THE LHC SUPERCONDUCTING RF SYSTEM

D. Boussard and T. Linneer

Abstract

The European Laboratory for Particle Physics (CERN), the largest high energy physics laboratory worldwide, is constructing the Large Hadron Collider (LHC) in the existing 27 km circumference LEP (Large Electron Positron) collider tunnel. For the LHC, superconducting cavities, operating at 4.5 K, will provide the required acceleration field for ramping the beam energy up to 7 TeV and for keeping the colliding proton beams tightly bunched. Superconducting cavities were chosen, not only because of their high acceleration field leading to a small contribution to the machine impedance, but also because of their high stored energy which minimises the effects of periodic transient beam loading associated with the high beam intensity (0.5 A). There will be eight single-cell cavities per beam, each delivering 2 MV (5.3 MV/m) at 400 MHz. The cavities themselves are now being manufactured by industrial firms, using niobium on copper technology which gives full satisfaction at LEP. A complete cavity prototype assembly including cryostat, tuner and couplers is now being tested at CERN. In addition to a description of the LHC RF superconducting system, results on the prototype cavity assembly will be reported.
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ABSTRACT

The European Laboratory for Particle Physics (CERN), the largest high energy physics laboratory worldwide, is constructing the Large Hadron Collider (LHC) in the existing 27 km circumference LEP (Large Electron Positron) collider tunnel. For the LHC, superconducting cavities, operating at 4.5 K, will provide the required acceleration field for ramping the beam energy up to 7 TeV and for keeping the colliding proton beams tightly bunched. Superconducting cavities were chosen, not only because of their high acceleration field leading to a small contribution to the machine impedance, but also because of their high stored energy which minimises the effects of periodic transient beam loading associated with the high beam intensity (0.5 A). There will be eight single-cell cavities per beam, each delivering 2 MV (5.3 MV/m) at 400 MHz. The cavities themselves are now being manufactured by industrial firms, using niobium on copper technology which gives full satisfaction at LEP. A complete cavity prototype assembly including cryostat, tuner and couplers is now being tested at CERN. In addition to a description of the LHC RF superconducting system, results on the prototype cavity assembly will be reported.

INTRODUCTION

The Large Hadron Collider (LHC), approved in December 1994, is now under construction at CERN, the European Laboratory for Particle Physics, near Geneva, Switzerland. This large-diameter circular particle accelerator will bring into collision intense beams of protons at high energy and luminosity, as well as heavy (Pb) ions at more modest luminosity. The two counter-rotating beams will be guided and focused by high-field superconducting magnets operating in pressurised superfluid helium, installed in the 26.7 km circumference tunnel of the existing LEP collider. The main parameters of the machine are given in Table 1. Two high-luminosity insertions are located at diametrically opposite straight sections, Point 1 (ATLAS) and Point 5 (CMS). A third experiment, optimised for heavy-ion collisions (ALICE) will be located at Point 2. A fourth experiment (LHCb) has now been approved and will be located at Point 8. The beams cross only at these four locations. Points 2 and 8 also contain the injection systems for the 450 GeV/c beams provided by the SPS. The other
four long straight sections do not have beam crossings. Points 3 and 7 are practically identical and are used for collimation of the beam halo and Point 6 contains the beam abort system. Point 4 contains the RF systems which are independent for the two beams, the beam separation being increased from 194 mm in the regular arcs to 420 mm in order to provide the transverse space needed.

<table>
<thead>
<tr>
<th>Table 1. Main parameters of the LHC</th>
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<tr>
<td>Collision energy (TeV)</td>
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<td>Dipole field (T)</td>
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<td>Distance between apertures (mm)</td>
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<td>Luminosity (cm^-2s^-1)</td>
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<td>Beam-beam parameter</td>
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<tr>
<td>Injection energy (GeV)</td>
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<tr>
<td>Circulating current/beam (A)</td>
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<td>Bunch spacing (ns)</td>
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<td>Particles per bunch</td>
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<tr>
<td>Stored beam energy (MJ)</td>
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<td>Normalised transverse emittance (µm)</td>
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<td>R.m.s. bunch length (m)</td>
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<td>Beam lifetime (h)</td>
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<tr>
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<tr>
<td>Energy loss per turn (keV)</td>
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<td>Total radiated power per beam (kW)</td>
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In the CERN tradition and for the sake of economy, the LHC will re-use the chain of existing, older accelerators as injectors (PS machine as pre-injector to 26 GeV, SPS as main injector to 450 GeV). This imposes the choice of the RF frequency of the LHC (400.8 MHz), which must be a multiple of the SPS RF frequency (200.4 MHz) to permit fast transfer of long bunch trains.

Intrabeam scattering (or multiple Coulomb scattering) between particles during beam storage at 7 TeV results in an increase in transverse emittance that can rapidly degrade the luminosity, unless the six-dimensional phase space density is artificially diluted by increasing the longitudinal emittance. In the LHC, the latter will be increased from its injection value of 1 eVs to 2.5 eVs at collision energy. This determines the maximum RF voltage needed to ensure a bunch length much shorter than the region of minimum transverse beam size (low-β) at the interaction points. The design value of the RF voltage is 16 MV per beam, to provide an r.m.s. bunch length of 7.5 cm. As will be seen in the following, operating RF voltages significantly higher than the design value can be anticipated giving more freedom in the choice of parameters (longitudinal emittance or bunch length); this is especially attractive in the case of heavy ion collisions where the luminosity lifetime due to intrabeam scattering gets shorter.

The beam structure along the orbit is composed of trains of bunches (bunch spacing: 24.95 ns, i.e. ten RF periods) spaced by empty gaps of various lengths necessary to accommodate the rise times of the various injection kickers (200 ns, 1 µs) and the risetime of the beam dump kicker (3 µs). The effect of the beam gaps on the RF system is to generate a strong periodic transient beam loading which manifests itself as periodic modulations (mostly in phase) on the beam and on the RF voltage. For a single gap of length \( \tau \) and no acceleration, the maximum phase modulation \( \Delta \phi \) is given by:

\[
\Delta \phi = \frac{1}{2} \frac{R}{Q_o} \frac{I_b}{V} \tau
\]
where $R/Q$ is the geometric cavity parameter, $\omega_0/2\pi$ the RF frequency, $I_b$ the RF component of the beam current and $V$ the cavity voltage. Phase modulation in turn entails a displacement of the collision points, which depends upon the position of the colliding bunches with respect to the beam gaps. This effect can be reduced to a negligible value in the LHC by choosing superconducting (SC) cavities, for which the critical parameter $(R/Q \times I_b/V)$ can be made one order of magnitude smaller than for normal-conducting copper cavities. Phase modulation could also be suppressed by brute force with any type of cavity, but at the expense of very high continuous RF power. Superconducting cavities offer instead the possibility of running the LHC with much less RF power (higher reliability, better robustness against power generator failures) and fewer units (small contribution to the overall machine impedance).

During the injection process at 450 GeV, each ring is filled by 12 consecutive injections and there is only partial filling of the ring; i.e. the beam gap is very large, as would be the phase modulation. Although the displacement of the crossing points is an irrelevant problem at injection, it was decided to compensate the phase modulation using the RF generator power in order to greatly simplify the injection procedure. As the RF voltage is low in this case (8 MV maximum as compared to 16 MV during storage), the necessary RF power ($VI_b/8 = 1$ MW per beam in the case of SC cavities) remains acceptable. The landing phase of a newly injected bunch is now fixed instead of being dependent on the previous injection history and beam intensity, as was originally envisaged, and much better injection tolerances can be anticipated.

Having different modes of operation for the cavities at injection (full beam compensation) and storage (minimum power), a variable RF coupler was necessary to optimise each mode. Moreover the coupling factor must be changed under power, during beam acceleration.

The nominal injection scheme, as described in the conceptual design, assumes small emittance bunches (0.63 eVs) from the SPS directly injected into 400 MHz buckets produced by an 8 MV per beam RF voltage. If the bunches leaving the SPS turn out to have a higher emittance (e.g. 1 eVs) this scheme no longer works and an alternative scenario is considered, in which the bunches would be captured by a 200 MHz copper cavity system (3 MV/beam), their injection phase oscillations damped and the whole beam transferred adiabatically to the 400 MHz RF system at the end of the injection process. In this scenario the 400 MHz SC RF system would be used as a harmonic of the 200 MHz RF system, to linearize the waveform and facilitate the damping of injection oscillations. Another operating mode of the SC cavities would then be to run them at very low voltage and opposite phase to the main 200 MHz voltage. In such a high beam-loading situation, full beam compensation is mandatory, leading again to the choice of a variable RF coupler for the SC cavities.

In all modes of operation the net energy delivered to the beam by the RF system is fairly small: at top energy the total synchrotron radiation power is only 3.7 kW per beam, and during the slow (20 min) ramping each cavity provides 32 kW to increase the beam energy. Contrary to that of lepton machines and high-current proton linacs, the installed RF power is not determined by the beam power, but by the need to maintain the specified RF voltage irrespective of the beam current.

**ACCELERATING CAVITIES**

Single-cell superconducting cavities with their individual RF power couplers are preferred to multicell cavities. This is to minimise the RF power requirements on each RF window and to simplify the design of the RF feedback circuit. Starting from the usual quasi-spherical shape which reduces the risk of multipacting, one can considerably decrease the $R/Q$ of the fundamental mode by increasing the radius of the beam tube. In doing so the maximum voltage capability of the cavity at constant peak
electric and magnetic fields is only slightly reduced. We have selected a beam tube diameter of 300 mm which gives $R/Q = 44 \, \Omega$ and a nominal voltage of 2 MV/cell for 11.8 MV/m peak electric field and 27.3 mT peak magnetic field on the surface. Referred to a cavity length of $\lambda/2$ (as used for multicell cavities), this corresponds to an accelerating field of 5.3 MV/m. There will be eight single-cell cavities per beam in order to produce the nominal voltage of 16 MV during storage. The two groups of cavities for the two beams will be symmetrically arranged in straight section 4. The beam separation of 420 mm is enough to accommodate the vacuum tank radius of 360 mm, but not to bring the other beam outside the cryostat. Consequently the second beam tube is also cold.

The frequency of the first higher-order mode (HOM) (deflecting mode $H_{111}$) approaches that of the fundamental when the beam tube diameter is increased. This is undesirable and can be corrected by reducing the length of the cavity cell (320 mm).

The eight single-cell cavities of a beam are arranged in two identical cryomodules. The four cavities of a cryomodule have a cell-to-cell distance of $3\lambda/2$ at 400 MHz (1122 mm) and are connected by the large diameter ($\varnothing = 300$ mm) beam tubes. The coupling between adjacent cells is negligible at the fundamental frequency, weak for the two lowest higher-order modes, but strong above the cut-off frequency of the 300 mm diameter tube. Above 700 MHz the location and magnitude of the HOMs differ markedly in the case of the coupled cavities as compared to that of a single cell with identical conical tapers. Moreover the peak and average values of the corresponding $R/Q$s are significantly more favourable for the coupled cavities than for a set of four individual cavities with conical tapers.

There is a so-called “trapped” mode at 1240 MHz which couples very weakly to the beam tube modes and which can be potentially dangerous. Its $Q_{\text{ext}}$ is critically dependent on the cell length ($Q_{\text{ext}} > 10^5$ for a cell length of 332 mm; $Q_{\text{ext}} = 300$ in the LHC case of a cell length of 320 mm).

The cavity technology is similar to that used successfully on a large scale for LEP2; it is based on niobium film on copper cavities operating at 4.5 K. 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; 17 cavities have already been accepted at CERN. Their typical performance is displayed in Figure 1 together with the acceptance curve. It shows a large safety margin in the voltage capability of the cavities. 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 and the tuning sensitivity 240 kHz/mm.

![Figure 1. Typical cavity performance and acceptance curve.](image-url)
Each cryomodule contains four single-cell cavities, each having its own helium tank. A prototype version having only two cavities was constructed (Figure 2) and tested.

A modular construction was adopted for the vacuum tanks of the cryomodule. Each tank is a stainless steel cylinder, without any welds, with four large lateral openings to permit easy access to the cavity. These openings are sealed by aluminium panels with long rubber rings. Each tank is joined to its neighbours or to the end flanges with Helicoflex® metallic joints (combined with rubber rings to allow vacuum testing before cavity assembly).

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 disassembling its neighbours.

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.

The helium supply at 4.5 K is provided from the main LHC cryogenic distribution line (QRL). The line is moved transversely in the LHC tunnel to accommodate the SC cavities’ cross-section (Figure 3).

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 of the coupler. Neither a magnetic shield nor a heat shield is necessary. The vacuum tubes for the second beam are attached to the side of each cavity cradle and connected together with standard shielded bellows. The measured static losses of the prototype cryomodule (having only two cavities, no couplers and no second beam tube) amount to 25 W.

Figure 2. The prototype cryomodule with two cavities (a series cryomodule will have four cavities).
A purely mechanical tuner was chosen to provide the large tuning range at full speed required to compensate beam loading and thus minimise power requirements at injection. The large spring constant of the cavity (20 kN/mm) imposes a very rigid structure surrounding the cavity to take the return forces with little deformation. The stainless-steel (type 304) cavity cradle, with its two thick end plates joined by four columns, forms a structure free of harmful resonances and very rigid (≤ 0.08 mm axial shrinkage at a force of 20 kN). The cavity is always under tension, its end plate and the cradle end plate being pulled together via thin (1 mm thickness, 200 mm high) aluminium foils which act also as torsion shafts (Figure 4). A high-performance aluminium alloy (2219 T851) was chosen for these critical elements because of its excellent fatigue properties and elastic limit at low temperature (better than stainless steel). The maximum constraint for a 1 mm displacement of the cavity (170 MPa) is far from the elastic limit (500 MPa). The two torsion shafts (foils and shaft are made of a single piece machined by electro-erosion) are driven by long lever arms which provide a lever action (ratio 14:1) without sliding parts or backlash.

The axial force and movement at the extremities of the two lever arms inside the cold cradle are transferred to the outside of the cryomodule via two thin-walled stainless-steel cylinders acting as counter-rotating torsion shafts. The latter are driven by stainless-steel cables (Ø = 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 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.

In a hadron collider RF phase noise at the synchrotron frequency (f_s) is of great importance, as it may limit the beam lifetime. The contribution of the cavity microphonics, including the tuner, to the overall RF phase noise at f_s (f_s = 20 Hz in the LHC) must be evaluated. Preliminary measurements on the LHC prototype cryomodule (without RF couplers) indicate a microphonics phase noise density \( S_\phi \approx 2 \cdot 10^{-8} \text{rad}^2/\text{Hz} \) which is adequate for the LHC. Note that the tuner in itself is too slow to compensate microphonics at f_s.
**VARIABLE POWER COUPLER**

The LHC variable coupler (Figure 5) is an upgraded version of the LEP2 fixed coupler. The general layout and improvements of the latter have already been described in detail.\(^7,8\) An open-ended 75 $\Omega$ coaxial line provides coupling to the cavity. The outer conductor (not represented in Figure 5) 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 solid copper rings brazed on its edges, is placed in the waveguide-to-coaxial transformer. A reduced height waveguide directly provides 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 and are used for coupler conditioning and interlocks.

The antenna can be moved (60 mm stroke) by making use of bellows about $\lambda/4$ long. This changes the $Q_{\text{ext}}$ of the cavity by a factor 20. A low impedance (7 $\Omega$) $\lambda/4$ line transformer brings the current in the bellows to low enough values, which do not then require copper plating of this stainless steel part. The displacement of the antenna is guided by a (motor driven) high precision device.

Two prototype LHC couplers have been manufactured, assembled and vacuum-tested. They are now mounted on the prototype cryomodule. 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, 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 $2 \times 10^{-7}$ 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, with no electrons picked up on the antenna and no influence of d.c. bias. It is suspected that multipactor occurred inside the $7 \Omega \lambda/4$ line, and therefore an additional bias on this is being studied. After conditioning of the low-power multipacting levels, 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, for any phase and any coupling the coupler sustains a 500 kW forward power (2 MW travelling-wave equivalent power) provided it is pulsed (50 ms on, duty cycle 10%) to avoid local overheating. After these tests the couplers were disassembled and thoroughly examined. No traces of damage were found on the surfaces exposed to RF. Before remounting the couplers on the cryomodule, all their components were properly cleaned (high-pressure water and alcohol rinsing), reassembled and conditioned again on the RF test bench.

**HIGHER-ORDER-MODE COUPLERS**

A special problem appears when the beam tube is enlarged to reduce the R/Q of the fundamental mode: the first dipole mode (TE$_{111}$) gets closer to the fundamental and its R/Q increases, making damping of this mode more difficult. The solution adopted in high current e+e- machines is to let this mode propagate towards beam tube ferrite loads using fluted or widened beam tubes. In the LHC design with four cavities in a cryomodule warm ferrite loads are ruled out and a more conventional approach with two types of HOM coupler is used. This is suggested by the HOM spectrum which shows the first two dipole modes near 500 MHz which do not propagate in the 300 mm diameter beam tube and a cluster of monopole modes above 750 MHz.
The first type of HOM coupler damps the first two dipole modes. Coupling is with a loop perpendicular to the cavity axis (Figure 6a) (the modes have a strong longitudinal magnetic field component at the vacuum tube wall). Rejection of the fundamental mode is achieved in a classical way with an LC notch filter. By a careful design of the coupler elements, the equivalent circuit of the coupler (two coupled resonators) exhibits two resonances (Figure 7) located at the two HOM frequencies to be damped. Optimum damping is thus achieved for a given loop size. The Qs achieved with a single coupler per cavity are 200 for both the TE_{111} mode (500 MHz) and the TM_{110} mode (534 MHz).

![Figure 6: (a) Narrow band dipole mode HOM coupler; (b) Broad band HOM coupler](image)

![Figure 7. Frequency response of HOM couplers](image)

There are also two broad-band HOM couplers per cavity cell. The coupling to these HOMs is predominantly electric with an open-ended antenna of about λ/4 length at the mid-band frequency (Figure 6b). The coupler includes a notch filter at the fundamental frequency and exhibits three resonances (Figure 7) to achieve the required bandwidth. The response peaks near the frequencies of the high R/Q mode TM_{011} (770 MHz) and the trapped mode TM_{012} (1240 MHz). 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.

Both types of HOM coupler are made out of solid niobium. They are cooled by independent liquid-helium circuits. The RF connection from the cold HOM connector to the outside is made, as in LEP, with a thin-walled stainless-steel (copper-plated) 25 Ω coaxial line. The inner and outer conductors of the line are fitted with spring RF
contacts at each end to allow for displacement during cooldown. This arrangement has been tested up to 800 W HOM power in the lab.

HIGH-POWER RF SYSTEM

Contrary to lepton machines, and high-current proton linacs, the RF power necessary to operate LHC is not determined by the power delivered to the beam, but rather by the need to control the RF voltage precisely under all transient beam loading conditions. From the analysis of the various situations (injection with or without a 200 MHz additional RF system, ramping, storage) it appears that a useful power of about 200 kW per cavity is adequate. With one klystron per cavity, the specified saturation power of the klystron should be in the range 250 to 300 kW, taking into account linear operation of the klystron, and circulator and waveguide losses. The choice of one klystron per cavity is justified technically: better control of microphonic noise, minimum perturbation in the case of a klystron trip. Klystrons of this power at a slightly different frequency are commercially available.

The klystrons will be installed vertically (4 m height available) in the klystron gallery running parallel to the machine tunnel at a distance of 10 m. They will be powered by the existing LEP HV supplies via HV feed boxes. The circulators are those used in LEP modified to operate at 400 MHz instead of 352 MHz. They are also located in the klystron gallery. Half-height waveguides connect the circulator output to the RF coupler via 900 mm diameter holes to be drilled between the two tunnels. Two waveguides for two cavities run in parallel in a common hole.

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