The LEP Main Ring High Power RF System

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Abstract The LEP Phase I high-power RF system, by which a total of 16 MW is generated at a frequency of 352 MHz, includes 16 1-MW CW klystron/Y-junction circulator assemblies and a WR2300 waveguide system. Via the latter the generated RF power is distributed and supplied to the 128 accelerating structures. All klystrons, circulators and waveguide components have been delivered, accepted by CERN and installed in the LEP tunnel. A general description of the RF generation and distribution system is given. The performance of the klystrons and circulators as well as results of the first high-power tests in the LEP ring tunnel are presented. In particular the tendency of the klystrons to produce spurious sidebands at high output power levels is discussed and the means used to cure it to a large extent are described. Furthermore an explanation is given of how the problem of frequent arcs in the waveguides between klystron and circulator was overcome.

1 Introduction

In LEP a total of 16 MW of RF power is generated by 16 1-MW CW klystrons[1] and supplied to the 128 accelerating structures via circulators and a WR2300 waveguide system. Two 1 MW klystron/junction circulator assemblies, 16 accelerating structures, the controls and interlock electronics and the associated waveguide system form an RF unit. Each of the eight identical RF units provides a maximum circumferential accelerating voltage of 50 MV, its frequency being 352 MHz.

The main change in layout, as compared to a previous report on the LEP high power RF system[1], is the insertion of a high power Y-junction circulator in the output line of each klystron. The reason for this is the tendency of each klystron to produce sideband signals at high output power levels the frequencies of which lie far outside the accelerating cavity resonance, a feature not yet known when reference[1] was published. These self-generated sideband signals are thus fully reflected by the cavities and become dangerous for the klystron as soon as they exceed 1.7% (VSWR = 1.3) of the main signal. The ferrite circulator, which presents a matched load to the klystron over a relatively wide frequency range diverts the reflected power from the cavities into a water-cooled RF absorber and thus protects the klystron. Second harmonic components of the operating signal, however, which are also produced by the klystron, are reflected by the circulator and can cause arcs in the waveguides between klystron and circulator.

2 General

The layout of each RF unit had to be modified only slightly in order to accommodate the circulators. The two 180° waveguide phase switches, the purpose of which was to divert the beam-induced RF power from the possibly non-driven cavities of an RF unit into two of the magic-tee water loads[1], are no longer required. One of the phase switches, however, has been inserted in the waveguide system between the magic-tee combiner and first power-splitter (Fig. 1) for the following reason. Whenever it is necessary to drive an RF unit with the frequency f_1 applied to klystron 2 a 180° RF phase delay must be inserted in the feeder line of one of the two groups of eight cavities in order to obtain the right phase relationship between all cavities of an RF unit. This requirement can be fulfilled by means of the five-piston motor-driven phase switch, which under normal conditions is in the 0° position.

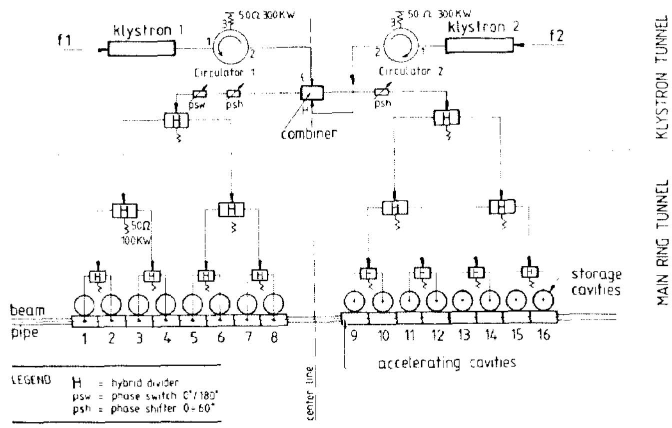

Figure 1: RF power distribution of a LEP RF unit

3 Klystrons

By now all 16 LEP 1-MW klystrons, which were developed and manufactured by two European firms, have been accepted by CERN and installed in the LEP klystron tunnels. The main operating parameters at rated output power (1 MW CW) are shown in Table 1.

Output power	1000 kW
D.c. operating voltage	88–90 kV
Beam current	17–18 A
Beam perveance	$0.7 \cdot 10^{-6} AV^{-1.5}$
Efficiency	67–69%
Max. load VSWR	1.3
Operating frequency	352.2 MHz
1 dB bandwidth	$\pm \geq$ 500 kHz
RF gain	40–42 dB
RF input power	60–100 W
Body dissipation	10–20 kW
Focusing coil current	9–10 A
Modulation anode current	$\leq$ 1.5 mA

Table 1: Main klystron parameters at rated output power

For the operation at significantly reduced output power requirements two additional working points have been chosen. At low output power levels the klystron efficiency is considerably lower

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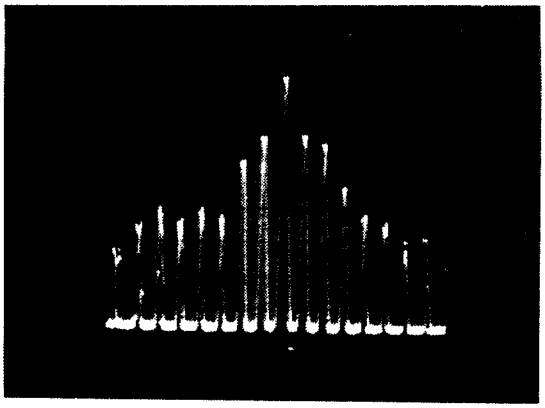

Figure 2: Frequency spectrum (1.6 MHz line separation) of amplitude modulated klystron output signal (f_c: 352.2 MHz, span: 20 MHz, vertical scale: 10 dB/div)

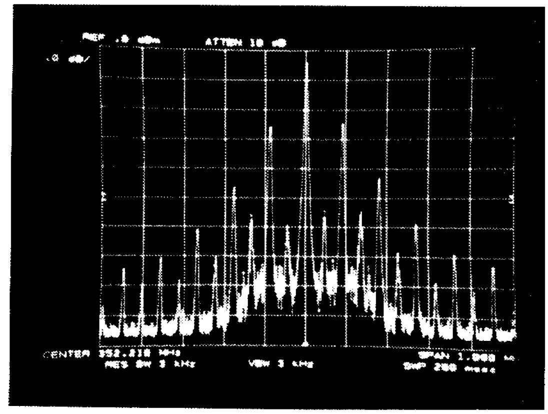

Figure 3: Frequency spectrum of klystron output signal showing the presence of instabilities with 90 kHz lines (f_c: 352.2 MHz, span: 1 MHz, vertical scale: 10 dB/div.)[1]

when a high d.c. operating voltage is applied. This is due to the lower RF gain when the klystron is operated at a low beam perveance (i.e. at high beam voltage but low current) and the available drive power which is limited to 200 W and thus below the required saturation level. A d.c. voltage of 66 kV is used at output power levels up to 420 kW and one of 77 kV at levels up to 720 kW, corresponding to 65% and 85% of the maximum RF voltage respectively. The focusing field settings remain unchanged at these additional working points whereas the drive levels have to be reduced in order to avoid oversaturation and consequently a drop in output power. The phase loop around the klystron can cope with the operating voltage variation between 66 and 88 kV without requiring additional adjustments[2]

The tendency of the klystrons to generate sidebands beside the main output signal was first observed when an attempt was made to run an RF unit at full power (2×1000 kW) for the first time in April 1985. At that time it was believed that no circulators would be required for the operation of the RF system at LEP Phase I[1]. The sideband signals appear mostly at output power levels between 700 and 900 kW and can then only be made to disappear by reducing the output power to about 500 kW. By means of a spectrum analyzer two types of klystron instability can be observed, both manifest as amplitude modulation[3] . The frequency lines of the first type are separated by about 2 MHz, (Fig. 2) whereas in the second case the distance between lines is 90 kHz (Fig. 3).

A tentative explanation of the first case is that some electrons in the klystron at high power levels are reflected back from the output cavity, at low energies, carrying low frequency signals into the gun area[4]. Beam intensity modulation takes place there via the modulation anode, at which an increased current is observed when sidebands occur. In the input cavity the electron beam, which is already intensity-modulated, experiences an RF velocity modulation. The amplitude-modulated beam then enters the first high-Q ($Q > 10000$) idler cavity, the resonance of which lies about 2 MHz higher than the operating frequency. Via its coupling loop it can be observeed that this cavity is excited at its resonance frequency when instabilities of the first type are generated. Velocity modulation then takes place at two RF frequencies (352 and 354 MHz) and, due to the strongly non-linear transfer characteristic of the klystrons, intermodulation products are generated, the order number observed being limited by the bandwidth of the output cavity. A remedy for reducing the probability of this type of instability would be the lowering of the gain at 354 MHz by reducing the Q value of the first idler cavity which, however, would inevitably result in a lower gain and efficiency at the operation frequency.

The instabilities, characterized by a frequency line separation of 90 kHz, are, contrary to those of the first type, externally caused, but are basically of the same origin. It should be recalled here that the operating frequencies of the two klystrons of an RF unit differ by 90 kHz which corresponds to twice the bunch repetition frequency. About half of the power reflected from the cavities at the lower frequency reaches the circulator which protects the klystron driven with the higher frequency and vice versa. Actually, a signal attenuated by about 40 dB of the other frequency can be observed at the output of each klystron. The reflected electrons in the klystron carry the 90 kHz beat signal back to the modulation anode where it modulates the forward beam as in the first case. Under certain operating conditions a positive feedback loop can develop and the output signal becomes amplitude-modulated. Without circulators, the signal of the other frequency observed at each klystron output port was only attenuated by about 20 dB with respect to the forward power signal and no klystron operation free of instabilities was possible above 600 kW.

4 Circulators

It was decided in 1986 that 16 high-power Y-junction H-plane waveguide circulators would be purchased from industry. These have now all been successfully tested, accepted and installed in the LEP tunnel. The specification calls for a rated forward and simultaneously applied reflected power of 1100 and 300 kW respectively, the latter being allowed to appear at any phase angle at the output port. In order to test the realization of these requirements at rated power levels the output port was terminated with a sliding waveguide short. The RF conditions at a specified forward (P_F) and reflected power (P_R) can be simulated with a shorted output port by applying an equivalent power (P_E) according to the formula

$$P_E = \frac{1}{4}\left(\sqrt{P_F} + \sqrt{P_R}\right)^2$$

At $P_F = 1100$ kW and $P_R = 300$ kW the equivalent power P_E is 637 kW. Under these conditions all circulators have been successfully tested at any reflection phase angle up to 800 kW, some of

[1]N.B. The spurious 45 kHz lines were present in the drive signal at the time the photo was taken.

them even up to 1000 kW. The latter corresponds to a reflected power of 900 kW at $P_F = 1100$ kW, which is to be compared with the specified value of 300 kW.

The main operating parameters at 1 MW input power are shown in the following table:

Input power	1000 kW
Operating frequency f_0	352.2 MHz
Isolation (S_{12})	
at $f_0 \pm 3\%$	$\geq$20 dB
at $f_0 \pm 5\%$	$\geq$10 dB
Input reflection (S_{11})	
at $f_0 \pm 3\%$	$\geq$20 dB
Insertion loss at $P_F \gg P_R$	$\approx$0.08 dB [2]

Table 2: Main operating parameters at 1 MW input power

Since the saturation magnetization of the ferrite material is temperature-dependent the circulator's working point changes with either water temperature or RF power variations. In order to obtain a stable operating point the external magnetization has to be changed with the ferrite temperature[5]. The external magnetic field is a combination of a permanent magnet and an electro-magnet, the latter being used for final *in situ* adjustments. The temperature gradient of the ferrite material and the magnetic behaviour of the electro-magnet gives a compensation current of 0.25 A/°C ferrite temperature increase . The mean ferrite temperature is evaluated by measuring the input and output temperature of the cooling water. A regulation system has been built for each circulator which corrects the external magnetic field as a function of the ferrite and permanent magnet temperature, the latter having a temperature gradient of -1.2 G/°C. With the same system deviations from nominal magnetization values are corrected by an offset current. A non-variable load is thus presented to each klystron at all output power levels and over a wide water and ambient temperature range, an important condition for a stable klystron operation.

5 First Operation Results

Six of the eight RF units, already installed in the LEP tunnel, are operational so far (March 1989), and the full RF power level, i.e. 2×1000 kW, has been reached in all of them. Klystron instabilities of the above-mentioned types, however, have been occasionally observed in the vicinity of 800 kW klystron output power. Very careful adjustments of the circulator regulation system and the klystron RF drive levels are required in order to achieve stable operation at about 6°C temperature variations of the klystron cooling water, so far observed. Even a slight load mismatch, producible by means of the circulator regulation system, which results mostly in a lower klystron efficiency, is sometimes required for sideband-free operation. According to our observations, it seems less likely that klystrons with a higher gun perveance, i.e. a higher repelling voltage for returning electrons between modulation anode and first drift tube, produce instabilities than those with a lower one.

A side effect of the LEP circulators is the reflection of second harmonic signals which are generated by the klystrons. In the standard WR 2300 waveguides installed in LEP, the possible 704 MHz transmission modes, besides the dominant one, are H_{01}, H_{20}, H_{11} and E_{11}. Due to the symmetrical structure(with regard to the H-plane) of the coax-to-waveguide doorknob transition of the klystron output it is very unlikely that the H_{01} and H_{20} modes are being excited. Because of the reduced height of the circulator's resonator and its waveguide coupling ports (about 40% with respect to the WR 2300 waveguide), the H_{11} and E_{11} mode cut-off frequency of which is 871 MHz, the second harmonic signals are reflected. It is supposed that these reflections were the cause of frequent arcs in the waveguides after the circulator's insertion. By installing $\lambda/4$-antennae on the centre line of the narrow waveguide side, where the electric field of both modes is at maximum, and terminating them with 50 Ω loads the problem was overcome. When only one antenna was installed approximately 5 kW of second harmonic signal was dissipated in its termination load. When the number of antennae is increased the total dissipated power decreases. Installation of six antennae was found to be a good compromise giving a total dissipated power of <1 kW and relatively cheap air-cooled 100 and 200 W coaxial 50Ω termination resistors can be used. The contribution of the fundamental 352 MHz, H_{10} signal to the above figure is about half a per cent (-23 dB).

RF phase measurements between cavities have been performed on all operating RF units using the directional couplers installed in the waveguides close to the input power coupler of each cavity[6]. Phase variations of up to 8° were measured. They are mostly related to deviations from the nominal mechanical length of the flexible waveguide sections and can thus be easily adjusted by either squeezing or stretching them. The electrical waveguide length between the two groups of cavities was found to differ by 12° (in addition to one waveguide wavelength). This deviation is due to the different coupling in the two groups and is compensated by means of one of the two phase shifters installed (Fig. 1).

[2] About half of this value is due to ferrite losses and half to waveguide and matching network losses[5].

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