FINAL TESTS AND COMMISSIONING OF THE 400MHZ LHC SUPERCONDUCTING CAVITIES

P. Maesen, E. Ciapala and G. Pechaud, CERN, Geneva, Switzerland.

Abstract

The four LHC RF modules, each containing four 400 MHz single cell cavities, were successfully completed and installed in the LHC tunnel in 2006. A number of minor modifications were made to the original construction to improve reliability in operation and to obtain tighter control on the otherwise large spread in the tuning ranges of individual cavities. After fitting of the variable power couplers, careful power processing was applied to bring all cavities to 8 MV/m, i.e. 1.5 times the nominal, and to the maximum 300 kW forward power. Reaching the goal of full performance without major incident has been the result of careful clean room assembly, careful vacuum operation and ensuring proper operation of all protection systems during RF operation. Preparation for operation in the LHC is now ongoing, where the modules will operate from same cryogenics distribution line as the LHC's superconducting magnets.

HISTORY

In the 1990s a prototype LHC bi-module was built for validation tests [1]. The final production design was based on four-cavity cryomodules. Five modules were produced, four for installation in LHC, two per beam, and one spare. A total of 21 single cell 400 MHz niobium sputtered copper cavities were produced in industry. Vertical cryostat acceptance tests were done at CERN to confirm individual Q/Eacc characteristics, against a specified Qo of 2.0E9 at 5 MV/m. Assembly of the cryomodules was completed in 2003 and initial tests started [2]. The subjects of this paper are the final acceptance tests, RF conditioning and the additional modifications that proved necessary before the modules were installed in the LHC tunnel.

DESIGN OF THE CRYOMODULE

The cryomodule houses four single cell cavities, designated A to D. The beam enters in cavity D. RF power is fed in via a port on the cut-off tube near the cavity. There are also ports for three field measurement antennas. Each cavity is mounted in a tuning frame [1]. This allows mechanical stretching of the cavity by approximately 1 mm, giving a frequency tuning range of roughly 175 kHz. The resonant frequency, 400.8 MHz, corresponds to mid-range. There are four HOM couplers per cavity, two narrowband to filter at 540 MHz, where the cavities have an additional resonance, and two wideband couplers to remove all frequencies above 700 MHz. Each cavity is housed inside an 80 l capacity helium tank, with a helium reservoir mounted on top. Four domes on the cryostat provide connections for safety valves, level and pressure gauges and other equipment. The helium reservoirs are interconnected by large diameter piping. Liquid helium is supplied to the module via another dome on cavity A and gas recuperated through a similar dome on cavity D. A particular feature is the 'second beam tube', NEG coated, which traverses the cryostat allowing the counter rotating beam to pass by the cavity with horizontal separation of 420mm.

Critical vacuum equipment like Penning gauges on the main couplers play a very important role in protection of cavity and coupler during RF operation as well as during conditioning.

Figure 1: Coupler mounting in class 10 clean room.

FINAL ASSEMBLY

The long process of series production and preparation of the complex high power mobile couplers [3] resulted in these only being available in 2004 for assembly onto the modules. The modules, otherwise complete, were returned to the clean room for this work.

Special procedures were followed in order to minimize the complexity of the work and the number of operations exposing the niobium of the cavity to normal atmosphere. The couplers with their mounting bolts were prepared in a separate small clean room. The module itself was suction cleaned, sprayed with dry nitrogen and thoroughly cleaned with dust free cloth when entering the class 1000 room, where it stayed for one day. After transfer to the adjoining class 10 room and another stay of at least of one night, the four couplers were mounted, using the minimum necessary personnel (Figure 1).

Vacuum procedures

As after any major operation, pumping and leak test on the vacuum of the cavity was carefully executed.

The accepted leak rate was < 2.0E-9 mbar.l /s.

After installation, in order to extract as much of the absorbed water on the coupler ceramics, the four couplers were baked out at 200 °C and again leak tested. This prepared the couplers for conditioning and also verified the robustness of all sealing joints under thermal stress.

The completed module was then installed in a radiation safety bunker for RF testing. A residual gas analyser was first attached and baked out before opening the vacuum valve connection. This provided a reference spectrum before starting RF power tests. Special attention was paid to continuous recording of cavity and insulation vacuum.

LOW LEVEL TESTS

External Q, frequency tuning range and antenna external Q.

A special waveguide transition with 'N' connector was installed on the coupler for measurement of the external Q vs. coupler position and the measurement of the tuning frequency range. Typical external Q varies between 12000 and 180000 according to the position of the variable coupler.

In Table 1, it can be seen that a 25 kHz change of resonance frequency of the cavity occurs over the coupler antenna excursion of 60 mm, with the tuner remaining fixed.

The antenna external Q is obtained from Eq. 1:

$$Q_{A\,ext} = \frac{4Q_{ext}}{10^{(T/10)}} \qquad (1)$$

Where T is the attenuation in [dB] from the coupler to the antenna, and Qext is the quality factor of the cavity loaded by its main coupler.

Table 1: Qext measurements on LHC 3 cavity A

Coupler Pos.	Res. Frequency [MHz]	Q ext	Attenuation [dB]
0	400.705	179600	-51.05
10	400.704	110600	-53.2
20	400.702	64800	-55.5
30	400.689	40400	-57.5
40	400.694	26300	-59.5
50	400.688	17200	-61.3
60	400.681	11800	-63.0

Tuning range

The cavity is mounted in a tuning frame and tuned by stretching, using a pair of rotating torsion blades. The lower limit of the tuning range depends on the natural un-tensioned geometry of the cavity. In order to be sure that this does not change during initial operation, when the cavity will be subjected to many cool-downs and warm-ups, all the cavities have undergone a process of thermal cycling. This consists of six cycles of cooling down to 50 K followed by warm-up to room temperature. It was found that a number of cavities had natural resonant frequencies substantially higher than the lower limit needed to give a good detuning margin in LHC operation. Plastic deformations were applied to almost all the cavities in the warm state in order to correct this, but after subsequent recycling a number of cavities still remained too high in natural frequency (see Figure 2).

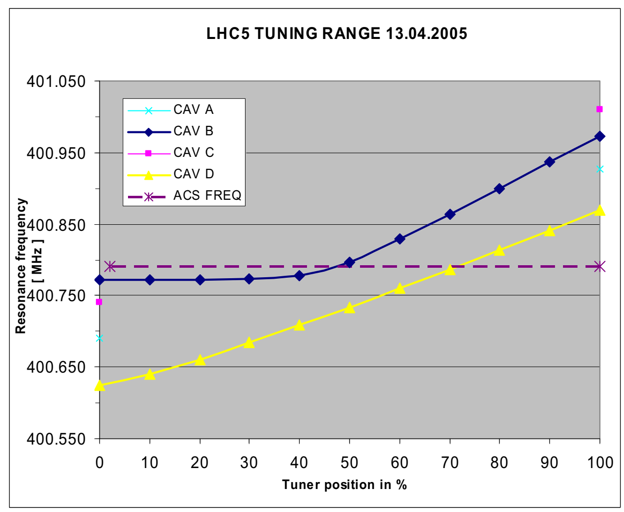

Figure 2: Module LHC 5 cavities tuning range after thermal cycling. Here cavities B and C are too high in frequency.

Tuning spring compensation

In order to reduce the natural resonance frequency of the cavity, a special screw adjustable spring mechanism was devised. This uses a column of disc springs to provide the required force to pre-compress the cavity and adjust the frequency *in-situ*. A set of four mechanisms are mounted between the fixed part of the tuner frame and the free side of the cavity, around its circumference. (See Figure 3)

Figure 4 shows the tuning ranges of the cavities of the same module after fitting compensating mechanisms on two of the cavities.

Compensation has been applied to just over half of the cavities, bringing the margin between the lowest tuneable frequency and the LHC frequency to better than 70 kHz on all cavities.

BUNKER POWER TEST SETTING UP

All the completed main couplers were power tested in pairs on a special cavity test bench [3] to ensure operational values could be obtained reliably and to minimise reconditioning after being mounted onto the module.

This operation carries very high risks; any damage to the ceramic could lead to vacuum breakdown and resulting catastrophic dust contamination of the cavities niobium surfaces. Complete protection has to be provided by the control and interlock systems.

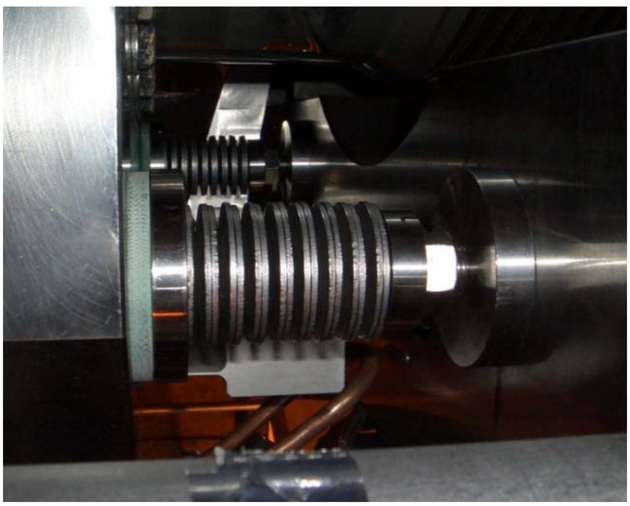

Figure 3: Two of the four tuning spring compensators mounted on a cavity.

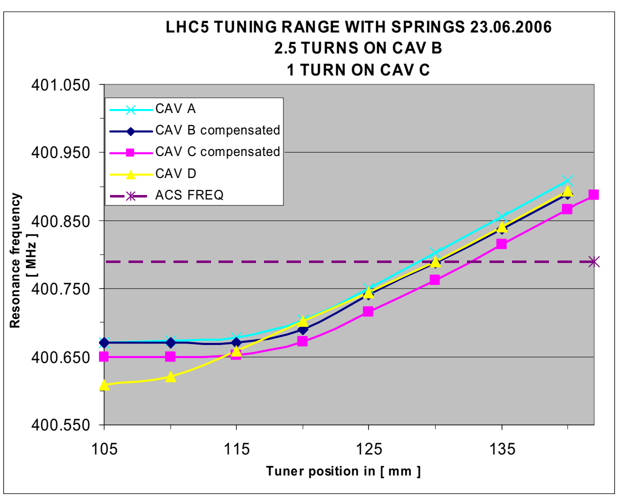

Figure 4: Module LHC 5 tuning range after fitting spring compensators on cavities B and C.

Slow interlock and control

Most of the 'slow' interlocks, e.g. on temperatures, cooling water and air flows are controlled by industrial PLCs [4]. The module's helium level and helium tank pressure are controlled by the cryogenics plant slow control processes.

Fast Interlock

Two types of hardwired, fast interlocks systems are used. One system for personnel protection interlocks HT equipment, emergency stops, bunker access and radiation monitoring equipment, shutting down the 60 kV power supply.

The second one rapidly (in 3 µs) shuts off the RF generator. It mainly reacts to He tank overpressure, waveguide arc detectors and vacuum pressure rise near the couplers. Full verification of both these protection systems before applying high power RF is mandatory.

Cooling Down

In order to avoid difficulties in stabilising the He level and bubbles forming in the helium tanks and interconnecting pipes, the best cooling procedure consists of slowly decreasing the temperature of the cavities towards 50 K over one night, using a smooth flow of He gas. This allows rapid filling the next morning. However, it takes three weeks of cold operation to fully bring all mechanical parts to their stable temperatures and obtain a constant tuning range.

POWER TESTS

RF coupler and cavity conditioning

Conditioning the main coupler [3] and the cavity field takes approximately two weeks per cavity. The process starts with pulsed RF, with a gradual increase of the pulse width and amplitude using an automatic control process, based on a fast loop using the vacuum analogue measurement. Radiation monitoring, faster than vacuum measurement, can also be introduced as a parameter to help with difficult surface cleaning-up, by avoiding fast quenches in the cavity. Frequency modulation is also applied. As the coupler is variable, the RF conditioning has to be repeated at different coupler positions. Maximum cavity field is obtained with the coupler set for minimum coupling, cavity conditioning is therefore dominant at this position. There was no evidence of time saving by starting conditioning the power in the coupler or the field in the cavity first.

All cavities have been conditioned to 8 MV/m and the coupler taken to 300 kW forward power. The nominal cavity gradient is 5.5 MV/m. While certain cavities could certainly have been conditioned to much higher field levels, this value was chosen due to time constraints, the resulting margin of almost 50 % being more than adequate for LHC operation.

Heat run

The last test on a cavity in the bunker consists of a 24 hours run at 300 kW cw onto the coupler with 6 MV/m in the cavity, checking possible temperature drifts and vacuum pressure rises due to the heating of the power coupler parts. Here, the precise flow of helium gas, towards the recovery line, inside the double-walled tube of the coupler is verified as well as the air cooling of the coupler antenna.

At the end of the power tests, another residual gas spectrum is compared to the reference one to detect possible degradation of the surfaces.

Other modifications

During the course of these tests, small modifications have been done to improve certain pieces of equipment on the modules. New tuner bellows have replaced the original ones which had defective welds. The helium domes on the module have been completely redesigned with welds replacing screw-tightened seals. Extended vacuum insulated double tubing was added to the safety valve outlets to avoid ice formation and risk of damage to the safety valve connections.

HIGHER ORDER MODE COUPLERS

Each cavity is equipped with four HOM couplers, two dipole mode and two broadband [5].

At the end of conditioning, on reaching maximum field, each HOM antenna signal was measured for fundamental rejection.

A full measurement of HOM attenuation efficiency has been made on one module. A typical result, the transfer function around 500 MHz with HOMs loaded and unloaded, is shown in Figure. 5.

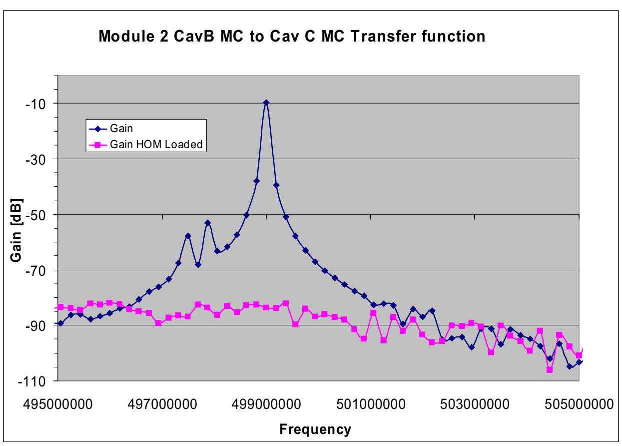

Figure 5: Loaded and unload HOM transfer function from one cavity input coupler to its neighbour, showing the attenuation of the unwanted mode.

CRYOGENICS ISSUES IN LHC

For reasons of economy and available space, the LHC RF cavities will be fed from the same cryogenic distribution line (QRL) that feeds the magnets. This presents certain difficulties and while a number of other operating scenarios have been studied for later implementation [6], a number of immediate issues had to be resolved for the present cryogenics configuration.

Protection against overpressure

Four safety valves of diameter 25 mm at 1.8 bar, plus four rupture disks of diameter 80 mm at 2.1 bar absolute, are mounted on each module. These protect the cavities against pressure rise associated with a full quench

Due to the operating pressure of the input line, the operating pressures of the helium tanks will be somewhat higher than originally foreseen, i.e. 1.35 bar instead of 1.25 bar. The resulting safety valve settings are consequently higher than the specified warm helium tank design pressure. A switch over system has been added, introducing safety valves at 1.5 bar, when the cavities are not cold.

A multiple magnet quench in the same machine sector as the cavities is expected to be able to produce up to 20 bar pressure in the output line D. Any pressure level approaching this would be catastrophic for the cavity helium tanks. There are three protection systems: the normal PLC control on the outlet valve of the module, a fast acting fail-safe closing of the valve using a pressure sensor and finally a non-return valve.

Warm recovery line

A Warm Recovery Line (WRL) is installed for the cavities in LHC to permit recovery of He from static losses in the module if the outlet lines have to be closed, and avoid opening of the safety valves.

In addition to the fitting of the new domes on the modules, one additional He outlet dome has been added on each module for the connection to the WRL. This was relatively straightforward, due to the modular design of the cavity and cryostat. The blanking pieces normally in place on the middle cavites, where there is no helium inlet or outlet dome, could be replaced with another connection to the helium circuit. Cavity B was taken.

INSTALLATION IN LHC

Transport

Each module contains 52 ceramic feedthroughs, one breakdown would need complete dismantling of the module to rinse the cavities. Transport has been organized at 10 km/h maximum speed, with cavities under vacuum and a shock log attached to the module. From the test area to its slot in the machine, acceleration no higher than 0.3 g has been recorded. Rapid vacuum pumping and monitoring confirmed the safe transport and installation in P4 of LHC.

Alignment

Survey experts have made reference measurements on the completed modules before transport. The beam tube flanges have been measured with respect to the alignment targets on the module. Once in place in the tunnel, the modules have been aligned according to their corresponding database longitudinal start point, together with the computed transverse references for tilt due to the tunnel slope. This is important as the two beams will go through the module.

Commissioning

All four modules have now been put in place and aligned. Cabling has been completed and all preliminary instrumentation tests completed. The in-situ pressure test of the helium tanks at 2.1 bar has been successfully completed. All cryo connections have been made and tests on the cryo system operation and control of valves is ongoing. The installed modules in the LHC tunnel are shown in Figure 6.

First cool-down of two modules is expected in November 2007. This will be carefully monitored for correct operation of all safety systems and to ensure that the cryogenic pressure regulation will be as stable as possible.

The first RF task will be low power tests, including verification of the Qext and tuning range.

In-situ conditioning of the cavities will precede a period of extensive hardware commissioning tests on the RF system.

Figure 6: Three of the four ACS modules in LHC tunnel with their He connection from QRL extensions on the roof.

ACKNOWLEDGEMENTS

The authors would like to thank Roberto Losito for his guidance through the taking over of test area responsibility, Joachim Tuckmantel for advice on the HOM tests, Luca Arnaudon and Maurice Prax for the interlocks, Olivier Brunner and Christophe Nicou for tuning springs design and help during the RF power commissioning in SM18, Eric Montesinos for the couplers and elaboration of the conditioning process and Max Gourragne for help in the mechanical work.

Finally we would like to acknowledge the many CERN colleagues involved in transport, vacuum, cryogenics, radio protection and DC power converters, without whose support the LHC RF cavity modules could not have been built.

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