GENERATION AND DISTRIBUTION OF RADIO-FREQUENCY POWER IN LEP

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Introduction

The beam energy in LEP Phase I at maximum luminosity is 55 GeV. With a circulating current of 3 mA per beam, an effective cavity shunt impedance of 40 MΩ/m and RF power losses in the waveguide system of 7.5%, a total of 14.9 MW RF generator power is required for achieving this energy¹, the respective values for injection being 20 GeV and about 0.26 MW. This RF power is generated by 16 klystrons and supplied to the 128 accelerating structures via a WR 2300 waveguide system. Two klystrons, together with 16 accelerating structures, the controls and associated waveguide system, form an RF unit.

The klystrons of an RF unit are operated in CW mode but at different frequencies, f_1 and f_2 . The two operating frequencies are identical to the resonant frequencies of the accelerating structures, each of which consists of a pair of coupled cavities.² In order to excite the coupled cavity system at both resonant frequencies a modulated signal must be fed to it. By combining the two klystron output signals in a waveguide magic-tee junction the required modulation is achieved. At one of its outputs then appears the sum signal ($A_1 \sin \omega_1 t + A_2 \sin \omega_2 t$) and at the other the difference signal ($A_1 \sin \omega_1 t - A_2 \sin \omega_2 t$). Each of the two modulated signals then passes three power-splitting stages before it reaches the input couplers of the accelerating structures, i.e. one signal is fed to the centre cell of eight accelerating cavities and the other to the storage cavity of the complementary eight coupled-cavity units.³ (Fig. 1) The mean of the two operating frequencies (352.209 MHz) corresponds to the 31 320th harmonic of the LEP revolution frequency, their beat frequency (≈ 45 kHz) being equal to the bunch repetition frequency.

General layout

The LEP Phase I RF system is grouped in two pairs

of stations, one station on either side of the two diametrically opposite collision points 2 and 6 (Fig. 2). Thirty-two accelerating structures are installed in the main-ring tunnel on either side of these intersecting points whereas the klystrons and other RF equipment are housed in special "klystron tunnels". These run parallel to the main-ring tunnel at a distance of 8 m. Each klystron tunnel is about 250 m long with a cross-section of 5.5 m in diameter and accessible through the service pits of the above-mentioned intersection points, even during machine operation periods. Equipment for two RF units is installed in each of the four klystron tunnels, i.e. 2×2 klystrons, 2×22 standard racks for controls, two high-voltage interface enclosures (containing HV capacitors, crowbar, modulators etc.) and about 210 m of WR 2300 standard waveguides, including two magic-tee power combiners and 2×2 magic-tee power splitters. Eight circular holes ($\phi = 90$ cm) link each klystron tunnel with the main-ring tunnel. Waveguides are installed in each of these holes (four are required for one RF unit) through which the RF power is fed to two further power-splitting stages, located in the main-ring tunnel, before it reaches the input couplers of the accelerating structures.

The d.c. operation voltage for the klystrons is supplied by thyristor-controlled a.c.-to-d.c. power converters each of which has a rated output of -100 kV and 40 A. The high-voltage d.c. power required by the two klystrons of an RF unit is supplied by one of these power sources via the high-voltage interface. All klystron high-voltage power sources are located at ground level, close to the pits of intersection points 2 and 6.

RF Generators (klystrons)

The klystrons used in the LEP main-ring RF system are being developed and manufactured by two European firms, each of which is supplying nine units. By the

Fig.1 - RF POWER DISTRIBUTION OF A LEP-RF-UNIT

end of April 1985 three klystrons from each firm had been delivered, all of which have successfully passed the acceptance test procedures at CERN.

A klystron unit is composed of the klystron body including two welded-on 8 l/s getter ion pumps, the main support girder, a set of focusing coils, the output waveguide transition and the oil tank for the interconnections between high-voltage cables and cathode, filament and modulation anode leads. Due to the limited space inside the tunnel the klystrons are mounted horizontally. They are housed inside lead-shielded "garages" since X-ray levels up to 400 mrem/h were measured in the proximity of the output cavity when the klystrons were operated at rated output power, i.e. 1000 kW. An interlock system permits only the HV to be switched on when all lead panels of the "garage" are in place. Additional lead shielding of the collectors is provided by the klystron manufacturers.

Each klystron is equipped with a modulation anode by means of which the cathode current can be controlled between 0 A and about 20 A. However, at beam currents below 4 A, full d.c. operation voltage (max. 90 kV) and nominal focusing field settings an increase of the body dissipation power is observed. The klystrons are therefore not operated at beam currents below this value when a d.c. voltage of $V_B > 85$ kV is applied to it.

The klystron body and collector are both water-cooled; additional air cooling is provided to the coaxial output window. The body cooling is split into two separate circuits: one is for the cooling of the RF output cavity and the other for the remainder of the klystron body. A total body dissipation power of 20 kW maximum is permitted. The collector is also cooled by demineralized water. At a flow rate of 800 l/min the maximum dissipated collector power is about 800 kW when no RF signal is supplied to the input cavity. When a loss of the RF drive signal occurs at d.c. input power levels higher than 800 kW a control system automatically reduces the cathode current within 1 s to about 4 A by means of the modulation anode voltage. The control of the modulation

anode voltage is performed by a 1.5 kW oil-insulated hard-tube modulator. However, the main application of the modulator is the control of the klystron RF output power. A feedback loop around each klystron provides, by means of the modulation anode voltage, a constant RF power level which is required during beam accumulation and physics operation.⁴ The same loop also controls the ramping, i.e. the increase of RF power for the acceleration of the injected e^+e^- beams.

The RF drive signal to the klystron, which is supplied by a 200 W solid-state amplifier, is kept constant for all possible klystron output power levels at any cathode voltage setting. It is adjusted so that at the respective maximum output power the klystron is operated in saturation. Due to the strong phase dependence of the RF output signal on the cathode voltage, the klystrons are operated at only two different voltages, i.e. either 66 or 86 kV. At the lower voltage level a maximum klystron output power of 420 kW and hence a LEP energy of about 45 GeV can be achieved, provided all klystrons and RF cavities are operational.

When the klystron output power is varied between its minimum and maximum values, by means of the modulation anode voltage, the RF phase of the output signal is delayed by about 70° . An RF phase shifter, which is installed at the input of each driver amplifier and within a phase loop around klystron and driver, maintains the output phase delay always constant. It also compensates the RF phase variations caused by the 600 Hz ripple superimposed on the d.c. operating voltage.⁴

The klystron output must cope with load mismatches of $V_{SWR} < 1.3$ at rated output power. The reflected RF power due to beam loading is expected not to exceed this value at construction Phase I. Therefore, no isolators are installed between klystrons and RF cavities. They may, however, be required in later phases and space has been reserved for this.

A fast detector and monitoring system receives the signal caused by reflections from a directional coupler, mounted in the output waveguide. It acts on

Fig. 2. LEP TUNNEL SHOWING THE REGIONS EQUIPPED WITH RADIO-FREQUENCY (PHASE I.)

a PIN-diode switch, which interrupts the RF drive signal to the klystron within 25 μ s when a preset threshold value is exceeded. A second control input of the fast RF switch is linked to a spark detector which is mounted on the klystron output to waveguide transition.

One of the most important features for the development of the LEP klystrons has been the d.c. input to RF output power conversion ratio, which was specified by CERN to be at least 68% at an RF output power of 1000 kW. All klystrons are equipped with idler cavities which are inserted on the drift tube between input and output cavity, all of them being integral parts of the klystron body. One of the idler cavities is tuned to the second harmonic of the operation frequency whereas the others are stagger-tuned to frequencies slightly above the latter. By these measures the specified power conversion ratio was achieved. At rated output power, a beam perveance of about $0.64 \cdot 10^{-6}$ A/V^{1.5} and a d.c. operation voltage of -88 kV, efficiencies between 67 and 69%, depending on the output load matching conditions, were measured. A drive power at the klystron's RF input connector of about 60 W is required under the above conditions, which corresponds to an RF gain of 42 dB. At lower HV settings (min 83 kV) the rated output power can be maintained when the beam perveance (cathode current) is increased correspondingly by means of the modulation anode voltage. Higher gain values at the expense of lower efficiencies are then measured.

During the acceptance test at CERN all klystrons are run for at least one hour at an output power of 1100 kW CW with a maximum HV operation voltage of -95 kV.

The electrical and mechanical specification, in particular the d.c. operation voltage, the rated output power, RF gain and efficiency, the mechanical overall length, the HV connectors, the output waveguide height and size, the connectors for RF input, ion pumps and focusing coils supply and the fittings for the cooling water circuits, permit the easy interchange of the klystrons of the two makes. Provided a spare klystron is available in the proximity of a faulty one a klystron replacement could be executed within a few hours, due to the application of quick-change connectors and fittings.

RF Power Distribution System

All waveguide components used in LEP are of the EIA standard type WR 2300, of which all those installed in the "klystron tunnels" and link holes between the two tunnels are of the normal two-to-one aspect ratio and all those in the main ring tunnel are of the "half-height" type, i.e. their height-to-width ratio is 1:4. The choice of the two different waveguide heights is due to space constraints in the main ring tunnel on one hand and the low specific insertion loss in those waveguides with a relative high RF power flow on the other. At an RF power flow of 1 MW the losses per metre are 320 and 560 W respectively. In spite of the relatively low losses in the "full-height" waveguides, they will be fitted with water-cooling pipes in order not to overload the air-conditioning system in the klystron galleries at full-power operation. All waveguides are made from aluminium alloy sheet. Due to the air cooling of both the klystron and the RF cavity windows the inside air pressure is slightly above that of the outside. This pressure difference is detected by manometers, the outputs of which are incorporated in the interlock system, i.e. when the waveguide system of an RF unit is not completely assembled no HT can be applied to the respective klystrons.

From the two colinear outputs of the magic-tee combiner onwards, the waveguide lengths to all 16 cavity input couplers must be identical. The coupling to the centre-cell of the accelerating cavities, however, requires more waveguide length compared to the storage cavity coupling at the complementary group of eight cavities. For compensating this the mounting position of the magic-tee combiner is displaced with respect to the centre-line of the RF unit. A three-piston phase shifter is installed in each of the two output branches of the magic-tee combiner for final adjustments of the RF phase relations between the two groups of cavities. By moving the three pistons simultaneously into the waveguide the RF phase can be delayed up to 60° without exceeding a VSWR of 1.05 due to the phase-shifter insertion.

Since the distance between two corresponding cavity cells of the two groups of eight cavities is an odd multiple of half a wavelength the RF phase relationships between these cells must differ by 180°. The chosen position of the cavity input couplers and association of the two operating frequencies with the zero- and π -mode ones require the lower frequency signal (f_1) to appear in antiphase and the f_2 signal in phase between the input couplers of the two cavity groups in order to achieve the above-mentioned phase requirement. This is achieved by feeding the f_1 signal into the E-port and the f_2 signal into the H-port of the magic-tee combiner. At all magic-tee power splitters the RF signal is fed into the H-port whereas the E-port is terminated via a waveguide to coax transition by a 50 Ω water load. Reflected RF power is absorbed in the demineralized water which circulates in these coaxial loads. At the LEP RF frequency the RF power attenuation of demineralized water is about 5 dB at 20°C and about 2.5 dB at 50°C per metre water column. The length of the water-filled section of the load is fixed to 2.5 m, the overall length being 2.9 m.

Whenever it is necessary to run LEP with some klystrons turned off the beam-induced power in the corresponding idling cavities has to be diverted into two of the magic-tee water-loads in order to protect the klystrons from excessive reflected power levels. A motor-driven phase-switch which delays the RF signal by 180° when the five pistons are inserted in the waveguide is mounted in each of the two signal paths so that the reflected power is diverted into the two loads of the first power-splitting stage. Both the 60° phase-shifter and the 180° phase-shifter were tested under full power; the spring contacts round the pistons then reached temperatures of up to 100°C corresponding to an insertion loss of 1-2°/oo. The magic-tee combiner was equally tested at full operation power, i.e. with 2×1 MW at the inputs. Under these conditions an insertion loss of 6 kW was measured by calorimetric means. The isolation between E- and H-port was found to be -38 dB. As at all "full-height" waveguide straight sections the magic-tees will be fitted with water-cooling pipes.

The total waveguide length required in LEP is about 1650 m of which 1100 m is of the full-height and 550 m of the half-height type.

References

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