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DESIGN AND CONSTRUCTION OF A 500 KW CW, 400 MHZ KLYSTRON TO BE USED AS RF POWER SOURCE FOR LHC/RF COMPONENT TESTS

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Abstract

A 500 kW cw klystron operating at 400 MHz was developed and constructed jointly by CERN and SLAC for use as a high-power source at CERN for testing LHC/RF components such as circulators, RF absorbers and superconducting cavities with their input couplers. The design is a modification of the 353 MHz SLAC PEP-I klystron. More than 80% of the original PEP-I tube parts could thus be incorporated in the LHC test klystron which resulted in lower engineering costs as well as reduced development and construction time. The physical length between cathode plane and upper pole plate was kept unchanged so that a PEP-I tube focusing solenoid, available at CERN, could be re-used. With the aid of the klystron simulation codes JPNDISK and CONDOR, the design of the LHC tube was accomplished, which resulted in a tube with noticeably higher efficiency than its predecessor, the PEP-I klystron. The integrated cavities were redesigned using SUPERFISH and the output coupling circuit, which also required redesigning, was done with the aid of MAFIA. Details of the tube development and test results are presented.

Figure I: 500 kW, 400 MHz LHC Klystron

1 INTRODUCTION

SLAC already constructed a 500 kW cw klystron for CERN in 1980. At that time this was a PEP-I tube with an operating frequency of 353.2 MHz, which at CERN was tuned to 352.2 MHz, the LEP/RF frequency. This klystron served for many years as RF power source, required for the conditioning of LEP RF cavities.

Since a similar RF power source would be required in 1997 for the testing of LHC/RF equipment, such as cavities, windows, couplers, circulators and absorbers, it was proposed by the first author, while on sabbatical leave at SLAC, to redesign the PEP-I klystron so that it could be operated at 400.8 MHz, the LHC/RF frequency. The redesigned PEP-I klystron, in the following referred to as LHC tube, was manufactured by SLAC and shipped to CERN in 1996. More than 80% of the original PEP-I tube parts could be incorporated, among them major components such as the collector with its water jacket, the electron gun assembly, parts of the five stainless steel RF cavities, and the coax-to-waveguide output transition with the cylindrical ceramic window. The first two components could be used without any modifications whereas the two latter ones had to be matched to the higher operating frequency. The re-use of auxiliary equipment of the PEP-I tube, still available at CERN, such as cathode oil tank with HV plug, beam focusing solenoid and main support girder, resulted in lower engineering costs too.

Prior to shipment the LHC tube was high-power tested at SLAC. The test results were in good agreement with those obtained at CERN, where the high-power test was repeated. As predicted by computer simulations the DC-to-RF conversion efficiency of the LHC tube, an important parameter for high power sources, was measured and found to be noticeably higher than that of its predecessor.

II DESIGN

As mentioned above, the PEP-I electron gun assembly and collector have been incorporated in the LHC tube without any modifications. The cathode is of the dispenser type which is less susceptible to poisoning by metal vapours and gases than an oxide one.

With a cooling water flow ≥ 400 l/min the collector can dissipate up to 770 kW. This corresponds to the DC input power required when the tube is operated at rated RF output (500 kW cw). Consequently there is no need to switch the HV off or to reduce it in case of an RF drive trip.

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The output transition, consisting of a 56 Ω coaxial line, a cylindrical ceramic window, and a reduced-height WR 2100 waveguide, followed by a full-height one, had to be matched to the higher operating frequency. After having repositioned an existing inductive post in the full-height waveguide section and properly terminated both line ends, the input reflection (S11) of the assembly was measured to be -44 dB (VSWR = 1.01) at 400.8 MHz.

Since the operating frequency of the LHC tube is only 13.5% higher than that of its predecessor, the drift tube diameter of 7 cm could be maintained as well. At nominal operating voltage (V_b =63 kV) and a focusing field of B = 210 Gauss, which is 2.7 times the Brillouin induction, the beam diameter is 4.5 cm, yielding a fill factor of 0.64 for both tubes. The normalized drift tube radii, the product of radial phase propagation constants,γ, and drift tube radius, of the PEP-I and LHC tube, are 0.5 and 0.57 radians respectively. Both values in combination with the given fill factor result in a high coupling coefficient between beam and cavity fields, a prerequisite for a good tube efficiency.

The unusually short drift tube between anode housing and input cavity of the PEP-1 tube was replaced by a longer one in order to reduce the risk of RF leakage from the first cavity into the cathode region. A 34 mm longer input drift section, already incorporated for the same reason in the B-Factory prototype klystron [1], was chosen. In order to preserve, however, the above-mentioned interchangeability of the beam-focusing solenoid both tubes must exhibit the same physical length between cathode plane and upper pole plate. Therefore the section between input and output cavity gap, constituting the RF interaction space, had to be made shorter in the LHC tube.

With the aid of the one-dimensional klystron simulation code JPNDISK and the two-dimensional CONDOR code the lengths of the drift sections between the five cavities and the cavity frequencies, required for optimum efficiency, were determined. The geometries of the cavities, which are all of the re-entrant type, were established by using SUPERFISH. It appeared that all but one of the cavity shells could be re-used without modifications; only the gap widths had to be widened by shortening one of the two drift tubes inside each cavity. In the penultimate cavity, however, the original gap was relatively wide and its width could not be further increased without sacrificing tube performance. Keeping the diameter of this cavity unchanged but reducing its length by 65.3 mm resulted in the desired gap transit angle of 0.78 radians.

For optimum efficiency all fundamental cavities have been tuned to frequencies which are higher than the tube operating frequency. The 2nd harmonic cavity, (cavity#3),however, had to be tuned 0.5% below the second harmonic of the operating frequency in order to achieve maximum tube efficiency. JPNDISK predicted that the efficiency would drop from 70 to 45% when the resonant frequency of this cavity is increased by less than 1% above its optimum value. Computer simulations also indicate that the 2nd harmonic cavity, when correctly tuned, contributes approximately 3% to the tube efficiency.

The output cavity resonant frequency and external Q could not be directly determined using SUPERFISH. The resonant frequency is due to the presence of the PEP-I output coupling loop typically about 2.5% lower than that of an uncoupled cavity. This was taken into consideration when the output cavity frequency of the LHC tube was calculated. SUPERFISH calculations indicated that the gap width had to be increased by 16 mm. Unfortunately, when the PEP-I loop configuration was kept unchanged, the measured Q_{ext} was then 123, much higher than the desired optimum of 83. At an external Q of 123 CONDOR simulations predicted an abundance of returning electrons from the output gap, a high electron interception by the output drift tube and an 11% decrease of tube efficiency.

It was decided that the so-called Kroll-Yu method [2] would be used to determine the required changes in the output loop configuration in order to achieve the desired external Q and resonant frequency. For this methode,the cavity with its coaxial output is shorted and modeled on MAFIA. The resonant frequencies of the cavity are calculated for several positions of the short. From these results the external Q and resonant frequency of the cavity, when terminated by a matched load, can be determined.

The Kroll-Yu methode predicted an external Q of 83 when the portion of the loop which is parallel to the tube axis is moved by 10 mm towards this axis. The output cavity was then built as modeled giving a measured Q_{ext} of 85, and the desired resonant frequency was obtained with a small change in the upper nose length.

Table I: Main Design Parameters

Operating Frequency, f_0	400.8 MHz
Beam Voltage, V_b	63 kV
Beam Current, I_b	11.8 A
Beam Perveance, μp	0.75 $\mu A/V^{3/2}$
RF Output Power, P_{out}	506 kW cw
Efficiency at rated Output Power, η	0.68
Saturation Gain, g	42 dB
RF Drive Power, P_{in}	20 W
Focusing Magnetic Field, B	210 Gauss
Reduced Plasma Wavelength, λ_q	4.69 m
Number of Cavities (incl. 2nd Harm.)	5
RF Interaction Length	1.962 m
Normalized Drift Tube Radius, γa	0.57 radians
Normalized Beam Radius, γb	0.37 radians
Beam Fill Factor, b/a	0.64

All design parameters, which are a compromise between using as many original tube parts as possible and yielding optimum tube performance, are listed in tables I and II. When inserting these parameters the efficiency calculated by means of the JPNDISK code is 70% and by using CONDOR 61%. Both values are 1.13 times higher than the corresponding ones for the PEP-I tube. Consequently there was good reason to assume that an LHC tube efficiency of approximately 68% could be achieved, since that of the PEP-I tubes was 60% in average.

Table II: Interaction Space Parameters

Cavity No.	Frequency (MHz)	R/Q (Ω)	Q_{ext}	Gap Transit Angles (Radians)	Drift Lengths (m; λ_q angle)
1	401.1	91	1000	0.47	0.442; 34°
2	402.4	103	∞	1.14	0.142; 11°
3	797.5	84	∞	1.27(@2f_0)	0.870; 67°
4	407.9	100	∞	0.78	0.508; 39°
5	401.5	94	83	0.78	

III KLYSTRON MANUFACTURING

The LHC klystron incorporated many of the manufacturing practices used at SLAC in the manufacture of high peak power pulsed klystrons. The incorporation of some of these more stringent techniques has had a clear benefit on the tube performance.

The SLAC klystron manufacturing philosophy is to obtain as high a vacuum as is economically achievable. Therefore, tube materials are carefully selected and tested, a high degree of cleanliness is maintained throughout the manufacturing process and the entire gun assembly is pre-processed at temperatures up to 1100°C by vacuum induction heating the assembly while simultaneously applying power to the cathode. This outgassing process takes approximately one week and removes the bulk of the gas load from the dispenser cathode assembly. The final processing of the assembled tube is at 550°C on a double vacuum bake station. A consequence of the relatively high bake temperature, combined with the ultra-high vacuum, is that high vapour pressure elements may coat surfaces in the tube. For this reason, silver, which is known to have a detrimental effect on cathode emission, and other high vapour pressure elements have been eliminated from materials used in the construction of klystrons at SLAC. Assembly brazing is therfore conducted in clean dry hydrogen furnaces by using only copper gold brazing alloys.

Another feature is the application of anti-multipactor coatings on suspected surfaces inside the klystrons. In the case of the LHC tube a titanium nitride coating was applied by evaporation technique to the output window and electron gun ceramic. In addition, titanium coatings were applied to the input cavity with coupling loop, cavity 2, the output cavity and output coax areas.

IV TEST RESULTS

The LHC tube was first high power tested at SLAC in June 1996. In less than three days of HV and RF conditioning an output power of 503 kW was achieved at an operating voltage of 65.5 kV and a beam current of 11.9 A.

From these values result a beam perveance and tube efficiency of 0.71 $\mu A/V^{3/2}$ and 64.5% respectively. As both parameters were 5% below their design values a higher operating voltage than the design one was required at saturated output power. A tube gain of 42 dB was measured, which corresponds to the value predicted by the simulation codes.

When the high-power tests were repeated at CERN a slightly higher efficiency, $\eta = 65\%$, was achieved by optimizing the focus coil currents. After about 100 hours of operation the beam perveance also increased slightly to 0.72 $\mu A/V^{3/2}$ so that an output power of 504 kW was attained at $U_b = 65$ kV. The -1 dB output bandwidth was measured to be 650 kHz with the -1 dB frequency points situated at 250 kHz below and 400 kHz above the operating frequency.

During high power tests at SLAC and at CERN no signs of instability were observed in the output signal. Possible causes of instabilities are returning electrons, which usually manifest in an amplitude modulation (side bands) of the output signal, and multipacting which results most likely in an unstable output amplitude.

The absence of multipacting and the short time required for the high-power conditioning are very probably to be attributed to the stringent manufacturing techniques which were applied.

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REFERENCES

[1] W.R. Fowkes, G. Caryotakis, T. G. Lee, C. Pearson, and E.L. Wright, Proc. 1993 IEEE Part.Accel.Conf. Vol.2, pp. 1259-1261.

[2] N.M. Kroll and D.U.L. Yu, Particle Accelerators, 1990, Vol 34, p. 231.