PHASE AND VOLTAGE CONTROL IN THE LEP RADIO-FREQUENCY SYSTEM

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INTRODUCTION

The LEP RF system is of modular construction where a basic module, an RF unit, consists of 16 coupled accelerating cavity/storage cavity assemblies driven by two 1 MW klystrons. The two klystrons operate at slightly different frequencies \( f_1 \) and \( f_2 \) with the difference determined by the bunch spacing in LEP.

For Phase 1 of LEP, 8 units have been installed in RF stations on each side of intersection Points 2 and 6.

The units are synchronized with the frequencies \( f_0 = 352.254024 \text{ MHz} \) and \( f_B = 44.997 \text{ kHz} \). They are transmitted to the RF stations from the LEP control center over fibre optic links. From the reference frequencies the klystron frequencies \( f_1 = f_0 - f_B \) and \( f_2 = f_0 + f_B \) are generated and applied in the klystrons through two identical chains of control electronics (Fig. 1). The klystron phase loop compensates for phase variations in the klystron and the circulator. The input power to the klystrons is controlled from the drive level control system which includes an AGC loop. This loop compensates for gain variations in the klystron and the circulator.

The cavity gap voltage is controlled with a voltage loop which acts on the modulation anode of the klystron. The correct waveform is obtained with a differential loop which corrects for differences in output power from the two klystrons. For use in the servo loops 350 MHz control elements have been developed. The most important are the voltage controlled attenuators with low phase shift variations and the voltage detectors with low VSWR.

The frequency generators

The two RF frequencies \( f_1 \) and \( f_2 \) are generated from the reference frequencies \( f_0 \) and \( f_B \) in phase locked loops with offset (Fig. 2). The incoming high frequency reference \( f_0 \) and the oscillator output frequency are applied to a double balanced mixer. The resulting IF signal is compared to the incoming low frequency reference \( f_B \) in a phase detector. The loop is closed by applying the resulting error signal to the voltage controlled crystal oscillator (VCXO) after amplification and filtering.

With this scheme the loop could lock on either the sum or the difference of the two reference frequencies. This ambiguity is eliminated by using VCXO's with a frequency range less than 2 \( f_B \).

The unity gain bandwidth of the loop is set to about 1 kHz. At a deviation from the carrier the phase noise of the VCXO is more than 100 dB below carrier. The spacing between the subharmonics of the overtone operated crystal oscillator is about 20 MHz. The band-pass filter keeps these unwanted signals below -60 dB.

These frequency generators are not included in a phase loop. Therefore the phase stability is important. Drift in the mixer is minimized by operating it with fixed input voltages of \( \pm 1 \text{ dRm} \). Temperature tests on the mixer used (Mini Circuit Lab. ZLW-1W) have shown that the output drift depends moderately on the input levels and is minimum for \( \pm 1 \text{ dRm} \) at both the RF and LO inputs. The RF input level is therefore stabilized with a TWA (voltage control loop) (AVC), where the electronic attenuator is designed for minimum phase variation over the attenuation range. As shown in Fig. 3 the attenuator consists of three PIN diodes in a 3 dB configuration. By keeping the mechanical dimensions...
small and compensating the series inductance of the shunt diode with a capacitor, the phase shift for an attenuation range of 30 dB is typically 2 degrees at 350 MHz (Fig. 4). With separate shunt and series control voltage the voltage standing wave ratio is kept below 1.5 at both the RF input and output.

The phase shifter is of the classical hybrid coupler type.\(^{1}\) For one 186P unit the phase shift is an almost linear function of control voltage. The insertion loss varies about 0.2 dB over the control voltage range. The temperature stability depends on the control voltage but is always less than ±0.01°RF phase between 20 and 50°C. By cascading 186P units, modules with ±2 and ±4 phase shift have been made.

The phase oscillation frequency in LEP can be as low as 500 Hz and could eventually coincide with the 600 Hz power supply ripple frequency. Therefore the phase loop has been designed with sufficiently large bandwidth to compensate for this ripple. The closed loop bandwidth is about 25 kHz and the open loop gain 2500. Measurements on a complete phase control loop have shown that the design goal, less than ±1° variation under all operating conditions, has been achieved. The largest error is introduced by the electronic attenuator when the klystron output power is varied from 10 kW to 1000 kW.

Ideally the return signal for the loop should be sampled at the cavities so that all phase variations in the power distribution system are compensated. In LEP this is not possible because the cavities are driven by two frequencies too close to each other to be separated when a loop bandwidth of about 25 kHz is desired. This means that phase changes in 35 m of waveguides are not corrected with the phase loop. When full power is applied to the cavities the waveguides are heated by the losses and phase changes of up to 15°RF have been measured. These variations are compensated by applying a correction, based on two temperature measurements, to the phase shifter used to set the RF reference phase.

Voltage control

The gap voltage in the LEP cavities is controlled with a feedback system which acts on the modulation anode of the klystrons. Usually the output power from a klystron is varied by changing the RF input power. For the LEP klystrons this is not possible because at full cathode current and low RF output power the maximum allowable collector dissipation would be exceeded at high cathode voltages. In addition, by operating the klystrons with saturated drive level and controlling the output power with the modulation anode the RF output to D.C. input power conversion ratio is maximized.

A block diagram of the voltage control loop is shown in Fig. 6. The peak voltage from cell No. 2 of each cavity is detected. The sum from all 16 cavities is compared to the reference voltage. The error signal is converted to a pulse train of 0.5 PLS pulses. For a voltage variation from 2 to 10 V the output frequency varies from 100 to 500 kHz. Via an isolating optical fibre link the signal is transferred to the klystron cathode voltage level of the modulator tube circuit, demodulated, amplified and applied to the modulation anode of the klystron.

Each of the two klystrons in one RF unit has its own loop but common summing circuit. Therefore a differential loop has been added: the difference between the output voltage of the two klystrons is detected. This error signal is, after amplification,
added to the reference voltage for the two main loops in such a way that the output voltage will be the same for both klystrons.

A critical element in the amplitude loop is the voltage detector (Fig. 7). A peak-to-peak detector with matched Schottky diodes is employed. With the quarter wavelength coaxial transformer the mismatch caused by the positive peak detector is compensated by a similar mismatch in the negative peak detector. In this way the VSWR is kept below 1.02 for all RF levels below 10 kVp and in the detected voltages caused by standing waves in the transmission line between the badly matched sampling loop in the cavity cell and the detector prevented. The temperature coefficient of the detector diodes is compensated by similar diodes in the feedback path of the input amplifiers. Temperature tests have shown an offset variation of less than 0.2 mV/°C. The linearity of the output is better than ±1% for voltage levels between 0.5 kVp and 10 kVp (Fig. 8). The RF peak detector is followed by a second detector which measures the peak amplitude of the envelope.

In the summing amplifier the gain of each channel is individually adjusted to compensate for the difference in attenuation in the different length coaxial cables between cavities and detectors. In front of the detectors 400 MHz strip-line low-pass filters with low VSWR are inserted to prevent passage of beam induced high frequency signals.

The bandwidth of the voltage loop is limited by the maximum rate with which the current in the klystron cathode power supply can be changed. A unity gain bandwidth of about 20 Hz has been obtained. This means that the loop is not able to compensate for the RF voltage ripple caused by the high voltage power supply. The 50 Hz and 600 Hz RF voltage ripple has been measured as a function of RF voltage. In the worst case (low RF output power) the 50 Hz ripple was 2.3 % peak and the 600 Hz ripple 0.9 % peak. Even if the synchrotron frequency coincides with the 600 Hz frequency this level would not affect the beam significantly.

Conclusion

All the electronics for the system is housed in racks in the "klystron gallery" a 250 m long tunnel which runs parallel to the main tunnel at a distance of 8 m. The components are therefore not exposed to synchrotron radiation and because the equipment is accessible during LEP operation, testing and maintenance is facilitated.

The analogue and digital variables can be controlled either locally via a touch screen connected to a "data manager" or remotely through the LEP control system. A large number of monitoring and status signals are sent to the control system, for example control voltages for phase shifters, VCXO's and attenuators, detector voltages and loop status signals.

The phase and voltage control system described above will also be used for the planned RF units with superconducting cavities. A few simplifications are possible because these cavities operate at only one RF frequency.

6 Acknowledgements

The authors would like to thank C. Post and J. Sladen for their participation in the development of the systems and also G. Castelli and R. Schuler for their contribution to the realization and construction of the equipment.

References

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