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 1MW 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 MHz and f_B = 44.982 kHz. They are transmitted to the RF stations from the LEP control center over fibre optic links[1]. From the reference frequencies the klystron frequencies $f_1 = f_0 - f_B$ and $f_2 = f_0 + f_B$ are generated and applied to 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 narrow-band, high gain, 200 W solid state driver amplifier.

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.

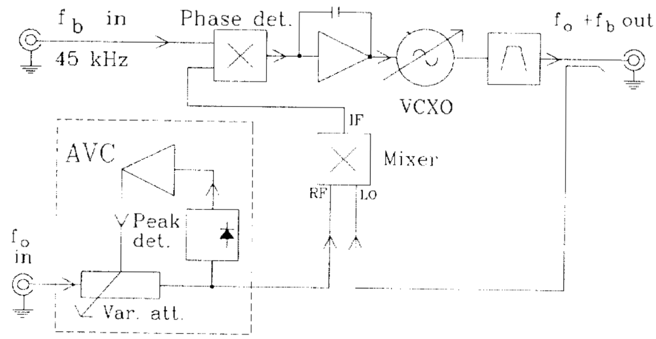

Fig. 2 Block diagram of an f_1 or f_2 generator

The unity gain bandwidth of the loop is set to about 1 kHz. At this offset from 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 bandpass filter keeps these unwanted signals below -60 dBc.

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 +1 dBm. 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 +1 dBm at both the RF and LO inputs. The RF input level is therefore stabilized with a 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 T configuration. By keeping the mechanical dimensions

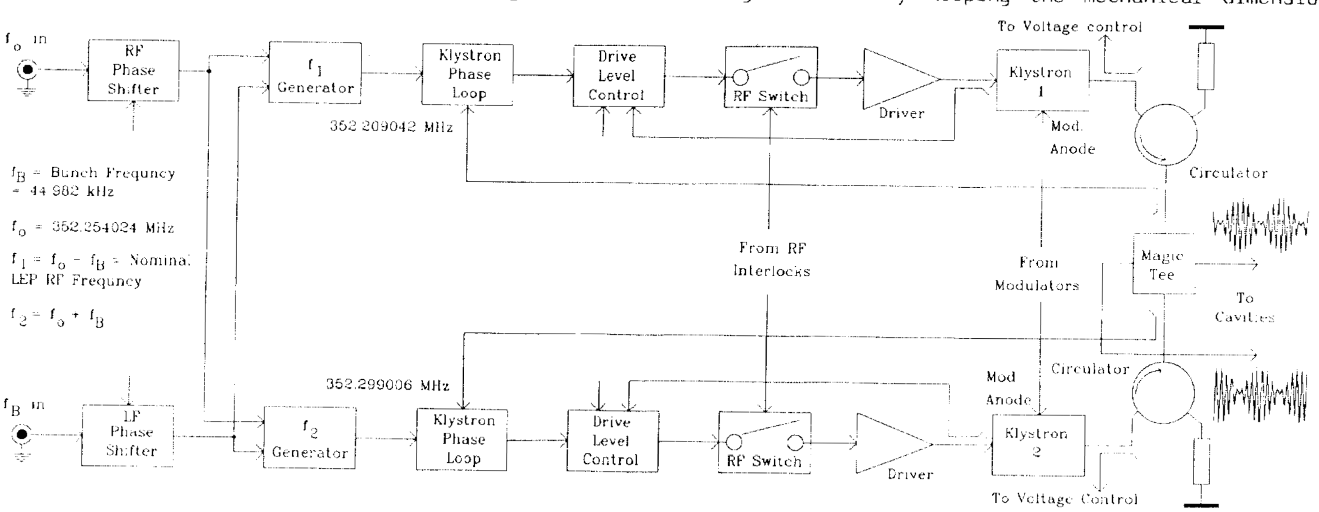

Fig. 1 Schematic block diagram of the LEP RF low power electronics

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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 1.2 at both the RF input and output.

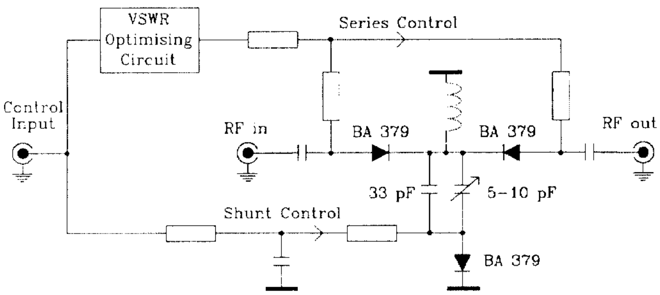

Fig. 3 350 MHz PIN diode attenuator

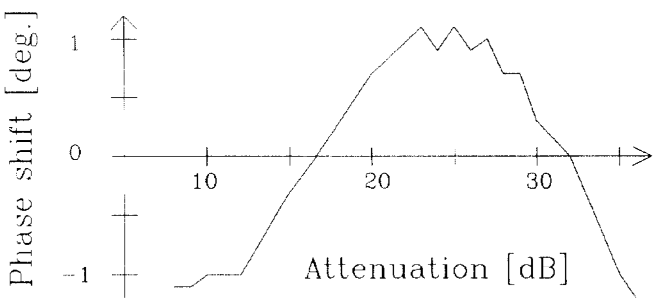

Fig. 4 Phase shift variation versus attenuation for a PIN diode attenuator

Phase control

When the klystron cathode voltage is varied between its minimum and maximum values for normal operation, 66 and 88 kV, the RF phase of the output changes by 260°. The phase change from minimum to maximum output power is about 70°. These and additional variations in circulator, driver amplifier and other components are compensated with a phase feedback loop (Fig. 5). A sample of the waveguide signal is phase compared with the generator signal in a double balanced mixer. The input levels to the mixer are kept constant at +1 dBm by using the technique described above. Through the loop amplifier the error signal is applied to the 180° electronic phase shifter. After additional filtering with a time constant of 70 ms the signal controls the 1260° phase shifter. The small and fast phase variations caused mainly by the power supply ripple are then compensated by the short range phase shifter and slow variations from high voltage changes and output power adjustments mainly by the large range phase shifter.

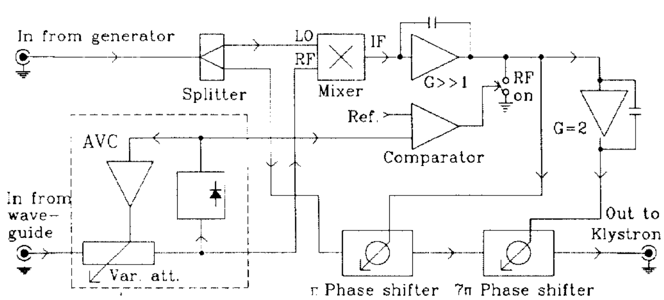

Fig. 5 The klystron phase loop

The loop is closed with the phase shifter control voltage in the middle of the +10 V to -10 V range when an RF signal is detected from the waveguide input. With a total of 8π phase variation available, saturation in a phase shifter is then prevented under all operational conditions.

The phase shifter is of the classical hybrid coupler type[2]. For one 180° 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 the drift is always less than 0.03° RF phase/C° between 20 and 50° C. By cascading 180° units, modules with 2π and 4π 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 about 2500. Measurements on a complete phase control loop have shown that the design goal, less than ± 2° 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 klystrons 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 then 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 µs 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[4], 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,

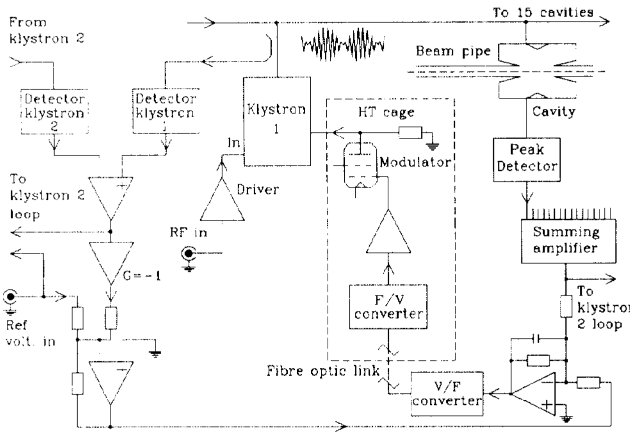

Fig. 6 The voltage control system

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 V_p and errors 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 that 0.2 mV/°C. The linearity of the output is better than ± 1% for voltage levels between 0.3 V_p and 10 V_p (Fig. 8). The RF peak detector is followed by a second detector which measures the peak amplitude of the envelope.

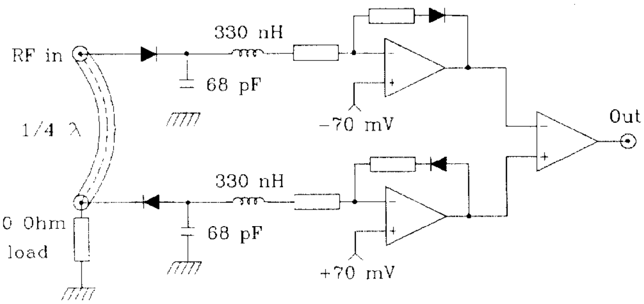

Fig. 7 350 MHz amplitude detector block diagram

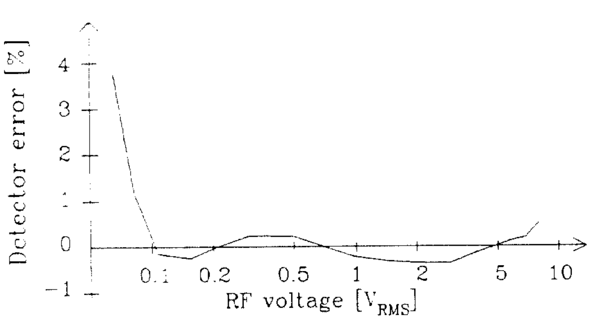

Fig. 8 Detector error as function of RF voltage for 350 MHz amplitude detector

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 ripple frequency this level would not affect the beam significantly[5].

Conclusion

All the electronics for the systems 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"[6] 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

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