FREQUENCY STABILIZATION OF THE TEXAS A&M CYCLOTRON BY INJECTION LOCKING*

R. C. Rogers, J. S. Chenoweth, and J. M. Cox
Texas A&M University, College Station, Texas

A technique for frequency stabilizing the R. F. oscillator of a cyclotron without the expense, complexity or power requirements of a fully driven system is described.

The system employs a low power (approximately one kilowatt) amplifier driven by a reference frequency signal. The output of the amplifier is coupled to the grid of the power oscillator. This injected signal in conjunction with the servo driven trimming capacitor reduces the average time jitter of the oscillator to less than 100 picoseconds.

No significant modification to the power oscillator circuit or in its operation is required. The total components cost for the system is less than three thousand dollars.

INTRODUCTION

The radio frequency power for the Texas A&M Cyclotron is provided by a panel tuned oscillator utilizing an RCA 6949 power triode. The resonator is shown in Figure 1. The original system used a servo driven trimming capacitor for fine tuning and frequency regulation. Frequency error was determined by a counter with a 0.1 second time base and a digital comparator circuit which provided a correction signal to the trim capacitor.

Using this system a short term frequency stability of from 20 to 400 Hz, depending on the frequency of operation, was obtainable. In a program to improve beam quality it was necessary to improve these stability figures.

The most obvious solution appeared to be conversion of the oscillator to a driven system. Because of the considerable amount of hardware that would need to be fabricated, the amount of driving power required, neutralization problems, and the known frequency drift rate of the tank circuit at high power levels this solution was considered unusable unless no other technique could be found. A further consideration was that the amount of beam time lost during the conversion to any system would have to be minimized.

These points led to the decision to try to synchronize the oscillator by injecting a small amplitude signal of high stability into the grid of the oscillator tube.

*This work was partially supported by the Atomic Energy Commission (Contract No. AT-(40-1)-3398) and a grant from the National Science Foundation.

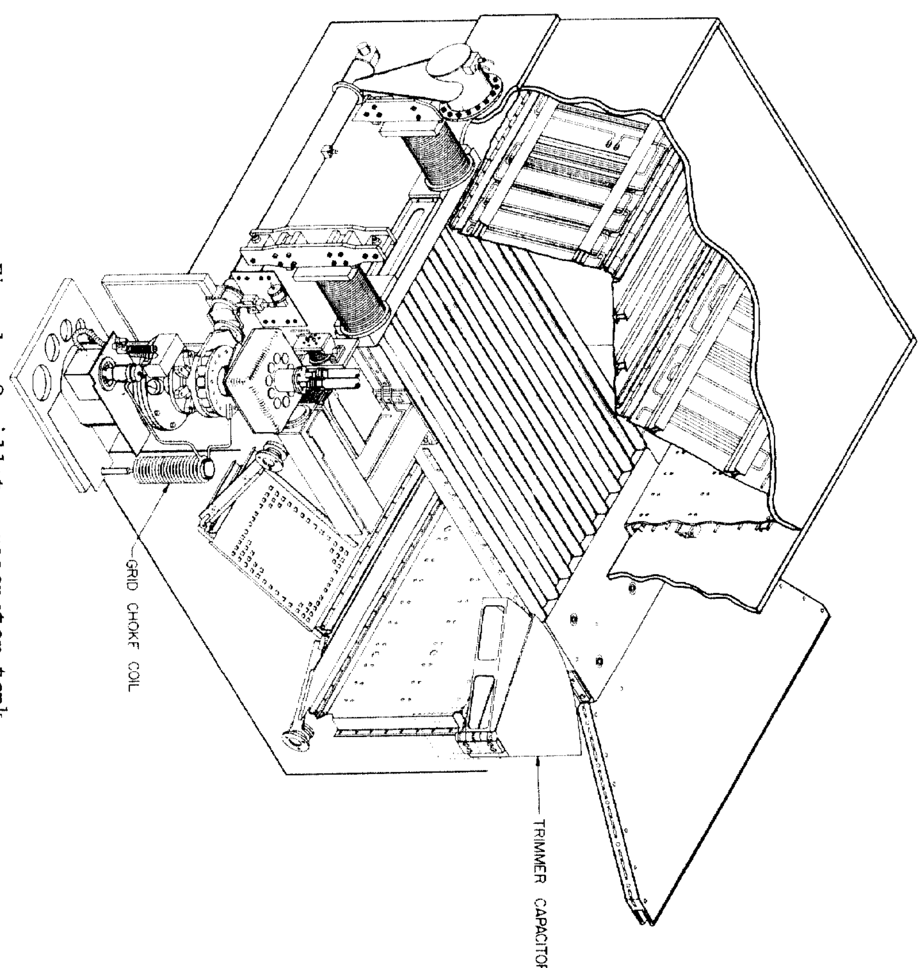

Fig. 1. Oscillator resonator tank

SYNCHRONIZATION

The tendency of coupled oscillators employing nonlinear active elements, and having similar frequencies, to operate in synchronism was first described in detail by Van der Pol[1] in 1934. A further discussion of synchronization and signal level requirements for grid injection was published by Adler[2] in 1946.

The amplitude of injected grid signal required for synchronization is dependent upon the Q of the oscillator tank circuit, the frequency of operation, the grid signal normally developed by the oscillator and the amount of frequency error. The relationship as published by Adler is

$$E_s = \frac{2QE_g \Delta\omega_{max}}{\omega_o} \quad (1)$$

where
- Q = oscillator tank circuit Q
- E_g = normal oscillator grid voltage
- ω_o = operating frequency
- $\Delta\omega_{max}$ = maximum frequency error
- E_s = injected signal amplitude

Measurement of the normal oscillator operating conditions resulted in values for E_s of approximately 50 volts peak at 16.5 MHz and 150 volts peak at 5.5 MHz. The decrease in required voltage with increasing frequency is the result of decreasing Q and decreasing grid signal.

CONSTRUCTION

The values of injected voltage derived above seem to indicate that synchronization of the oscillator will be relatively simple. However, a few other factors will now become apparent.

If synchronization is achieved, the technique of counting the frequency will no longer suffice as a method for deriving the error signal for the trim capacitor. Therefore a new regulating system as shown in Figure 2 was installed. This regulating system uses an integrated circuit phase-frequency detector which compares the radio frequency signal from the cyclotron to a stable reference source on a phase lead or lag basis. This detector then, through some additional circuitry, provides the error

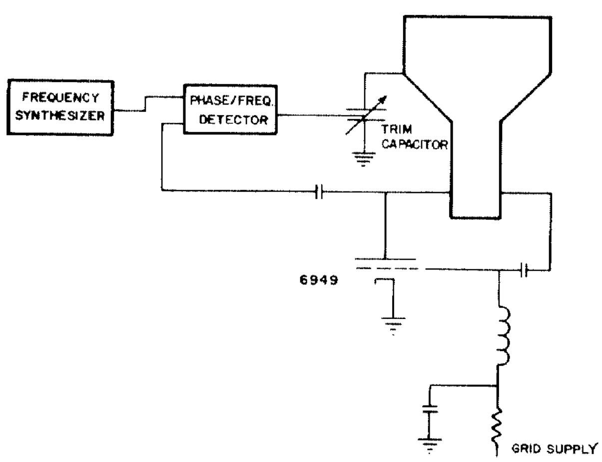

Fig. 2. Regulator circuit block diagram

signal to the trim capacitor regardless of whether the system is in either a regulated or synchronized mode of operation.

Since the tank circuit begins to cool immediately and hence drift in frequency if the machine sparks off, some method of determining when the synchronizer should be turned on must be provided.

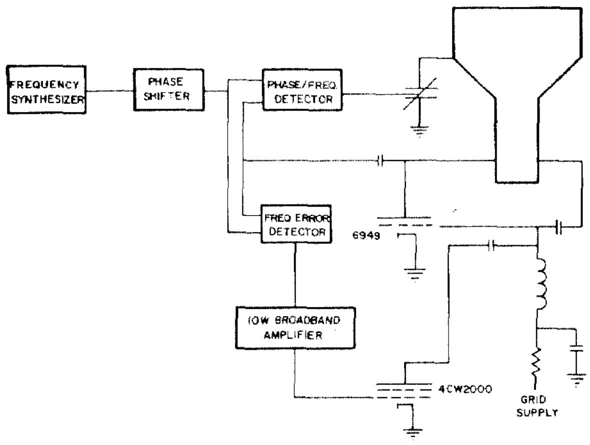

Fig. 3
Synchronizer circuit block diagram

Figure 3 shows the complete regulator and synchronizer block diagram. The frequency error detector[3] shown determines when the cyclotron frequency is within ±80 Hz of the reference and automatically switches the drive signal to the synchronizer amplifiers.

Under conditions of synchronization the phase detector should ideally measure the phase shift between the grid and anode signals of the power tube and adjust the trim capacitor for a nominal 180° shift. To do this would require that the input to the phase detector be switched from the reference source to a grid signal. This switching is avoided by the phase shift network which provides a change in the reference phase such that it duplicates the phase of the grid signal. In practice the phase shift is simply adjusted for the best locking action.

The most serious problem to be considered is the method of injecting the synchronizing voltage into the grid of the 6949. The grid voltage has a maximum peak value of two kilovolts so the final synchronizer amplifier must be able to connect directly into this voltage source without being damaged or affecting normal machine operation. Further, no grid tuning can be used and any attempt at impedance matching only leads to larger voltages being transmitted into the synchronizer circuit.

A beam power tetrode vacuum tube, in this case a 4CW2000, biased to cutoff and capacitively coupled to the 6949 grid provides the necessary characteristics. Figure 1 shows the location of the synchronizer tube and its connection to the grid choke coil. Under these conditions the impedance seen by the oscillator is sufficiently high so that its operation is unaffected. The 4CW2000 can withstand the grid voltage swing easily under cutoff conditions. When the synchronizer drive is operating the average anode current of the 4CW2000 is 400 to 600 milliamperes.

A complete circuit diagram of the synchronizer final amplifier appears in Figure 5 and the complete phase-frequency detector is shown in Figure 4.

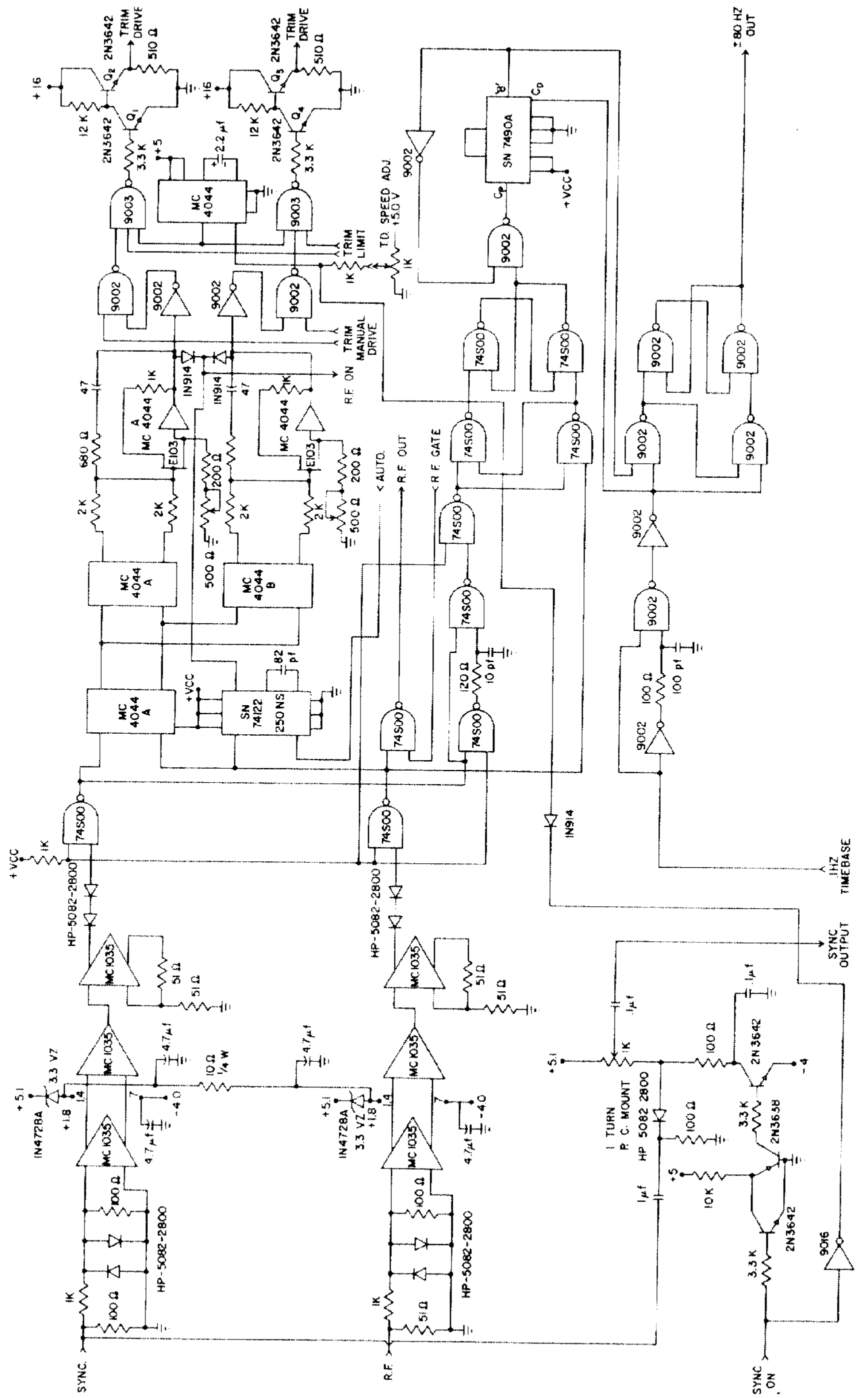

Fig. 4. Phase-frequency detector circuit

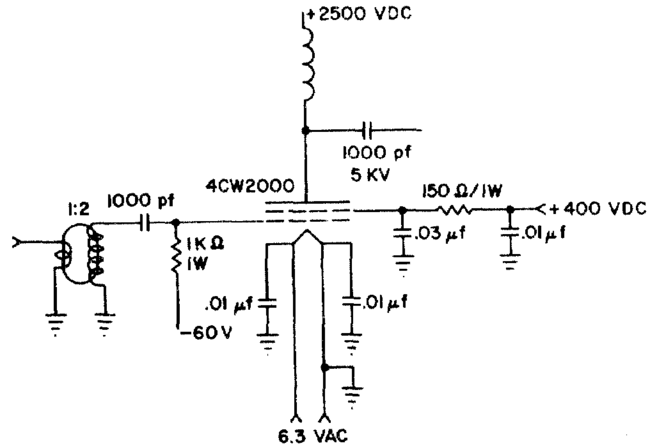

Fig. 5. Synchronizer final amplifier

RESULTS

In operation the synchronizer limits the total phase wobble of the oscillator to ±20 degrees with the extremes occuring in no less than a 5 millisecond period. This results in a maximum time jitter, as seen by any beam pulse, of ±50 picoseconds.

With this apparent improvement in phase stability some improvement in both energy resolution and beam pulse width is expected. As of this time no opportunity to measure the beam pulse width has been available. However, the beam transmission through the analyzing magnet and 0.05" slits was improved by some thirty percent.

The total cost of the system including the conversion of the regulator circuit was less than $3000.00.

ACKNOWLEDGEMENTS

The authors wish to thank Drs. R. A. Kenefick and L. C. Northcliffe for their generous sharing of beam time for testing of the synchronizer system.

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