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Construction and Processing of the Variable RF Power Couplers for the LHC Superconducting Cavities

E. Montesinos, CERN, Geneva, Switzerland.

Abstract

The Large Hadron Collider (LHC) will accelerate beams of protons with a main RF system of sixteen 400 MHz superconducting cavities. The different requirements at injection and collision together with the heavy beam loading have imposed the use of a variable power coupler with a coupling value varying by a factor 20. The power requirements are high; 250 kW cw forward for several hours and pulses of 1.85 MW local peak power. In order to withstand these levels, copper sealing rings are used on the main ceramic. To avoid multipactor occurring at high powers and beam intensities, a second ceramic is used to provide a second DC polarization of the antenna. Twenty-five couplers have already been fully conditioned using a special dedicated FM+AM conditioning process, with 16 installed in the cavities in the LHC tunnel for first powering tests.

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CONSTRUCTION AND PROCESSING OF THE VARIABLE RF POWER COUPLERS FOR THE LHC SUPERCONDUCTING CAVITIES

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INTRODUCTION

The LHC power coupler is a 400 MHz mobile RF power coupler with very high power requirements; 250 kW cw forward (unmatched conditions) for several hours, and in pulse mode, in the worst case, 300 kW forward + 670 kW reverse, including beam loading, i.e. 1.85 MW local peak power.

Challenge

The different requirements at injection and collision with the heavy beam loading have imposed the use of a variable power coupler. The main challenge was to design a mobile RF power coupler without any sliding contacts for these very high power levels.

Main design features

The general layout and design features of the LHC power coupler have been described in detail [1], [2], [3].

An open-ended 75 Ω coaxial line provides coupling to the cavity. The outer conductor is a copper-plated stainless-steel double-walled tube, cooled with 4.5 K helium gas. The inner conductor (antenna) is a copper tube cooled by forced air.

A cylindrical ceramic window, with solid copper rings brazed on the ends of the ceramic, is placed in the waveguide to coaxial transformer and provides vacuum integrity.

A reduced height waveguide directly provides the matching to the coaxial line, avoiding the usual "doorknob".

The antenna has a 60 mm stroke, without sliding contacts, using bellows λ/4 long. This changes the Q_{ext} of the cavity by a factor 20.

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Another λ/4 line transformer with low impedance, 7 Ω, brings the current in the bellows to a low value, avoiding copper plating of this stainless-steel part.

In order to suppress multipactor effects during operation, two DC biases are applied. A first, 2.6 kV, on the outer conductor of the low impedance λ/4 line transformer, is isolated from ground by a coaxial capacitor in the waveguide. A second, of 2.6 kV + 400 V, on the antenna, is isolated from the λ/4 line transformer by a disc ceramic capacitor between the line transformer and the bellows.

Air cooling is provided on the main ceramic window through the first DC bias capacitor contacts. It also cools the antenna and other critical elements of the coupler.

The antenna movement is guided by a high precision assembly using linear bearings, a satellite rollers screw mechanism and is driven by a d.c. motor with gearbox and electromagnetic brake. The position of the antenna is measured by a linear potentiometer.

A vacuum gauge is located close to the main ceramic window and is used for the coupler conditioning and interlock. Optical arc detectors, temperature probes and air pressure sensors are also used to protect the coupler.

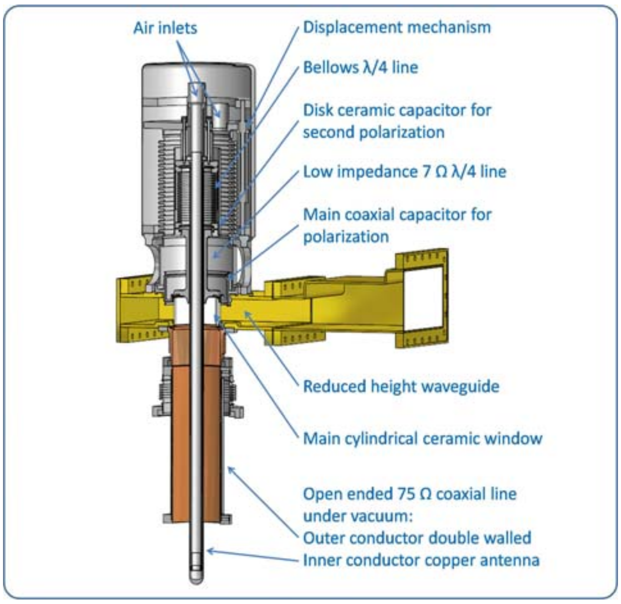

Figure 1
Main design of the coupler.

DESIGNING THE COUPLER

All the coupler components have been thoroughly and carefully studied. Each component has been simulated and tested, from simple parts such as screws to the specially forged copper used. The fabrication of some key elements however proved particularly challenging.

Double-walled tube

The double-walled tube had to be made of stainless steel for mechanical strength and thermal insulation, but required copper plating on the inner surface to minimize losses. Copper plating of this long stainless-steel component brought several difficulties. Sometimes defects appeared during the bake out process, but sometimes also before the bake out. After fine adjustment of the plating process, durably plated tubes were finally achieved. Nevertheless, it was found essential to always first condition with RF before going to low temperatures.

Antenna mechanism

As can be seen in Figure 1, the antenna is centred in the coaxial line with only one special insulated piece at the top of the coupler. The antenna passes through the narrow width low impedance 7 Ω λ/4 line transformer, and must be very well centred. During the first high power tests, it was discovered that the insulated piece became slightly deformed. The horizontal mounting of the coupler on the test cavity was initially suspected, but finally the material was changed and the piece reinforced.

Reduced height waveguide

First design simulations of the waveguide to coaxial transition started with a half height waveguide around the main ceramic. However with such a waveguide, a very big "doorknob" would have been necessary. All the resulting simulations showed that the weak point would not be the copper rings, but the "doorknob" itself. A quarter height waveguide corresponded nearly exactly to the distance between the two copper rings of the main ceramic and removed the need for the doorknob. As the waveguide used to bring the power from the klystron is half height, we also had to design a λ/4 waveguide line transformer, considered as a part of the coupler. The air cooling used for the antenna and the main ceramic is also used to cool down this waveguide subassembly.

Special forged copper

Solid copper was used as far as possible in the construction of the coupler parts in order to gain the best power capability for the final coupler, and to ensure easiest vacuum leak free brazing. The low impedance 7 Ω λ/4 line transformer and the main body line are each made from a single copper piece. Some difficulties were initially encountered to obtain a good vacuum insulation. After detailed investigation, it was found that the problem was the structure of the copper itself. The solution turned out to be quite simple; use of special copper, forged in the 3 axes, gave perfect results.

The main ceramic

The fundamental component of the coupler is the main ceramic. The aim is to have a ceramic cylinder with solid copper rings directly brazed on its ends to allow higher RF power levels by better cooling. A major difficulty encountered was that the ceramic would present vacuum leaks unsystematically at various stages in the whole process of coupler assembly. After a detailed and long study, it appeared that some non-fully traversing cracks were being created during the first brazing of the copper rings, but would only develop at later times. To locate the problem, non-destructive tests were first tried, such as X-ray photography, sound transmission measurements and infrared cameras, all without good results. Destructive methods then had to be used.

Figure 2
Main ceramic.

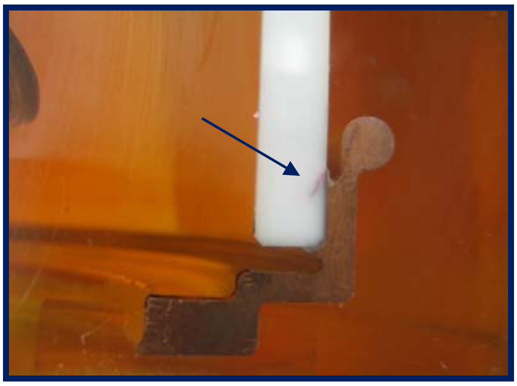

Figure 3
Developing crack in a ceramic, masked by a copper ring.

The best technique found was to clean the ceramic, paint it with a special ultra fluid leak tracing paint (Figure 2), clean it again, then encase it in a resin mould, and finally cut it in two parts. With this method un-coloured cracks coming from the cutting process (no paint traces) could be distinguished from the coloured original cracks (Figure 3). In this way it was understood that the problem came from cracks developing from the first brazing, masked by the copper rings. The copper ring design was changed to minimise mechanical stress with temperature change during brazing. While this cost a few ceramics and a lot of time, there were no further cases of broken ceramics.

Polarization ceramic

Another very difficult item was the second polarization ceramic. After several power tests of prototype couplers, it appeared that multipactor effects along the low impedance 7 Ω λ/4 line transformer could happen at any forward power level above 1 kW, depending on the reflection factor of the cavity. Although, after conditioning, these multipactor levels disappeared, to ensure continual operational reliability a second polarisation on the antenna was added. Unfortunately, series production of components was well advanced and a solution without significant component modifications had to be found. A second capacitor was therefore added between the outer conductor of the low impedance line and the bellows, at the region where the RF current is minimum. The capacitor consists of a ceramic ring on the vacuum side (Figure 4) and of a radiation and temperature resistant insulating disk on the air side.

Figure 4
The ceramic capacitor between two soft copper seals.

To achieve vacuum-tightness, the ceramic ring, with two niobium disks brazed on each side, was placed between two specially designed helicoflex copper seals. Niobium was chosen after a number of tests, being sufficiently hard for the helicoflex seals and having dilatation characteristics near to that of the ceramic to facilitate the brazing. Nevertheless, the assembly remained very delicate.

THE CONSTRUCTION OF THE COUPLER

The building of a coupler starts with the machining of all the individual pieces. There are more than 250 different components in such a coupler, with various levels of complexity. Among the most important are the main ceramic (fabrication time around 8 months), the polarization ceramic (6 months), the antenna (9 months), the body and λ/4 line assembly (9 months), the double-walled tubes (10 months). Some pieces have to sustain preliminary thermal cycle tests and thorough metrological controls.

Once all the components are built, a first step consists in the construction of the sub assemblies. Many operations such as titanium and copper sputtering, titanium coating, brazing, electron beam welding, machining and vacuum leak detection are necessary just to obtain the main line. These operations take again 6 months. A pre-assembly is done first to check that there is no incompatibility due to individual tolerances (and possible errors). Then, inside a clean enclosed area, all the pieces are cleaned with demineralised water, and rinsed with pure alcohol. The final assembly is done in a class 100 clean room to avoid any risk of contamination of the coupler. At that stage, after 15 months of construction, the first vacuum leak test is made on the whole assembly.

All the couplers are then baked out under vacuum at 250 °C. This operation is important for two reasons. The first is to reduce the water level in the ceramics, which will help with the RF conditioning. The second, validated by experience, is to check for any dilatation effects and mechanical constraints produced on the most sensitive parts, in particular the main ceramic and the polarization ceramic. Many defects have been discovered at this stage, avoiding later serious difficulties.

CONDITIONING THE COUPLERS

Once the coupler is baked out, its RF ‘life’ can start. Two couplers are installed face to face on a test cavity mounted on a special test stand. The assembly is done in a clean enclosed area, with laminar air flow

The whole system is then vacuum leak tested, and after 18 months of construction, the RF tests can finally start.

RF power is applied to one coupler (input) and the other (output) is connected to a movable short circuit. The main aim of conditioning (or RF processing) is to increase the power under vacuum control and ultimately reach full power operating conditions with minimum vacuum activity.

Important constraints on first conditioning

It is vitally important that the first conditioning be done without any polarization applied, and, in the case of conditioning in-situ on an SC cavity, with no helium cooling the double tube. These are essential and crucial points. If not followed violent destructive discharges are likely to occur in the couplers.

Principles of the conditioning process

The conditioning process must always start, under vacuum control, with very short pulses, initially with 20 μs pulses every 20 ms. With such short pulses, and sufficient rest time, heavy vacuum outgassing is removed without any danger for the coupler. Since the vacuum gauges have a response time of around 2-3 ms, the repetition time is much longer than the vacuum measurement recovery time. With longer pulses, the RF input energy is high and outgassing is too rapid for the conditioning system to react correctly due to the measurement integration time. This makes it more difficult to increase the power.

We also apply a Frequency Modulation (FM) to be sure to condition the coupler over all its bandwidth. The modulation is asynchronous compared to the amplitude pulsing, and is around +/- 50 kHz.

For each coupler position, under vacuum control, we increase the power level in steps, up to full power, passing slowly through all the power levels, and staying around

10 minutes at each step. For each power step, we move the short circuit over a whole λ/2 length, to be sure that all phases have been seen by the couplers.

When we have achieved maximum power, we restart the process with an increased pulsed length from the first power level step. This is repeated until we are in CW mode. The whole process is carried out at all couplers positions. The principle of the conditioning process is shown in Figure 5.

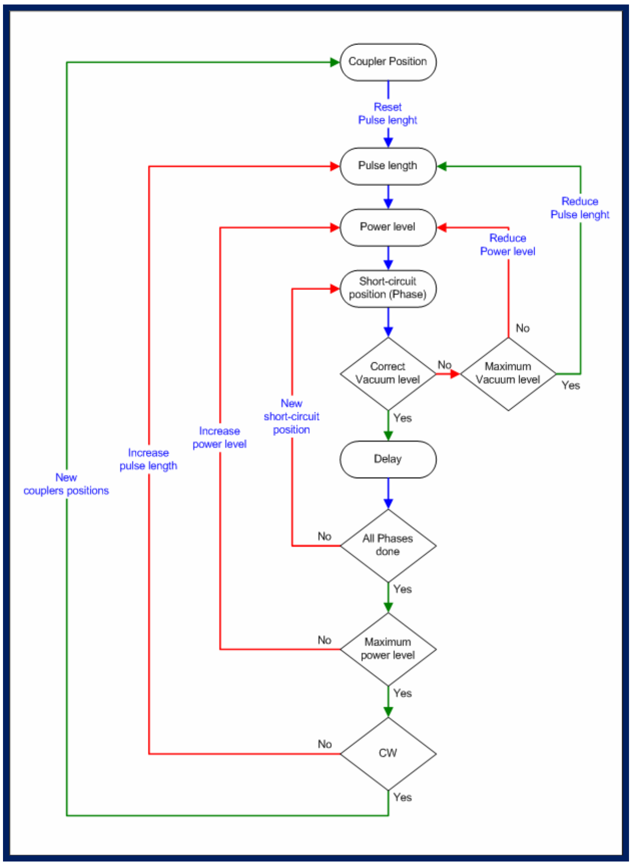

Figure 5
Principle of the conditioning process.

In total, the process was applied for three input coupler positions (0 mm, 30 mm, 60 mm), 3 output coupler positions (idem), 25 short-circuit positions (as λ/2 length is 488 mm, 20 mm steps were taken), eight pulse lengths (20 µs, 50 µs, 100 µs, 250 µs, 500 µs, 1 ms, 2 ms and cw), 3 power steps (50 kW, 250 kW, 300 kW), i.e. 5400 different combinations conditioned. The process is automated, running 24/24 hours a day, 7/7 days a week. It should take about 3 to 4 weeks to complete the whole process, but in practice it takes 5 to 6 weeks due to inevitable down-time. This may be considered long, but is fully justified by the over-riding need to have thorough, reliable and safe conditioning to high power.

Electronic loop

The heart of the conditioning process is an electronic loop which modulates the RF power level in response to the vacuum level. It also ensures that RF is never applied if the vacuum level exceeds 2.0 10^{-7} mbar. In addition an RF switch is cut if the vacuum level exceeds 2.5 10^{-7} mbar. The interlock and maximum electronic loop level values are close, but as the loop is fast enough, the interlock is rarely triggered. A second computer-controlled loop controls either the vacuum, the coupler positions, the short-circuit position, the pulse length, or the power level and ramping. The loops are based on the same voltage controlled attenuator, but for safety reasons, there are two individual attenuators.

Throughout the process, the gain and the offset of the loops are continually adjusted manually to optimize the conditioning, to be neither too conservative, nor too aggressive for the coupler.

Coupler power tests

Very high power tests were carried out on a first set of couplers, up to the maximum power available. The maximum power could only be obtained in cw, due to klystron collector power limitations. We ultimately obtained forward powers up to 575 kW cw full reflection for some hours, which corresponded to local peak power of up to 2.3 MW. With these conditions, the test system was at its limits, and local heating of the waveguides reached 70 ˚C (Figure 6). The 550 kW power load was also running above its nominal ratings.

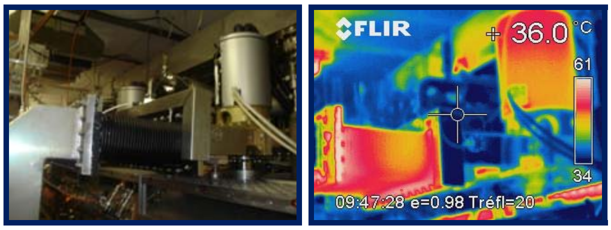

Figure 6
Waveguides heated up to 70 ˚C

Nevertheless, the couplers could be shown to work perfectly at these levels, and the tests were repeated successfully with a second set of couplers.

These values largely exceed the operational LHC requirements of 250 kW cw and 1.85 MW local peak power with 5us/10us cycle (worst case, with ultimate beam). Subsequent tests were limited to 450 kW cw reflected at all phases, allowing us a good safety margin. Unfortunately, during later tests, the klystron failed (not because of the tests, but because of some water cooling leaks inside the vacuum part).

Thus, for the remaining couplers, conditioning is done with a LHC production klystron limited to 300 kW cw, and around 10 minutes stable power at each phase position and with full reflection at all phases. This is above the specified continuous power levels but below the pulsed local peak power.

Conditioning of couplers on the LHC cavities

Once the conditioning process is finished in the test area, the test cavity is brought back to the clean area. The couplers are removed from the cavity, and stored under vacuum. Later, they are mounted on a LHC module, or stored as spares.

Once the coupler is mounted on its cavity, the same conditioning process is repeated, except for the short circuit which is replaced by the cavity. Again, ***the double-walled tube must not be cooled down during the first conditioning on the cold cavity*** and ***full conditioning must be performed before applying any DC polarization***.

The pulse processing follows, from the beginning, the same procedure as previously described on the test cavity The FM modulation ensures that all the bandwidth has been conditioned. Changing the FM modulation rates sometimes facilitates passing through some 'difficult' power levels, but in any case, at the end, the vacuum level must be stable at any fixed frequency over all the bandwidth.

Conditioning of the cavity itself goes concurrently with this process. Conditioning can be started with the coupler fully in (maximum coupling, minimum field) with the coupler conditioning more than the cavity, or fully out (minimum coupling, maximum field) with cavity conditioning rather than coupler conditioning, but the whole process always takes around the same time. The cavity conditioning time is now around one week per cavity/coupler on a cold cavity.

For safe operation in LHC, the couplers must be reconditioned regularly, without DC bias, to keep the secondary electron emission low. Helium processing of the cavity must be avoided, since during this procedure the vacuum control is lost.

The first LHC cryo-module of four cavities with couplers was conditioned and tested to full power and field in November 2004.

LHC Installation

We have now finished 25 couplers, 16 are already mounted on four modules of four cavities installed in the LHC in December 2006 [4]. Four more are mounted on a spare module of 4 cavities, one is on a test cavity, and four others are stored as spares.

Nevertheless, the coupler remains a delicate component. As the construction process and the conditioning times are very long (around 18 months and 2 months respectively), eight more couplers are being built. Another necessity is to maintain the essential know-how of all the specialists, experience having shown that long delays between two operations, even done by the same person, were not efficient.

CONCLUSION

More than 60 conditionings have been carried out with no damage having occurred to a coupler. This is certainly due both to the reliability of the coupler and to the many precautions taken during conditioning e.g. starting the conditioning process with short pulses and without DC polarization. The first conditioning takes some time, but the following ones are faster. Every effort has been made to condition for all beam conditions, but this will have to be confirmed with the beam.

None of the conditionings have required the use of the polarizations to reach full power. However, in LHC, we will not be able to guarantee the same operating conditions and cleanliness as maintained during the tests, and the use of the polarizations remains essential to preserve the couplers from multipactoring effects.

The whole project started 9 years ago, and the accumulation of 'know-how' has been one of the key points. Each expert has gained experience to find the right solution, and such a coupler requires a variety specialist skills. Keeping this 'know-how' will be the next challenge.

ACKNOWLEDGEMENTS

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REFERENCES

[1] H.-P. Kindermann, E. Haebel, M. Stirbet, V. Veshcherevich, "Status of RF power couplers for superconducting cavities at CERN", CERN, Geneva, Switzerland, 1996. Presented at 9th SRF workshop, Sante Fe, USA, 1999. http://doc.cern.ch/archive/electronic/cern/preprints/sl/sl-96-026.pdf

[2] H.-P. Kindermann and M. Stirbet, "The variable power coupler for the LHC superconducting cavity", CERN, Geneva, Switzerland, November 1999. http://doc.cern.ch/archive/electronic/cern/preprints/sl/sl-99-074.pdf

[3] D. Boussard and T. Linnecar, "The LHC superconducting RF system", LHC Project report 316, CERN, Geneva, Switzerland, December 1999. http://doc.cern.ch/archive/electronic/cern/preprints/lhc/lhc-project-report-316.pdf

[4] P. Maesen, E. Ciapala and G. Pechaud, "Final Tests and Commissioning of the 400MHz LHC Superconducting Cavities", CERN, Geneva, Switzerland. Presented at 13th SRF workshop, Peking University, Beijing, China, 2007.