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THE LHC SUPERCONDUCTING CAVITIES

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Abstract

The LHC RF system, which must handle high intensity (0.5 A d.c.) beams, makes use of superconducting single-cell cavities, best suited to minimizing the effects of periodic transient beam loading. There will be eight cavities per beam, each capable of delivering 2 MV (5 MV/m accelerating field) at 400 MHz. The cavities themselves are now being manufactured by industry, using niobium-on-copper technology which gives full satisfaction at LEP. A cavity unit includes a helium tank (4.5 K operating temperature) built around a cavity cell, RF and HOM couplers and a mechanical tuner, all housed in a modular cryostat. Four-unit modules are ultimately foreseen for the LHC (two per beam), while at present a prototype version with two complete units is being extensively tested. In addition to a detailed description of the cavity and its ancillary equipment, the first test results of the prototype will be reported.

1 INTRODUCTION

Cavities having a large stored energy (low R/Q, high voltage) are best suited for the LHC to minimize the effects of transient beam loading due to the long gaps (up to 3 µs) in the high intensity (0.56 A) proton beams [1]. This leads naturally to single-cell superconducting (SC) cavities with large beam tubes very similar to those designed for the high current e^+e^- factories. There will be eight 400 MHz cavities per beam, grouped by four in each of two cryomodules. Each cavity is connected inside a cryomodule to its neighbours by large diameter (∅ = 300 mm) beam tubes and (unshielded) bellows. The operating voltage of the cavities (2 MV during storage, i.e. 5 MV/m) is quite low by to-day's standards, but gives ample margin to boost the LHC RF voltage and reduce bunch length in the future, if necessary.

A variable coupler will equip the LHC cavities in order to give maximum flexibility for the various modes of operation of the cavities during injection, ramping and storage. The cryomodules are located on either side of a long straight section (point 4) where the distance between the two beams has been increased from 195 mm to 420 mm. Additional room-temperature 200 MHz cavities will be installed in the LHC for optimum capture of beams having a large emittance (~ 1 eV.s).

2 CAVITY MANUFACTURE

The cavity technology is similar to that used successfully on a large scale for LEP2 [2]; it is based on niobium film on copper cavities operating at 4.5 K and on a modular cryostat with easy lateral access. Bare cavities are produced by spinning and electron-beam welding and are coated with a thin (1 to 2 µm) thickness) film of niobium by magnetron sputtering. The series production of 21 bare cavities is now being carried out by industry; seven cavities have already been accepted at CERN. Their typical performance is displayed in Figure 1 together with the acceptance curve. The copper wall thickness results from a compromise between tuning force and mechanical stability against buckling. With a thickness of 2.8 to 3 mm, the cavity axial spring constant is about 20 kN/mm.

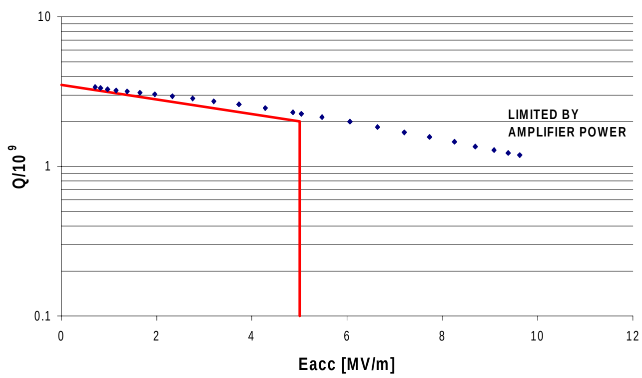

Figure 1: Typical cavity performance and acceptance curve

The helium tank of each cavity is made of 2 mm thick stainless steel. Its cross-section is cylindrical around the cavity cell and octagonal at the location of the ports. The four helium tanks within a cryomodule are interconnected at the liquid and gas levels in such a way that a common helium feed and a common gas return are sufficient (Figure 2). Individual safety exhaust pipes with rupture disks are, however, provided for each cavity. As in LEP, each cavity cradle is suspended inside the cryostat to allow for contraction during cooldown. The longitudinal fixed point corresponds to the main coupler position to avoid stresses on the double-walled tube. Neither a magnetic shield nor a heat shield is necessary. The measured static losses of the prototype cryomodule (having only two cavities, no couplers and no second beam tube) amount to about 25 W.

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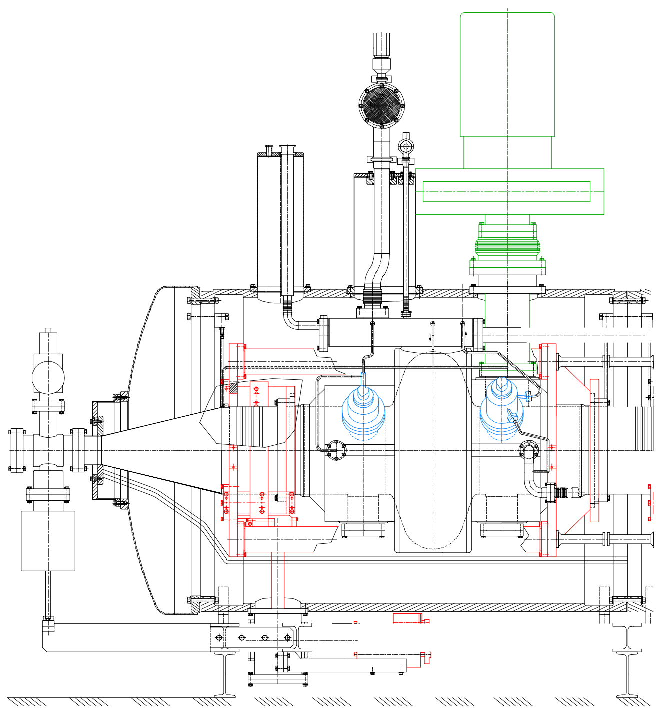

Figure 2: Partial view of the prototype cryomodule with two cavities (a series cryomodule has four cavities)

A modular construction was adopted for the vacuum tanks of the cryomodule (Figure 2). Each tank is a stainless steel cylinder, without any welds, with large lateral openings to permit easy access to the cavity. The four cavities are connected together with the wide bellows in a clean room; this assembly is then rolled inside the complete vacuum tank. The main couplers are mounted last, again in a clean room. It is also possible to disassemble and reinstall a single cavity in the middle of a cryomodule, without moving its neighbours. The second beam tube (cold) is attached to the side of the cavity cradle.

3 TUNER

Contrary to the case of LEP cavities [2], the LHC cavity tuner is purely mechanical in order to provide the large tuning range at full speed required to compensate beam loading. The cavity cradle, with its two thick end plates joined by four columns forms a rigid assembly, free of harmful resonances, which can take the strong tuning forces (~ 20 kN) without excessive deformation. The cavity end plate and the cradle end plate are pulled together via thin (0.75 mm) stainless-steel blades and torsion shafts with long lever arms (Figure 3). This arrangement provides a lever action (ratio 14:1) without sliding parts or backlash. The internal stresses (290 Mpa) inside the blades stay below the elastic limit.The axial force and movement at the extremities of the two lever arms, inside the cold cradle, are transferred to the outside via two thin-walled stainless-steel cylinders acting as counter-rotating torsion shafts The latter are driven by stainless steel cables (∅ = 3 mm) providing again a transmission without friction or backlash.

Furthermore, this system allows displacement of the cradle during cooldown and provides a low heat conductance. A slightly different version of this tuner

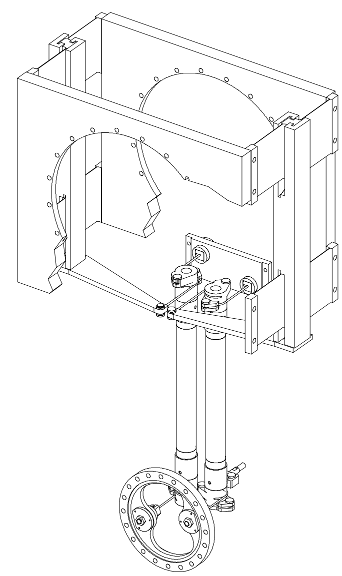

Figure 3: Tuner mechanism

was successfully tested on the prototype cryomodule; the achieved tuning range and speed (limited by the stepping motor) were 180 kHz and 9 kHz/s respectively. The resolution is too small to be measurable.

4 POWER COUPLER

The LHC variable coupler is an upgraded version of the LEP2 fixed coupler [2][3] (Figure 4). An open-ended 75 Ω coaxial line is coupling to the cavity. The outer conductor (not represented in Figure 4) is made of copper-plated stainless-steel (double-walled) and cooled with 4.5 K helium gas, while the inner conductor (antenna) is a copper tube cooled by forced air. A cylindrical ceramic window, with massive copper rings brazed on its edges is placed in the waveguide-to-coaxial transformer. A reduced height waveguide provides directly the matching to the coaxial line, avoiding the usual “doorknob”. In order to suppress multipactor during operation, a d.c. bias of 3 kV is applied to the antenna, isolated from ground with a coaxial capacitor mounted in the waveguide. Air cooling is provided on the window and other critical elements of the coupler. A vacuum gauge and an electron pick-up antenna are located close to the window.

The antenna is moved (60 mm stroke) by making use of bellows about λ/4 long. A low impedance (7Ω) λ/4 line transformer brings the current in the bellows to low enough values, not requiring copper plating of this stainless steel part. The displacement of the antenna is guided by a (motor driven) high precision device.

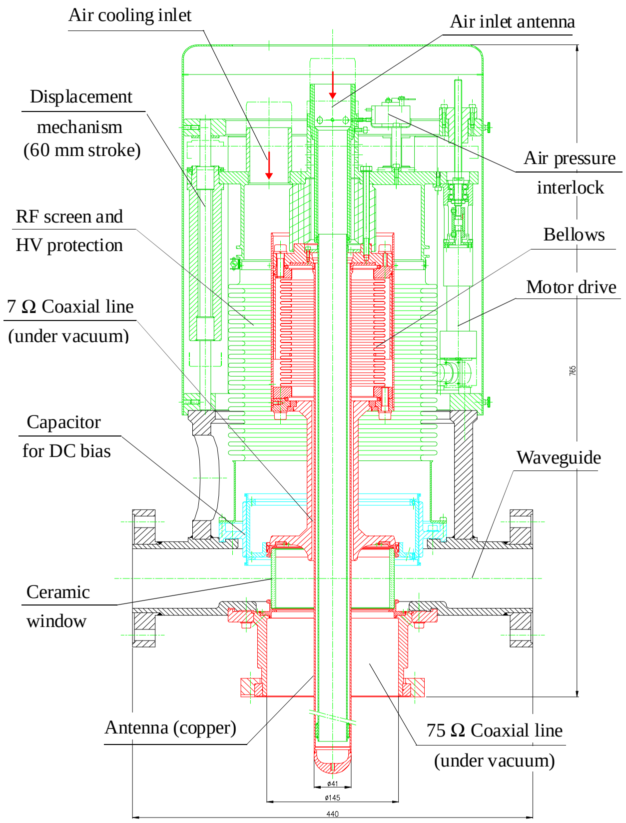

Figure 4: The LHC variable coupler

Two prototype LHC couplers have been manufactured, assembled and vacuum-tested. Technical problems occurred during electron-beam welding of the ceramic window to the copper body and during titanium coating of the vacuum side of the ceramic, resulting in the breaking of some ceramic windows. Solutions to avoid these failures have been found. We also suffered from the bad quality of the OFE copper material used for the copper body, which developed vacuum leaks after baking out at 200°C for 24 h. In the future forged OFE copper will be used.
High-power RF tests at room temperature were done with two couplers, mounted horizontally on a 400 MHz copper test cavity. One coupler is connected to a 500 kW 400 MHz klystron [4], via a circulator, the second to either a 1 MW load or to a mobile short circuit. In travelling-wave mode, and with a pressure limit of 2×10^{-7} mbar, the RF power could be ramped between 15 and 500 kW, crossing several multipactor levels, for which d.c. bias was effective. Below 15 kW multipactor occurred inside the 7Ω λ/4 line, with no electrons picked up on the antenna and no influence of d.c. bias. (An additional bias on the λ/4 line is being considered.) The maximum power could be sustained for long periods (400 kW for 150 hours, 500 kW for 50 hours) with no sign of damage inside the coupler.
At full reflection, any phase and any coupling the coupler sustains a 500 kW forward power (2 MW equivalent power) provided it is pulsed (50 ms on, duty cycle 10%) to avoid local overheating.

5 HOM COUPLERS

During the design of the LHC cavity its higher order mode (HOM) characteristics were carefully studied [5]. Due to the large iris diameter and a cell length smaller than λ/2 , only two of the HOMs do not propagate into the intercell beam tubes. These are the two dipole modes TE_{111} and TM_{110} which also have the highest coupling impedance of all transverse modes. Clearly for damping them beam tube couplers near the cells are needed. These are of a doubly resonant type and tuned to provide equal shunt impedances (R/Q)*Q of about 1.5 kΩ for the two modes with one coupler mounted for each polarization.
In addition two broadband couplers are installed per cell. Derived from LEP design they can each carry a HOM power of 800 W. They have response peaks near the frequencies of the high (R/Q) mode TM_{011} (770 MHz) and the trapped mode [5] TM_{012} (1240 MHz) respectively. On a model cavity external Qs of 500 have been measured for these modes ensuring that even if mode excitation by the LHC beam is resonant the RF power coupled out will not exceed 500 W.

6 ACKNOWLEDGEMENTS

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