RF POWER GENERATION IN LHC

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Abstract

The counter-rotating proton beams in the Large Hadron Collider (LHC) will be captured and then accelerated to their final energies of 2×7 TeV by two identical 400 MHz RF systems. The RF power source required for each beam comprises eight 300 kW klystrons. The output power of each klystron is fed via a circulator and a waveguide line to the input coupler of a single-cell superconducting (SC) cavity. Four klystrons are powered by a 100 kV, 40 A AC/DC power converter, previously used for the operation of the LEP klystrons. A five-gap thyratron crowbar protects the four klystrons in each of these units. The technical specification and measured performance of the various high-power elements are discussed. These include the 400 MHz/ 300 kW klystrons with emphasis on their group delay and the three-port circulators, which have to cope with peak reflected power levels up to twice the simultaneously applied incident power of 300 kW. In addition, a novel ferrite loaded waveguide absorber, used as termination for port 3 of the circulator is described, including its advantages with respect to a water-load. A system to measure the harmonic content in the klystron output signal is also presented.

INTRODUCTION

The European Laboratory for Particle Physics (CERN) is presently constructing the Large Hadron Collider in the existing 27 km circumference LEP tunnel. The two counter-rotating proton beams are captured and then accelerated by two identical 400 MHz RF systems. Superconducting cavities, operating at 4.5 K, provide the required accelerating field for ramping the beam energy up to 7 TeV. A maximum of 4800 kW of RF power is generated by sixteen 300kW/400 MHz klystrons. Each klystron feeds, via a Y-junction circulator and a WR2300 (half-height) waveguide line, a single-cell SC cavity. Eight of these cavities of are installed on each side of the former LEP intersection ‘Point 4’. Four of them are housed in a common cryostat. The two beams are separated by 420 mm for about 45 m on each side of ‘Point 4’. This allows the SC cavities to be installed without interfering with the vacuum pipe of the respective other beam. All klystrons with their circulators and loads, the HV interface bunkers, and the racks with the controls and interlock electronics are located on the ground floor of the former ALEPH experimental cavern, about 6 m below the beam lines. The average waveguide length between klystron and cavity is about 22 m.

Four klystrons are powered by one 100 kV/40 A power converter, previously used for the LEP klystrons. Their HV interface equipment, consisting of four modulators, a thyratron crowbar, a smoothing capacitor and an HV commutator, is housed in a fire-proof bunker. This forms, together with four cavities, an ‘LHC/RF Module’ (Fig.1).

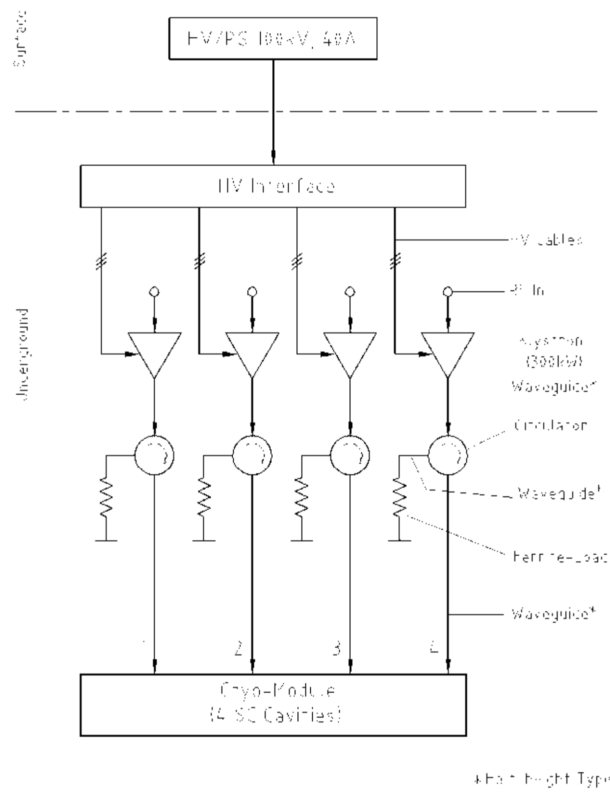

Figure 1: Schematic diagram of an LHC/RF module.

KLYSTRONS

The LHC klystrons were developed by a European company according to CERN specifications. By May 2003 (PAC 2003), five of the 20 klystrons ordered have been delivered and accepted by CERN. The main operating parameters at the rated output power (300 kW) are shown in Table 1.

An important parameter for the LHC klystrons is their group delay. CERN demands the group delay to be as short as possible since a fast vector feedback loop around each klystron/cavity assembly is required for beam stability. The total delay of this loop should not exceed 500 ns. At the acceptance test of the prototype a delay slightly over 100 ns was measured. For the series klystrons a value of ≤ 120 ns within the frequency range of $f_0 \pm 1$ MHz was then specified. Such a low group delay is obtained by tuning the five klystron cavities each either above or below the operating frequency. In particular the first two cavities are stagger-tuned. This increases the bandwidth of the klystron as required for low group delay. In addition, the loaded Q factor of the input cavity is well below 200 and that of the output cavity is 35. The penultimate cavity is tuned to more than 2% above the operating frequency, and therefore contributes little to the total group delay within the specified frequency range. The third cavity is tuned to a few MHz below the second harmonic of the operating frequency; it does not contribute to the group delay but enhances the klystron efficiency by about 4-5%. About 10% of the group delay is due to the electron transit time between input and output cavity.

The relatively low Q and the detuning of the input cavity causes, however, a low overall signal gain of only 37 dB; this is unusual for klystrons.

Table 1: Main Klystron Parameters at Rated Output Power

Rated Output Power	300 kW cw
Operating Frequency (f_0)	400.8 MHz
RF Input-to-Output Gain	≥ 37 dB
DC-to-RF Conversion Efficiency	≥ 62 %
-1dB Bandwidth (@1dB below rated output power)	≥ ±1 MHz
Group Delay at f_0±1MHz and 1dB below rated output power	≤ 120 ns
Load VSWR at any RF Phase	≤ 1.2
Harmonic Content in Output Signal at 2nd and 3rd Harmonic	≤ -30 dB
Beam Voltage (U_B)	54 kV
Beam Current (I_B)	≤ 9 A
Gun Perveance	1.5mA/$V^{3/2}$ -0/+10%
Modulation Anode Voltage (U_{MA})	≤ 35 kV
Modulation Anode Current (I_{MA})	≤ ±2.5 mA
Body Dissipation	≤ 10 kW
Collector Dissipation Capability	≥ 500 kW
Test Power at U_B ≤ 58kV and I_B ≤ 10A (for at least 1 hour)	330 kW cw

A special feature of the LHC klystron is the built-in modulation anode. It allows the cathode current to be controlled between 0 and 10 A. Unlike the LEP klystron, the LHC one does not require the cathode current to be ramped down in the absence of an RF drive signal, because the water-cooled collector of the LHC klystron can dissipate the full DC input power of 500 kW. The modulation anode is used only for optimizing the working point of the klystron.

The tube operation is stable up to the rated output power for a load mismatch of VSWR ≤ 1.2 which is assured by a three-port junction circulator in the output line of each klystron. In case of a higher VSWR (e.g. an arc in the output waveguide) a fast PIN-diode switch interrupts the RF drive signal to the klystron.

CIRCULATOR WITH TERMINATING LOAD

The LHC/RF three-port circulators must cope with high peak power levels, induced in the SC cavities by the proton beam. During injection they can be as high as twice the incident klystron power of 300 kW. These reflected signals are in the microsecond range and their contribution to the power dissipation in the circulator is negligible. However, the superposition of incident and reflected signals could cause arcing between the ferrite plates. This was simulated on the prototype circulator by short-circuiting the output port and applying the appropriate input power (P_{IN}), which is defined by:

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

For P_F = 300 kW and P_R = 600 kW the input power P_{IN} is 440 kW. No arcing was observed when 440 kW were applied with the short-circuit at port 2 being moved by steps of 5 cm over half a waveguide wavelength.

The saturation magnetization of the ferrites is temperature dependent. The external magnetization of the ferrites has therefore to be adjusted as a function of their temperatures, which depend on the incident and reflected power and cooling water temperature. The external field is generated by both a permanent and an electro magnet. The temperatures of the cooling water and the permanent magnet are measured, and the 'Temperature Control Unit' adjusts the current of the electro-magnet accordingly. At RF power levels up to 330kW and inlet water temperature variations of 25 ± 3°C the input match (S_{11}) and isolation (S_{12}) of the circulator can, thus, be kept at ≤ -28 dB within the specified bandwidth of f_0 ± 1 MHz .

For reasons of better performance and smaller size it was decided to use 330 kW ferrite-loaded waveguide absorbers instead of water-loads as port 3 terminations. In such a load small ferrite tiles are glued onto the inner walls of a waveguide, which is short-circuited at its far end. A crucial parameter is the power dissipated per unit surface of ferrite, which should not exceed 15 W/cm^2. It is achieved by choosing thin ferrite tiles at the input of the load and by gradually increasing their thickness towards the shortened end. The advantages of ferrite compared to water loads are the absence of water inside the waveguide or coaxial line, smaller size, higher bandwidth, and a nearly invariable phase angle of its reflected signal as a function of the absorbed power.

The total input reflection of the circulator is composed of S_{11}, S_{12}, and S_{13} (see Fig.2). The magnitudes of S_{12} (isolation) and S_{13} (reflection from ferrite load) are both about -28 dB. The phase angle between these two signals is virtually constant and independent of input power and load mismatch at port 2. By adjusting the electrical length of the waveguide between circulator and ferrite load this angle can be made 180°. The input reflection can thus be reduced substantially and becomes nearly independent of the load conditions at port 2. An almost constant circulator input impedance is essential for stable klystron output power.

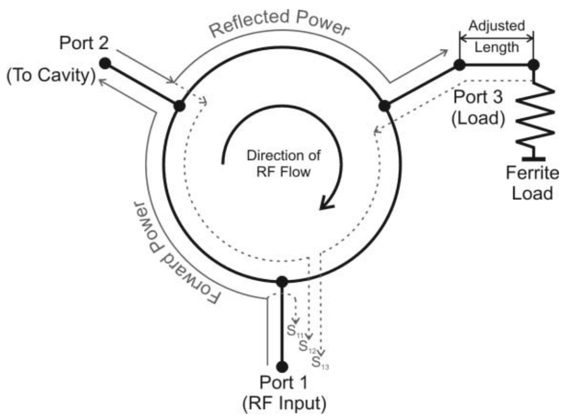

Figure 2: Schematic Diagram of Circulator with Termination Load

The standard 'Temperature Control Unit' (TCU) can cope with slow water temperature and load mismatch variations only. This is due to the time constant of the circulator's cooling circuit. If there are fast and large variations of one or both parameters the input VSWR of the circulator could briefly exceed the specified value. To avoid this, the TCU monitors the reflected RF signal between klystron and circulator. An additional built-in microprocessor controlled loop acts on the magnet current and minimizes rapidly the reflected signal as can be seen in Fig. 2. In this measurement the inlet water temperature was periodically varied by a few degrees.

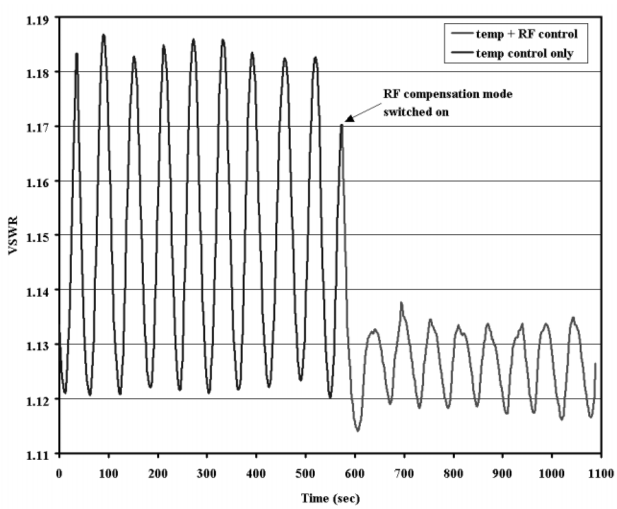

Figure 3: Input VSWR of the circulator with and without RF control at varying water temperatures

HARMONIC SIGNAL MEASUREMENTS

An advanced system for measuring the harmonic content in the klystron output signal based on [1] was developed. It consists of a piece of WR2300 half-height waveguide equipped with calibrated RF probes, an RF switching matrix, band filters, a vector voltmeter and a control computer. The system measures the power levels of all possible propagating modes at the fundamental (TE10), second (TE10, TE20, TE30), and third harmonic (TE10, TE20, TE30, TE40, TE11, TM11, TE21, TM21, TE01). Three probes are used at the narrow and nine probes (including a reference one) at the wide wall of the waveguide for measuring the electric field pattern. These data are inserted into a set of field equations, and the control computer calculates the power of each propagating mode. In its present state, measurements can only be performed using a wideband load, which is matched (VSWR≤1.12) in the frequency range from 400 to1200 MHz.

Measurements performed on the klystrons delivered so far indicate that the 2nd harmonic content is more than 50± 1 dB, and the 3rd harmonic more than 28±1 dB below the fundamental signal. The TE_{30} mode of the 3rd harmonic signal contains about 50% of the parasitic energy. These measurements will help to determine the type of HOM dampers, which may be required in the waveguide system to avoid arcing.

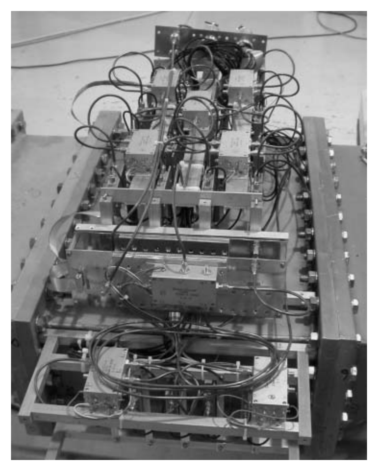

Figure 4: Harmonic measurement device

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REFERENCES

[1] W.R. Fowkes and E.S. Wu, "Multimode Harmonic Power Output Measurement of SLAC High Power Klystrons". SLAC-PUB-3009, November 1982