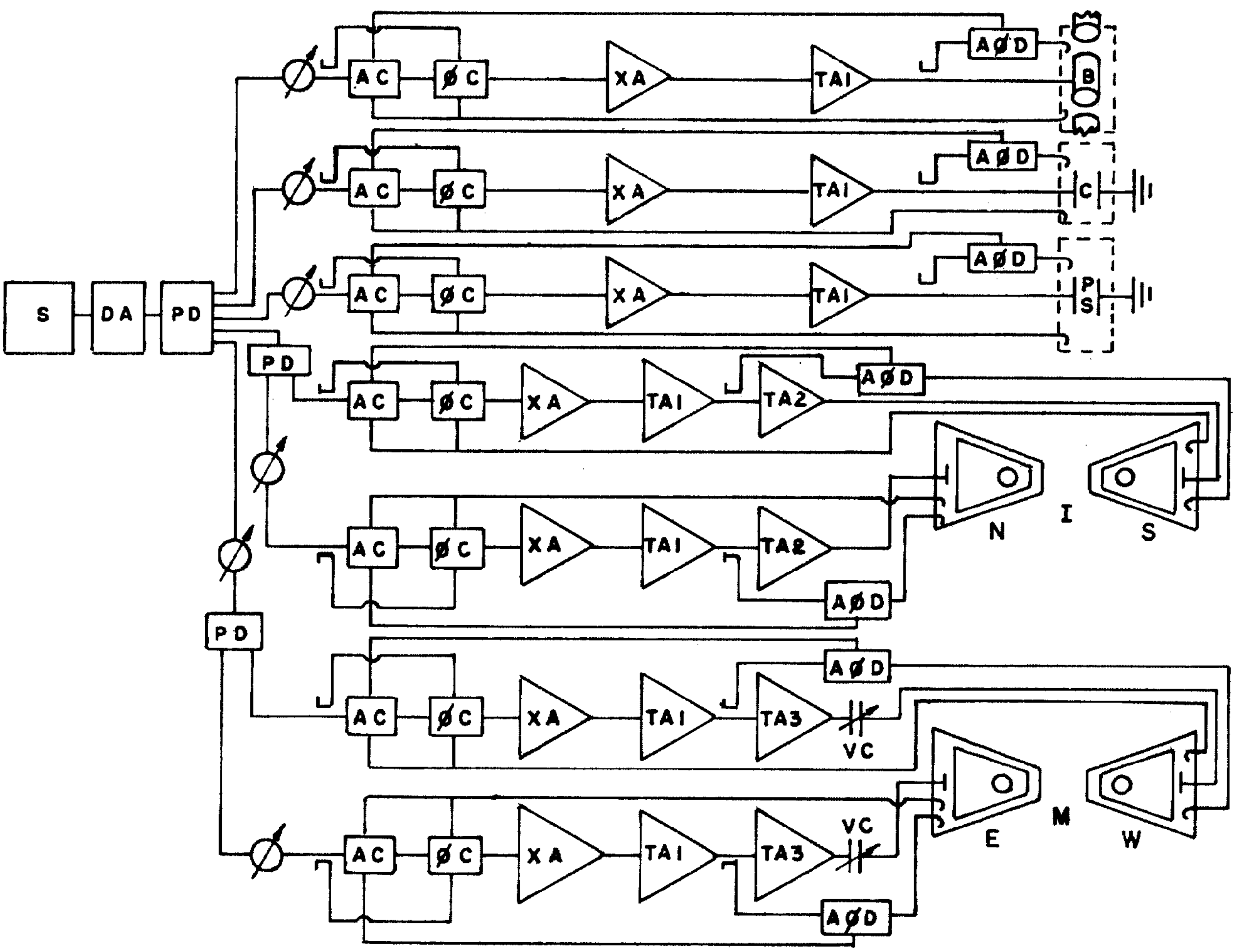

Figure 1

- S Frequency Synthesizer
- Ø 400 degree mechanical phase shifter
- DA Distribution Amplifier
- AC Amplitude controller, pulser and Auto-tune
- AØD Auto-tune Phase Detector
- ØC Phase controller
- PD Power Divider
- XA Transistor Power Amplifier
- TA1 Intermediate Power Tube amplifier, 4CW800
- TA2 High Power Tube Amplifier, 4CW25,000
- TA3 High Power Tube Amplifier, 4CW100,000E
- PS Pulse Selector
- B Buncher
- C Chopper
- I Injector Cyclotron
- M Main Cyclotron

is adjusted for 20 Db of control. The output is adjusted for 5 watts which is then divided eight ways in a ferrite power divider, thus providing eight relatively independent, amplitude controlled, phase coherent signals as drive power or timing references to different parts of the accelerator.

AMPLIFIER SYSTEM: GENERAL

Insofar as possible the several items making up the seven amplifier chains were made identical. As indicated in Figure 1, the three amplifiers chains for the buncher, chopper and selector are identical except that the amplifier for the selector has a lower low frequency cut-off. These three amplifiers are designed for a maximum power output of 1 KW. The injector cyclotron amplifier chain has one additional stage to boost the maximum power to 25 KW. In the Main accelerator the added final has a maximum power output capability of about 200 KW. Maximum drive power for the 200 KW amplifier is about 1 KW and that for the 25 KW amplifier is 500 watts which makes it reasonable to use the same amplifier as the final stage for the three low power devices and as the driver for the high power finals for the two cyclotrons.

Identical phase and amplitude controllers are used with all seven systems.

PHASE SHIFTERS

The first item of equipment after the distribution amplifier in each amplifier chain is a mechanical phase shifter. Since it is necessary to be able to adjust any of the seven resonators to any phase angle, these phase shifters were designed for a minimum of 400 degrees phase shift at all frequencies. Basically, variable delay line technique was employed in the design. Schematically, the circuit used is as shown in Fig. 2.

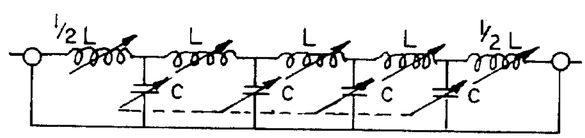

Figure 2.

A phase shifter of this type must satisfy the following equations:

$$\text{Delay} = \tau = \sqrt{LC} \qquad (1)$$

$$\text{Impedance} = Z_0 = \sqrt{L/C} \qquad (2)$$

$$\text{Cutoff Frequency} = f_c = I/\pi\sqrt{LC} \qquad (3)$$

In the circuit of Figure 2 both the inductances and capacities are shown as variable. The four capacitors are sections of a 4 gang rotating variable capacitor with a capacity range of 260 Pfd and this is the variable element. The inductances also are shown as variables andare made adjustable so that the device can be tuned for uniform loss and linearity. The frequencies involved in this application are high enough that stray capacity and inductance, especially lead inductance, become significant factors, and hence the design formulas do not give the practical unit values. For this reason it was necessary to make the inductances variable. A uniform loss over the useable phase range is highly desireable in this application and it was found that the loss factor could be substantially linearized by proper adjustment of inductances.

Performance of a typical unit is shown in Figure 3 for two frequencies near the extremes of the frequency range. Both phase shift and loss are shown as a function of capacitor rotation. The useable part of the phase shift curve is determined by the loss curve. Only that part of the phase shift excursion that introduced less than 1 Db variation in loss is utilized, but at all frequencies this leaves at least 400 degrees of phase control. Long time stability (over 4 hours) and resettability of these phase shifters is about 1/4 degree

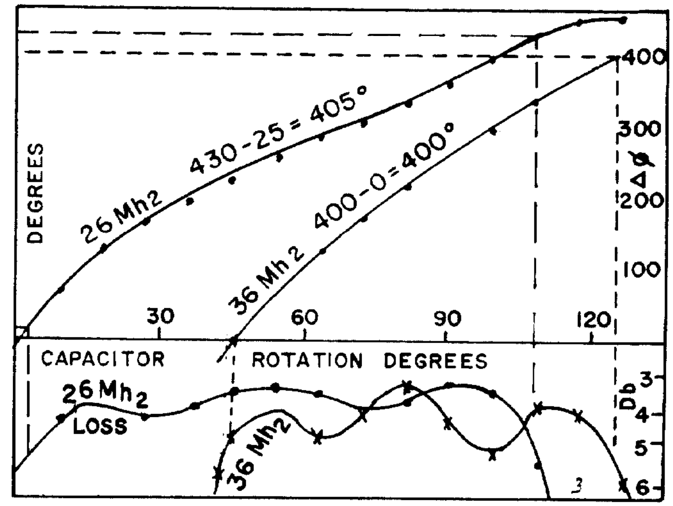

Figure 3

AMPLITUDE CONTROLLER

The next item in each amplifier chain is the amplitude controller. Besides maintaining constant cavity field, this controller also pulses the drive to the following amplifier and automatically keeps the cavities tuned to exact resonance.

Amplitude control is accomplished by varying the attenuation of the drive signal with a double balanced diode mixer used as a current controlled attenuator. The attenuator is driven by a rectified and amplified sample of cavity field.

The pulser is a square wave generator which interrupts the current to the drive attenuators at a 20 Hz rate. With this device the rise time of the drive signal is of the order of nanoseconds resulting in a correspondingly fast rise in application of power to the resonators which is necessary to break through multipactoring. When normal cavity field is attained a feedback loop locks out the pulser and the amplitude controller takes over.

The auto-tuner compares the phase of cavity field with the grid voltage of the final amplifier tube, or to the transmission line voltage through a directional coupler in the case of the buncher, chopper and pulse selector. The phase detector output is amplified and controlls the drive to stepping motors which actuate the tuning mechanisms in the resonators. A three degree phase change due to miss-tuning will actuate the tuning mechanism. A three degree phase change is accompanied by negligible amplitude change. The auto tuner is inactive until normal cavity field is attained. Then it is activated by a feedback loop. A block diagram of the system is shown in Figure 4.

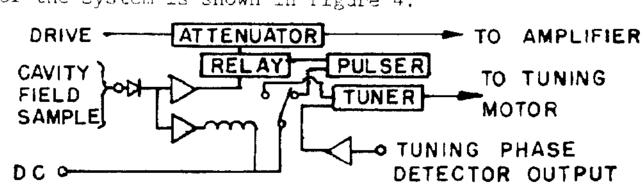

Figure 4

PHASE CONTROLLER

Some random fast phase errors are introduced into the system by cavity tuning, amplifier gain changes due to power supply ripple and thermal effects, mechanical vibration of resonators and by the amplitude controller. To compensate for these errors a phase controller is included in the system after the amplitude controller. This device compares the cavity field phase with the drive reference. The point of reference is at the output of the mechanical phase shifters. This point is stable and phase coherent with other parts of the system between this point and the reference signal source.

The active element in the phase controller is an electronic phase shifter which applies a phase correction to the drive signal proportional to the phase error between the drive reference and cavity field as indicated by the amplified output of a double balanced diode bridge phase detector.

The electronic phase shifter is similar to the mechanical phase shifter in that it is based on delay line techniques but the variable elements are varactor diodes instead of rotating variable capacitors. These are designed for 100 degrees of phase range with a maximum of 10 volts bias. Figure 5 shows a schematic and the loss and phase change of a typical unit.

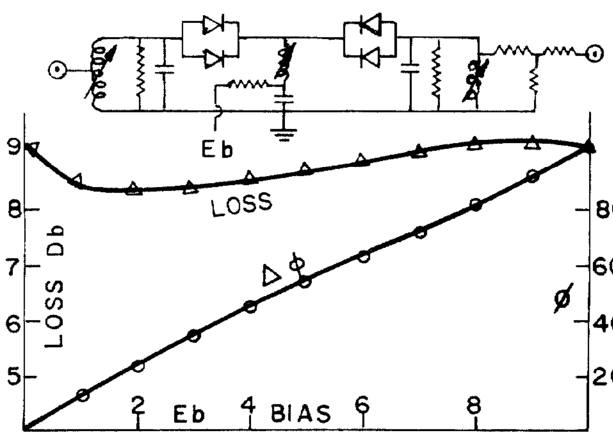

Figure 5

AMPLIFIERS

The first stage of RF amplification is a commercial solid state amplifier with a bandpass of 20 to 38 Mhz. This was a modification of a stock model with the bandpass tailored to this application. The amplifier has a gain of 46 Db and a maximum power output of 30 watts.

The second stage is an IU designed balanced amplifier using two water cooled 4CW800 tubes. Both input and output employ broadband ferrite transformers and compensating bandpass networks to match tube impedances to 50 ohm lines. These amplifiers are designed for a bandpass of 25 to 36 Mhz with an average gain of 20 Db and a power output of 1 KW at any frequency. Bandpass characteristics roll off sharply above and below design frequencies to minimize spurious and harmonic response. A schematic and typical gain curve are shown in Figure 6. This amplifier is used as the driver for the high power finals which excite the accelerator resonators and as the final power stage for the buncher, chopper and pulse selector.

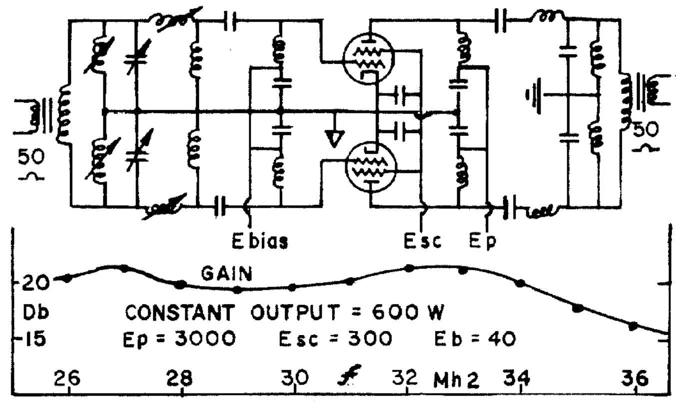

Figure 6

The high power finals for the four accelerator resonators are essentially identical except for the type of tube and their power ratings. These are all single ended amplifiers with a broad band input circuit driven from a 50 ohm line and their output is coupled directly to the resonators. The amplifier assembly is actually mounted on the vacuum chamber housing the resonators. The coupling to resonators is capacitive using two capacitors in series, one is a fixed capacitor inside the vacuum chamber and the other is a variable mounted in the amplifier cabinet. Normal operation is with the variable capacitor at minimum and for this condition the fixed capacitor is adjusted to match the very high impedance of the resonator to the tube. During turn-on when multipactoring occurs the resonator impedance is drastically reduced and increased coupling is required to enhance breakthru. This is accomplished by increasing the variable capacitor. This capacitor is two 8 inch discs which with air dielectric have a capacity of 12 pfd. By insertion of alumina between these discs their capacitance can be increased to about 70 pfd thus increasing the coupling capacitance to the resonator by 50%. In this device the alumina is manipulated with a hydralic actuator. A schematic of the final amplifier is shown in Fig. 7 below.

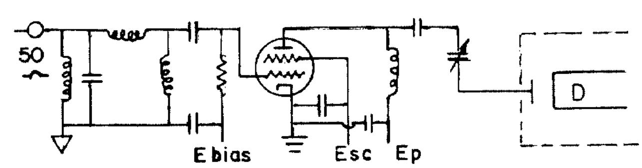

Figure 7

RESONATORS

Low Power Resonators. The chopper and buncher resonators are inductively loaded coaxial cavities tuned with a capacitor at the grounded end of the center conductor. The pulse selector, which covers twice the frequency range of the other systems, will be a long coaxial cavity tuned with a sliding short.

Injector Cyclotron Resonator. The injector cyclotron has a D structure supported on two coaxial stubs extending above and below the accelerator vacuum chamber. The cavity is tuned by moveable plates at the wide end of the D. These plates are actuated by ball screws and stepping motors.

Main Machine Resonator. The main cyclotron resonator is similar to that of the small machine in that it is a resonant cavity, however, the structure is large enough to be self resonant without the coaxial stubs. In this machine the resonator is constructed of 1/8" OHFC copper and is supported in an aluminum frame. All seams are GTA welded using Anaconda 372 copper filler rod. Water cooling tubes are brazed to the non-RF surfaces of the D,D stem, tuner and resonator walls with Handy & Harmon 720BT brazing alloy. The complete RF assembly is inserted into the vacuum chamber, thus it is not subject to the stress of vacuum, and it can be tested and all adjustments of sampling loops and input coupling can be made in air at reduced power.

The main resonator is tuned with two panels mounted and actuated as in the small machine. The mechanical supports are arranged as a parallelogram so that the panels remain parallel to the D as their position is moved. Current to the moveable panels is conducted thru a double hinge arrangement with a very high deflection. The hinge itself is double layered with 0.015 beryllium copper providing mechanical strength. This is paralleled on the RF side with 5 mil OHFC copper to carry the current which may reach as much as 100 amperes per inch. Stress in the hinge material was calculated by considering the hinge as a cantilever having very high deflection. For this condition elementary theory cannot apply and a correction is made by comparing deflected length to $P\ell^2/EI$. (Ref 1). The hinge design is shown in Figure 8.

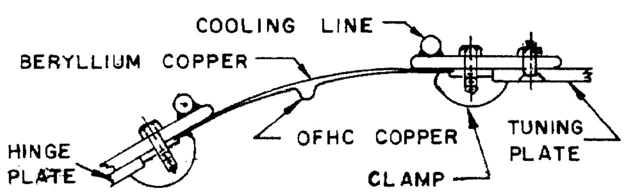

Figure 8

A full scale model of plywood lined with 5 mil copper was used initially to determine the size of the D stem (inductance) and tuning panels, (variable capacitance) and to determine tuning range, shunt impedance and "Q". Also, the D stem position was adjusted to get the desired voltage distribution along the accelerating gap. In this machine the gap voltage varies by a ratio of 4.1.

The finished main machine resonator was tested in air to determine tuning range, shunt impedance and "Q" under actual operating conditions with the power amplifier in place and coupled into the cavity. In one test the cavity was actually driven to a gap voltage of 20,000 volts with the final amplifier lightly coupled. Cavity "Q" was measured by varying the frequency to the half power points and calculating "Q" from the $f_0/\Delta f$ relationship. Tuning panel capacity for various frequencies was calculated and from this total effective capacity was determined. With this data, shunt impedance, R_S, was calculated from the relationship.

$$R_S = Q/\omega C$$

Results of these measurements are shown in Figure 9.

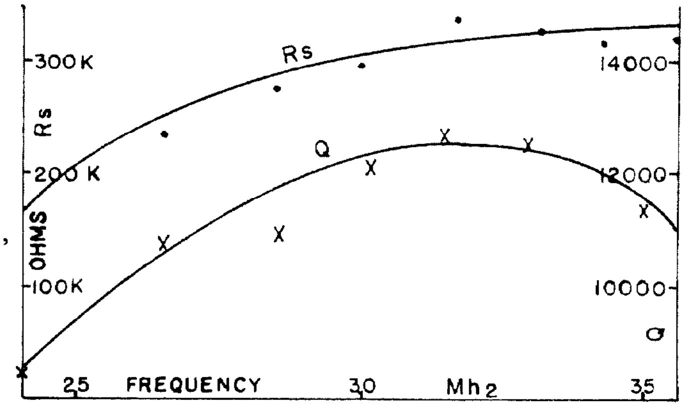

Figure 9

As a check on the above measurements, actual gap voltages for a fixed amount of power input were measured and shunt impedance calculated from power-voltage relationships. For this measurement a new value for "Q" was determined to take into account the loading effect of the power input loop. Measurements were made with several values of coupling and frequencies. Results of the two methods of measurement were in reasonable agreement, the average descrepancy being 14%.

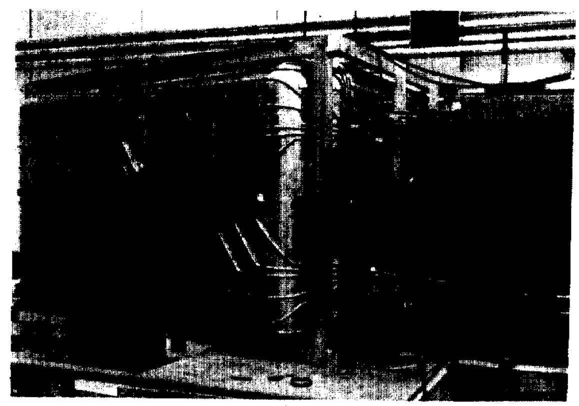

Photo 1
Main Accelerator Resonator with Final Amplifier Set Up for Preliminary Tests in Air.

Photo 2
Interior of Main Accelerator Resonator Showing Tuning Panel, Input Capacitor and "D" Structure

REFERENCES

1. "Mechanical Springs", Wahl, Chapt. 14.

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