RF PHASE CONTROL SYSTEM*

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Summary

A system for automatically controlling the instantaneous phase of the accelerating voltage at each of the six accelerating stations at the Cornell 12 GeV Electron Synchrotron has been developed. The phases are controlled to ±5° relative to a master oscillator. The system comprises electronic phase shifters to compensate for variations in klystron phase shifts during the acceleration cycle, and mechanical phase shifters to compensate for drive cable delay variations. Near full energy, when different klystron modulator waveforms are used in each station, the phase control provides an effective increase of 20% in RF power by cancelling the 180° phase shift which occurs in each klystron as it is brought up to full power. The phase control system is also a great aid in obtaining correct phasing when more than one station is used to pick up the beam.

Introduction

Stabilization of the phases of the various accelerating stations in the synchrotron relative to each other is necessary if the maximum acceleration attainable from these stations is to be realized. The system which has been devised to accomplish this can be considered as three independent systems. The first of these corrects for changes in the phase lengths of the drive cables delivering a reference signal to each of the stations. The second compensates for phase shift changes in the amplifier klystron located in each station as the klystron power output varies over a 30dB range. The third controls the temperature of the cooling water circulating around the accelerating structure in such a way that the phase velocity of the accelerating voltage is independent of average RF power. A block diagram of the system is shown in Figure 1.

Automatic Mechanical Phase Control

A reference signal from a master oscillator is sent to each of the accelerating stations through 50 ohm coaxial cables, which vary in length from 100 ft to 1000 ft, depending on the location of the accelerating station relative to the master oscillator. The farthest accelerating station is thus 792 wavelengths from the master oscillator at the operating frequency, which is 714 MHz. Since it is desirable to control the phase of each station to ±5°, a relatively small change in the phase velocity in the cable would be objectionable. Heating of the cable when the RF is first turned on, variations in the ambient temperature, and relaxation of mechanical strains in the cable are each capable of causing phase shifts larger than the tolerable limit. These phase shifts take place on a relatively slow time scale (minutes to weeks), and cause gradual degradation of system performance if not compensated.

Since the phase shifts are slow, a mechanical compensating scheme is quite satisfactory. Power from a master oscillator, after being amplified by a klystron and split into one branch for each station, is passed through a high power circulator (200 W CW) which prevents reflected power in each drive line from interfering with the forward power in the same line and in the other lines. The power emerging from the circulator passes through a directional coupler and travels through the long drive line to the appropriate accelerating station. In the station, the power (which is reduced to 12 W by cable attenuation) passes through a trombone phase shifter, a 20 dB directional coupler, and a coaxial relay to a short. The power reflected from the short travels back up the drive line to the 10 dB directional coupler and is terminated in the load attached to port 3 of the circulator. At this point, the power level is typically 0.5 W. The directional coupler picks off a phase sample of the reflected power. Since the power ratio passing through the directional coupler is 400:1, it is important to have a high directivity in this coupler. A double stub tuner in one branch of the directional coupler permits the effective directivity to be made better than 55 dB because the frequency and forward to reverse power ratio are fixed. The coaxial relay in the station permits the drive signal to be terminated while adjusting the double stub tuner. In addition, an adjustable length line on the output of the directional coupler permits effects due to the temperature coefficient of impedance of the 50 ohm, 40 W load to be cancelled by placing reflections from this load in quadrature with the forward power sample at the inputs to the balanced mixer. The sample of the return power in the drive line is delivered to one terminal of the balanced mixer. A forward power phase sample is also delivered to this mixer. The resulting direct coupled output is sent to the automatic mechanical phase controller. If a phase error exceeding 0.9° at the station occurs (half the round trip phase error), the controller actuates a motor driven trombone in the station and eliminates the phase error. The controller also overrides the phase control and moves the trombone to another stable position one wavelength away in the event that the trombone reaches one of its limits of travel.

Automatic Electronic Phase Control

The automatic mechanical phase controller provides a stable reference phase at each accelerating station. However, the klystron amplifier which is used to amplify this signal up to the 100 kW level required to drive the accelerating structure introduces a phase shift of 180° from the time it is turned on to the time it reaches full power output.

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In an electron synchrotron with a 60 Hz resonant magnet excitation system such as the one at Cornell, the RF power required at the beginning of the acceleration cycle is relatively small. As the magnetic field rate of climb increases, the RF power required also increases. At the end of the cycle, the rate of climb of the magnetic field decreases, but the synchrotron radiation losses require a substantial amount of RF power, which, at high energy, exceeds the power requirement in the middle of the cycle. An additional consideration is that the klystrons can be tuned for optimum efficiency only at a single instantaneous output power level; if the instantaneous power is above or below the selected value, the efficiency decreases.

In view of the above two considerations, it is customary to operate the klystrons in the various stations with different modulator anode waveforms. Normally, only one station is on at the beginning of the cycle. The other stations are turned on one at a time during the cycle, and are operated either with ramped waveforms or with rectangular waveforms. A typical RF power waveform is shown in Figure 2. The beam is injected at time t_0. The station illustrated turns on at time t_1. The beam is extracted from the synchrotron between times t_4 and t_5, and the station power is turned off at time t_6.

Since the phase shift of each klystron changes approximately linearly with output power, it is apparent that use of different waveforms would make it impossible to keep all station powers in phase at all times throughout the cycle without the use of a phase compensation scheme.

The rate of phase shift in the klystron is too fast to compensate with a mechanical system, so an electronic phase shifting system has been devised. The heart of this system is a varactor delay line comprising 10 varactor diodes, type 1N5461B. One end of these diodes is connected to a ground plane, and the other end is connected to a length of 14 gauge wire parallel to the ground plane. The diodes are spaced 1.20 cm apart, and the center of the wire is 1.16 cm above the ground plane. One end of the line is open, and the other end is connected to an elevated strip line 0.60 cm from the first diode in the line. It is important that dimensional tolerances be held to ±0.01 cm, and that the capacitances of the diodes be graded so that the highest capacitance occurs at one end and the lowest at the other. The impedance of the line is centered around 25 ohms, and is matched to a 50 ohm line by a quarter wave stripline having a 35.3 ohm impedance. The inductance of the diode leads acts to advantage by increasing the effective tuning range of the line. The line described provides a useful tuning range of 2.7 wavelengths at 714 MHz as the varactor bias is varied from 30 volts to approximately 7 volts. In order to prevent excessive harmonic distortion, the varactor line is operated with an RF input of 20 mW.

Again referring to Figure 1, the reference signal derived from the 20 dB directional coupler, after passing through a splitter, is delivered to one input of a balanced mixer, where it is used for a phase reference. The other output of the splitter is directed into the varactor line by a circulator. After passing down the varactor line and reflecting back from the open end, the signal is directed by the circulator into a stripline PIN diode attenuator which has a small phase shift with attenuation. The signal then is amplified by a six transistor 40 dB RF power amplifier up to a 10 W power level. An RF limiter consisting of a stripline shunt PIN diode followed by a hot carrier diode, one end of which is connected to the stripline and the other end of which is connected to a dc source, sharply limits the RF power transmitted and thereby protects the output stages of the amplifier. The output of the amplifier, after passing through a circulator for open circuit protection, passes through a 30 dB directional coupler. The coupled signal is used, via a diode detector, the RF amplitude controller, and the PIN diode attenuator, to maintain the output signal at the 10 W level. Amplitude control is necessary because the attenuation of the varactor line varies nearly 10 dB over its range, primarily due to losses in the diodes. With the power leveling loop, however, the variable line attenuation is no problem.

The amplifier signal is then delivered to the amplifier klystron, where the power is raised to the 100 kW level. A 50 dB directional coupler on the klystron output is used to derive a phase signal and an amplitude signal. The main portion of the klystron power is transmitted to the traveling wave iris-loaded accelerating cavity.

The klystron phase reference signal is compared to the drive signal phase by a balanced mixer, the output of which is sent to the RF electronic phase controller. The amplitude signal, after being converted to a video signal by the diode detector, is also sent to the same controller. When the amplitude exceeds a preset threshold, which is 30dB below the peak klystron output power, the phase controller provides an output signal which biases the varactor line in such a way that the balanced mixer output is maintained at zero. Again referring to Figure 2, this threshold occurs at time t_2. About 20 microseconds later, at time t_3, the value of the varactor bias is sampled and held. The phase regulation continues as long as the amplitude is above threshold. At time t_6, the controller resets the varactor bias to the value in the sample and hold circuit. If no above-threshold signal occurs within the next several accelerating cycles, the varactor bias is set to a reference value, which is at the center of the varactor line's range. It is also set to this value at the end of any cycle during which the varactor bias approaches either its upper or lower limit. The controller then regulates to the nearest phase balance point at the beginning of the next cycle.

The phase control error of ±5° results from balanced mixer variations of phase with amplitude.

The RF phase fault detector sends a fault signal to the control room if the amplitude gets out of regulation or if the phase error (excluding balanced mixer error) exceeds ±2°. This fault signal lights a fault light during the fault and for 10 seconds after it ends.

Accelerating Cavity Temperature Control

In order to maintain a constant phase velocity of the accelerating voltage in the traveling wave iris-loaded accelerating structure, a temperature probe well has been drilled radially into one of the irises. Since there is a thermal gradient across the copper which depends on the average power level, there is a point within the iris which will remain at a constant temperature when the phase velocity remains constant with changing average power. A temperature probe is placed at this point, and is used for regulation of the water temperature.

Manual Phase Control

The set point of the phase in each station is adjusted manually using a motor driven trombone located in one leg of the electronic phase controller's balanced mixer. The proper setting is determined by setting the energy of the synchrotron high enough that two stations are incapable of attaining full energy. The beam is picked up with one station, whose phase is set for maximum acceptance, and the station whose phase is to be adjusted is then turned on. Its phase is adjusted so that the beam is accelerated to the highest possible energy.

In addition to utilizing the RF more efficiently, the phase control system has been very useful for picking the beam up with more than one station. Once the phasing of the stations relative to each other has been done as described above, the relative phasing is known to be correct at injection time, and only the phase relative to the linac need be adjusted.

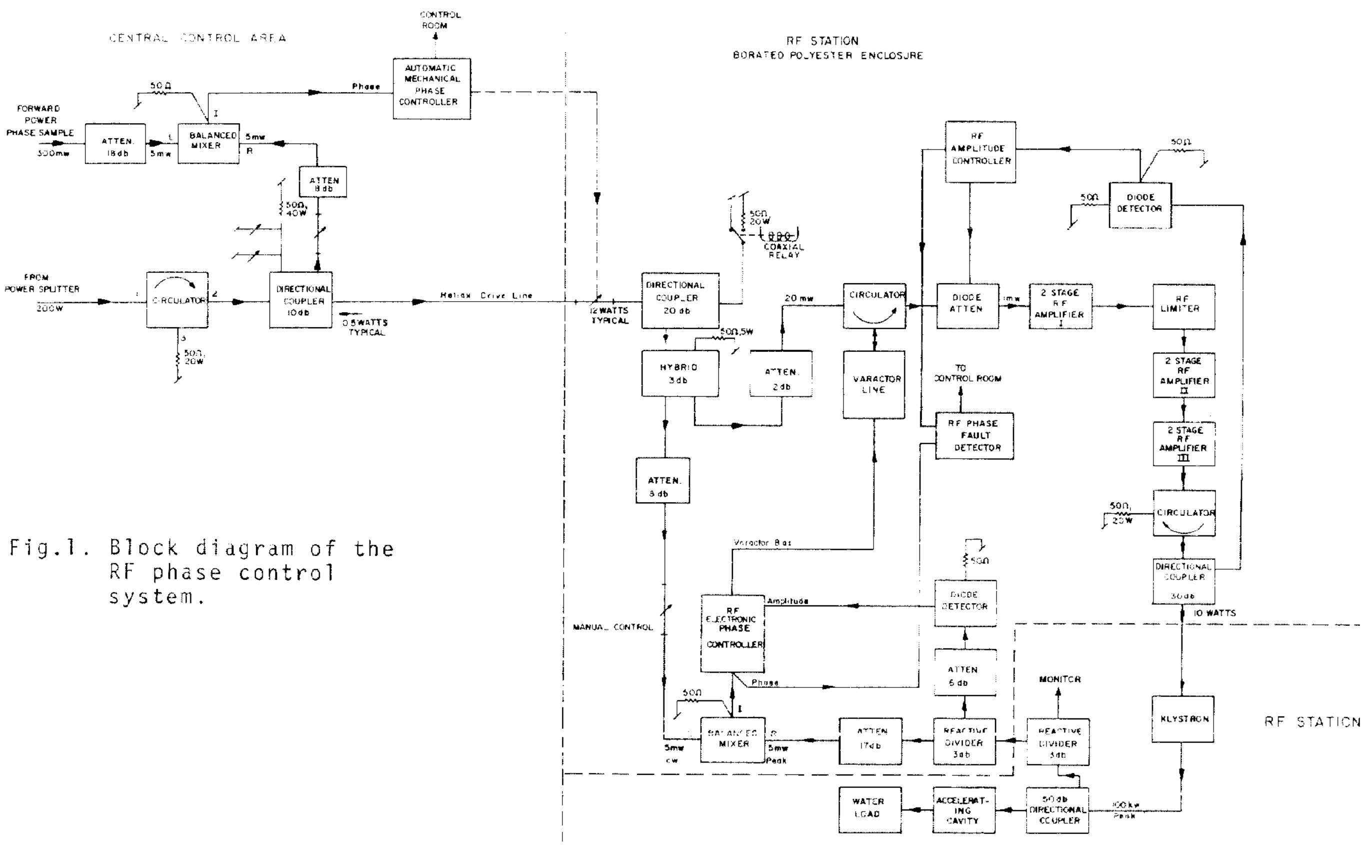

Fig.1. Block diagram of the RF phase control system.

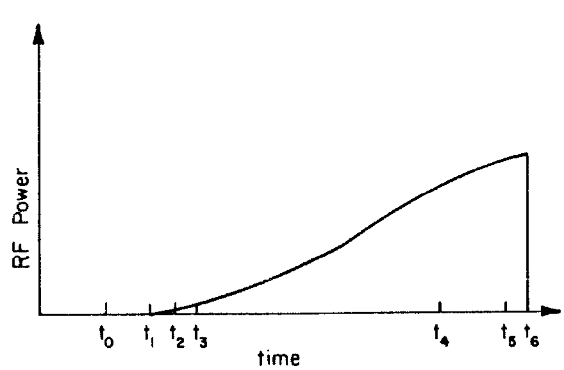

Fig.2. Typical RF power waveform during one acceleration cycle.