CHAPTER 6

THE RF SYSTEMS AND BEAM FEEDBACK

6.1 INTRODUCTION

The design of the RF and Beam Feedback systems has evolved in certain respects since the publication of the Conceptual Design, the “Yellow Book”, in 1995 [1]. The injected beam will still be captured, accelerated and stored using the 400 MHz superconducting cavity system as before but longitudinal injection errors will now be damped using the same system. There will not be a separate longitudinal damper. Transverse injection errors will be damped by a system of electrostatic deflectors that will also ensure subsequent transverse stability. A new capture system at 200 MHz to reduce injection loss and ease operation has been proposed and designed and will be installed at a later stage if the injected emittance increases when intensities much higher than nominal are reached. The different RF and Beam Feedback systems are now concentrated around the centre of point 4 and extend from the UX45 cavern area into the tunnel on either side. The klystron power plant and racks of equipment for the different systems are in both the UX45 and US45 sides of the cavern. Previously the RF systems were in the tunnel and the old LEP klystron galleries were used for the RF power. IR4 is already equipped with klystron power converters from LEP.

6.1.1 Beam Parameters

The beam and machine parameters that are directly relevant to the design of the RF and Beam Feedback systems are given in Tab. 6.1. At nominal intensity in the SPS an emittance of 0.6 eVs has now been achieved giving a bunch length at 450 GeV of 1.6 ns. The phase variation along the batch due to beam loading is within 125 ps. This emittance is lower than originally assumed and is the result of a significant machine studies and upgrade programme in the SPS leading to reduced machine impedance, improved control of beam loading at the fundamental frequency with both RF feedback and feed-forward, and further instability control using both coupled bunch feedback for low-mode number instabilities and Landau damping of high order modes using a 4th harmonic RF system. As a result, an RF system in the LHC of frequency 400.8 MHz, compatible with this bunch length, can be used to capture the beam with minimal losses and then accelerate and finally store it at top energy [2]. Higher frequencies, while better for producing the short bunches required in store, cannot accommodate the injected bunch length. At ultimate or higher intensities the emittance from the injector may increase and a separate 200 MHz RF system [3] can be used to capture the longer bunches. This system will not be installed for initial commissioning. However, space is allocated in the machine and certain preparatory work has been done. A brief description of this system will also be given below.

No separate longitudinal damping system is used. The main RF system provides some damping of injection errors and natural Landau damping is used to stabilise the beam against longitudinal beam coupled bunch instabilities during the cycle. This defines the maximum allowable machine impedance, in particular for higher order modes in cavities [4]. There will be some emittance increase at injection but this will be within the capabilities of the RF system for acceleration and in particular will be below the final emittance needed in storage. This final emittance is defined by intra-beam scattering lifetime in the presence of damping due to synchrotron radiation, RF lifetime and instability threshold considerations. Controlled emittance increase will be provided during acceleration by excitation with band-limited noise, the emittance increasing with the square root of the energy to optimise both narrow and broadband instability thresholds [4].

For the transverse plane, a feedback system damps the oscillations coming from injection errors to minimise emittance increase resulting from decoherence produced by magnetic and space-charge non-linearities and stabilizes the beam against the resistive wall instability [5].
Table 6.1: The Main Beam and RF Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Injection 450 GeV</th>
<th>Collision 7 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch area (2σ)*</td>
<td>eVs</td>
<td>1.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Bunch length (4σ)*</td>
<td>ns</td>
<td>1.71</td>
<td>1.06</td>
</tr>
<tr>
<td>Energy spread (2σ)*</td>
<td>10⁻³</td>
<td>0.88</td>
<td>0.22</td>
</tr>
<tr>
<td>Intensity per bunch</td>
<td>10¹¹ p</td>
<td>1.15</td>
<td>1.15</td>
</tr>
<tr>
<td>Number of bunches</td>
<td></td>
<td>2808</td>
<td>2808</td>
</tr>
<tr>
<td>Transverse emittance V/H</td>
<td>µm</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>Intensity per beam</td>
<td>A</td>
<td>0.582</td>
<td>0.582</td>
</tr>
<tr>
<td>Synchrotron radiation loss/turn</td>
<td>keV</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>Longitudinal damping time</td>
<td>h</td>
<td>-</td>
<td>13</td>
</tr>
<tr>
<td>Intrabeam scattering growth time - H</td>
<td>h</td>
<td>38</td>
<td>80</td>
</tr>
<tr>
<td>- L</td>
<td>h</td>
<td>30</td>
<td>61</td>
</tr>
<tr>
<td>Frequency</td>
<td>MHz</td>
<td>400.789</td>
<td>400.790</td>
</tr>
<tr>
<td>Harmonic number</td>
<td></td>
<td>35640</td>
<td>35640</td>
</tr>
<tr>
<td>RF voltage/beam</td>
<td>MV</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Energy gain/turn (20 min. ramp)</td>
<td>keV</td>
<td>485</td>
<td></td>
</tr>
<tr>
<td>RF power supplied during acceleration/ beam</td>
<td>kW</td>
<td>~275</td>
<td></td>
</tr>
<tr>
<td>Synchrotron frequency</td>
<td>Hz</td>
<td>63.7</td>
<td>23.0</td>
</tr>
<tr>
<td>Bucket area</td>
<td>eVs</td>
<td>1.43</td>
<td>7.91</td>
</tr>
<tr>
<td>RF (400 MHz) component of beam current</td>
<td>A</td>
<td>0.87</td>
<td>1.05</td>
</tr>
</tbody>
</table>

* The bunch values at 450 GeV are an upper value for the situation after filamentation, ~ 100 ms after each batch injection. The bunch parameters at injection are described in the text.

6.1.2 RF System Parameters and General Design

The final emittance at 7 TeV of 2.5 eVs and a maximum bunch length given by luminosity considerations in the experiments, leads to a required maximum voltage of 16 MV / beam. Transient beam-loading, coming from the high RF beam current (~ 1 A) combined with the long beam gap (~ 3 µs) due to the abort gap dominates the design of the LHC RF system and leads to the choice of SC cavities with wide beam aperture (30 cm). With high RF voltage per cavity and the low R/Q due to the wide aperture, the stored energy in the cavity is high and the cavity field phase swing due to reactive beam loading in the beam gap is minimized. Furthermore the required voltage is achieved with fewer cavities than with a copper system and, again due to the wide beam aperture, the R/Q of the Higher Order Modes in the cavity are lower. With strong HOM damping in the cavity the total machine impedance can be kept low.

During acceleration the real power supplied to the beams is relatively small (275 kW/beam) but the installed power required to control these beams is much larger. The challenge in the design of the RF system is to minimize the beam handling power in order to arrive at acceptable levels for the power couplers. If separate cavities can be used for each beam, the RF beam current and hence transient beam-loading in the cavities is halved and the coupler power requirement at injection also reduced to more realistic levels. An added advantage is the possibility of independent control of the beams. However, the standard distance between beams in the machine, 194 mm, is insufficient. Consequently the beam separation must be increased in the RF region to 420 mm by means of special SC dipoles. With this separation and also by staggering the cavities longitudinally, the “second” beam can pass outside the cavity. It must still, however, pass through the cryostat. In coast some static relative longitudinal displacement of the bunches can be tolerated to further relax the power requirements.
6.2 MAIN 400 MHZ RF ACCELERATING SYSTEM (ACS)

6.2.1 Parameter Specification

The two independent RF systems must each provide at least 16 MV in coast while at injection about 8 MV is needed. The frequency of 400 MHz is close to that of LEP, 352 MHz, allowing the same proven technology of niobium sputtered cavities to be applied.

All reactive beam power has to be carried by the RF couplers. The present design using single cell cavities each with 2 MV accelerating voltage, corresponding to a conservative field strength of 5.5 MV/m, minimizes the power carried by the RF window. Even so the peak power requirements for the coupler are significantly higher than previously achieved on SC cavities. A large tuning range is required to compensate the average reactive beam component. Each RF system has thus eight cavities, with $R/Q = 45 \Omega$ and of length $\lambda/2$, grouped by four with a spacing of $3 \lambda/2$ in one common cryostat [2]. Each cavity is driven by an individual RF system with klystron, circulator and load. Complex feedback loops around each cavity, described below, allow precise control of the field in each cavity, important for the unforgiving high-intensity LHC proton beam. The use of one klystron per cavity also avoids problems such as coupling between cavities and ponderomotive oscillations that plagued the LEP RF system when one klystron supplied eight cavities.

Energy and phase errors at injection require strong coupling between cavity and klystron (low external Q, $Q_{\text{ext}}$) but the higher field in coast demands a high $Q_{\text{ext}}$ to limit the power needed. The power coupling must therefore vary during the ramp. The variable coupler has a range of $Q_{\text{ext}} = 10,000$ to $Q_{\text{ext}} = 200,000$.

To control the transient beam-loading the installed power is 300 kW – the average RF power being much lower. Simulations [6, 10] have shown that under some conditions the power to be handled can be even higher for a fraction of a µs; hence the RF drive has to be limited to avoid klystron saturation. Simulations also show that short reflected power spikes much larger than the installed RF power are possible, the energy being taken from the beam or the cavity stored energy. Therefore, the peak power capabilities of circulator and loads have to be increased correspondingly. Due to the staging of the 200 MHz capture system the 400 MHz RF system has to provide all injection damping. Simulations have verified that this is possible but the system’s power-handling capabilities are stretched to the limits.

All higher-order modes (HOM) have to be damped as strongly as possible, partly for machine impedance reasons but also to avoid extracting excessive RF power from the beam through the coupler [2]. To couple to the different polarities of the multi-pole modes, two wide-band HOM couplers are used placed at $120^\circ$ around the circumference. The wideband couplers have a notch filter at 400 MHz which causes reduced coupling to these modes. Two dipole modes at respectively ~500 MHz (TE$_{111}$) and ~534 MHz (TM$_{110}$) are particularly dangerous since they do not propagate in the tubes of the inter-cavity beam tubes with 700 MHz cut-off frequency. A second set of narrow band couplers is therefore needed for these two modes, resulting in a total of four HOM couplers for each cavity.

The recent choice of graphite as collimator material has caused some concern for the superconducting RF cavities. These are sensitive to any dust but especially to carbon dust. Charged dust particles, held by the beam electric field and travelling along the beam pipe, would be intercepted by an electrostatic dust-trap. The study of such a dust-trap has been launched.

6.2.2 SC Cavities, Modules and Couplers

Cavities and cryomodule

The use of niobium sputtering on copper for construction of the cavity has the important advantage over solid niobium that susceptibility to quenching is very much reduced. Local heat generated by small surface defects or impurities is quickly conducted away by the copper. During the low-power tests the 21 cavities produced all reached an accelerating field of twice nominal without quenching. The niobium sputtered cavities are insensitive to the Earth’s magnetic field and special magnetic shielding, needed for solid niobium cavities, is not required.

Four cavities, each equipped with their helium tank, tuner, HOM couplers and power coupler, are grouped together in a single cryomodule. This reduces the overall static thermal losses and requires less total space.
for installation compared to the previous bi-module configuration. The conception of the cryomodule is itself modular; all cavities are identical and can be installed in any position. If a problem arises with a cavity it can "easily" be replaced. The time taken to do this, from experience already gained with one module which suffered a degraded cavity after initial assembly, would be less than one month.

**Figure 6.1: Four-Cavity Cryomodule**

**Tuning**

The cavity is tuned by elastic deformation, by pulling on a harness using stainless-steel cables that are wound around a shaft. A stepping motor, fixed to the outside of the cryostat, drives the shaft. The motor therefore works in normal ambient conditions and can be easily accessed for maintenance or repair.

**HOM Couplers**

The HOM couplers have been designed to stand the 1 kW HOM power expected in the worst case and have been tested up to 600 W at 4.5 K without any evidence of overheating. The fundamental mode is almost completely rejected by a tuneable filter in the couplers. At nominal field, no more than 10 W fundamental power couples out of each HOM coupler.

**Cryogenics**

Each cryomodule has a single inlet for liquid helium and a single outlet for the helium evaporated by static and dynamic losses. The level is regulated by the input valve using feedback from superconducting wire level gauges in the cryomodule. The static losses are 150 W per module. At nominal field the RF losses are 100 W and at twice the nominal field 800 W per module, making the total losses 250 W and 950 W, respectively.

For operation at nominal field the pressure inside the helium tank has to be carefully controlled to avoid frequency variations of the cavity, the sensitivity being an appreciable 150 Hz/mbar. The maximum excursion around the nominal value of 1350 mbar has been fixed to ±15 mbar. The operation of the cavities will be very critical from the point of view of safety: they have been designed to withstand a maximum pressure of 2 bar and will be connected to the QRL line D in which pressure can rise to up to 20 bar if magnets quench. A pressure switch will therefore close the output valve if the pressure is above 1500 mbar. A possibility presently being studied is to provide a connection to the Warm Recovery Line (WRL) to ensure the safe discharge of evaporating helium in any operating mode. The cavities will in any case be equipped with safety (quench) valves to discharge the helium in case of insulating vacuum loss or inability to discharge into line D or the WRL.
Variable Power Coupler

The LHC variable coupler, Fig. 6.3, is an upgraded version of the LEP2 fixed coupler. The general layout and improvements of the latter have already been described in detail [8, 9].

Figure 6.3: 400 MHz Variable Power Coupler

An open-ended coaxial line provides coupling to the cavity. The outer conductor, not shown in the figure, made of copper-plated stainless-steel (double walled) is cooled with 4.5 K helium gas. The inner conductor (antenna) is a copper tube cooled by forced air. A cylindrical ceramic air-cooled window, with solid copper rings brazed on its edges, is placed in the waveguide-to-coaxial transformer. This provides an excellent solution for RF heating but at the expense of more difficult technical manufacturing challenges, compared to
the use of kovar rings. A reduced height waveguide directly provides matching to the coaxial line, avoiding the usual “doorknob”.

The antenna can be moved 60 mm by using bellows about \( \lambda/4 \) long, allowing changes in \( Q_{\text{ext}} \) of the cavity by a factor 20. A high precision assembly guides the antenna movement. In order to suppress multipactor during operation, two dc bias voltages are applied. A vacuum gauge and an electron pickup antenna are located close to the window and are used for coupler conditioning and interlocks.

High-power conditioning is done at room temperature with two couplers mounted horizontally on a 400 MHz copper test cavity. One coupler is connected to a 1.5 MW pulsed (1.0 MW average) 400 MHz klystron via a circulator, the second either to a 500 kW load or to a mobile short circuit. After conditioning of the multipacting levels with a pressure limit of \( 5.0 \times 10^{-7} \) Torr, the coupler sustains > 500 kW continuous forward power (2.0 MW travelling-wave equivalent), at full reflection for any phase and any coupling. The d.c. biasing is effective at all multipactor levels.

6.2.3 ACS Vacuum

The 400 MHz superconducting RF cavities have three different and independent types of vacuum systems: for the cavity, the secondary beam and the cryostat. The cavities are pumped at room temperature by two 60 l/s ion pumps mounted at each end of the RF modules. At 4.5 K, an additional huge pumping speed of more than 300,000 l/s, for hydrogen, comes from the cryogenic pumping of the cavity walls. The background pressure, without RF, will be very low and not measurable using the Penning gauges (<10^{-12} mbar). Pressure signals provided for RF control are a hardware interlock from the ion pumps to cut the high voltage and readout from the Penning gauges, one per coupler, to limit the RF power, for example during conditioning. Signals for vacuum control come from both Pirani and Penning gauges mounted on the pumping ports. The cavity vacuum can be isolated by two all-metal valves at the ends of each module, to maintain vacuum during transport and installation.

Due to the size of the cryostat the second beam has to pass in its own vacuum tube through the cryostat insulation vacuum. The second beam tube has been designed so as not to interfere with the removal of a faulty cavity. It is composed of two vacuum chambers of about 3 m in length connected by a shielded bellows. The chambers are made of stainless steel tube (ID 67 mm, 1.5 mm thick), coated by electrodeposition with a copper film 1 mm thick to give low impedance, and then coated with NEG to reduce the pressure and avoid electron cloud effects. The vacuum chambers are baked using thermo-coax heaters fixed onto the vacuum chamber by a sprayed aluminium coating. This 1.5 mm coating gives very good thermal contact. Two coaxial heaters are rolled around the chamber, the current leads and temperature measurements leaving via a special feed-through. The coating can resist a bake-out at 300 °C. A reflective aluminium film covers the heaters to reduce thermal radiation towards the super-insulation layers around the cryostat when at 4.5 K. At 250ºC and after 24 h of bake-out, the temperature of the super-insulation layers in front of the baked chambers does not exceed 62 ºC. A special spacer installed on the secondary beam tube prevents it coming into contact with the super-insulation during bakeout.

The insulation vacuum is less demanding in terms of pressure, the modules being pumped to 10^{-3} mbar before being cooled down. When cold, the insulation vacuum also benefits from the cryogenic pumping of the cold surfaces and the operating pressure will decrease to 10^{-7} mbar. Turbo molecular pumps are used and pressures are measured using Penning and Pirani gauges. Intense gamma radiation is produced during cavity RF conditioning, which will be done \textit{in situ}. Special radiation stoppers will be installed at the RF zone extremities to limit the radiation reaching nearby equipment and the machine tunnel. The use of the existing valves on the modules is excluded due to the risk of damage due to radiation. The stoppers will be modified versions of LEP sector valves, mounted independently and relatively easily removable in the event of problems.

6.2.4 RF Power System

A maximum of 4800 kW of RF power will be generated by sixteen 300 kW 400 MHz klystrons. Each klystron will feed, via a Y-junction circulator and a WR2300 (half height) waveguide line, a single-cell SC cavity. The average waveguide length will be about 22 m. The klystrons, the circulators and loads, the HV interface bunkers and the control racks will be located on the ground floor of the UX45 cavern, approximately 6 m below the level of the beam lines.


**High-Voltage Interface**

The four main 100 kV power converters, re-used from LEP, are located on the surface with transformers and rectifiers in the open air. Each converter will power four klystrons. The high-voltage interfaces will be located in four fireproof bunkers in the cavern. Each interface consists of high-voltage connections to the klystron guns, filament supplies, a fast protection unit (thyatron crowbar), a high-voltage commutator, smoothing capacitors, four hard tube modulators and insulation transformers. These components are immersed in oil. The klystrons are located about 30 m away from the HV bunker whereas the distance to the HV power converter at the surface is about 500 m.

**Klystrons**

The klystrons have been developed by a European company, according to CERN specifications. The main operating parameters at the rated output power are shown in Tab. 6.2.

An important parameter for the LHC klystrons is their group delay. This should be as short as possible since an RF feedback loop with total delay < 700 ns is required to ensure beam stability. Low group delay can be obtained by carefully tuning the klystron cavities (five per klystron). This increases the bandwidth of the klystron but reduces the RF gain to 37 dB.

The LHC klystrons are equipped with modulation anodes. Tetrode modulators set the klystron current to the best working point of the klystron. During operation the fast klystron power changes will be controlled by the RF drive signal level via the low-level control system.

Most auxiliary equipment for the klystrons has been recuperated from the LEP RF system, modified where necessary. This includes the power supplies for the focusing coils, the power supplies for the klystron vacuum pumps, the 200 W solid-state RF driver amplifiers and the arc detectors.

<table>
<thead>
<tr>
<th>Klystron:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power</td>
<td>300 kW</td>
</tr>
<tr>
<td>Operating frequency $f_0$</td>
<td>400.8 MHz</td>
</tr>
<tr>
<td>dc to RF conversion efficiency</td>
<td>$\geq 62%$</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>$\leq 54$ kV</td>
</tr>
<tr>
<td>Maximum beam current</td>
<td>9 A</td>
</tr>
<tr>
<td>Gain</td>
<td>$\geq 37$ dB</td>
</tr>
<tr>
<td>Group Delay at $f_0 \pm 1$ MHz and 1 dB below rated output power</td>
<td>$\leq 120$ ns</td>
</tr>
<tr>
<td>1 dB bandwidth</td>
<td>$\geq \pm 1$ MHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Circulator:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency $f_0$</td>
<td>400.8 MHz</td>
</tr>
<tr>
<td>Type</td>
<td>3-port junction circulator</td>
</tr>
<tr>
<td>Ports</td>
<td>WR2300 half-height waveguide</td>
</tr>
<tr>
<td>Maximum CW forward power</td>
<td>300 kW</td>
</tr>
<tr>
<td>Maximum CW reflected power</td>
<td>330 kW, at any phase</td>
</tr>
<tr>
<td>Insertion loss at rated forward power</td>
<td>$\leq -0.1$ dB</td>
</tr>
<tr>
<td>Isolation:</td>
<td></td>
</tr>
<tr>
<td>a) within frequency range $f_c \pm 0.25$ MHz</td>
<td>$\leq -28$ dB</td>
</tr>
<tr>
<td>b) within frequency range $f_c \pm 12$ MHz</td>
<td>$\leq -20$ dB</td>
</tr>
<tr>
<td>Group delay at $f_c \pm 0.25$ MHz</td>
<td>$\leq 30$ ns</td>
</tr>
</tbody>
</table>

**Circulators and Loads**

Each klystron will be protected against reflections by a three-port junction circulator. To ensure stable klystron operation a temperature control system will automatically adjust the circulator’s magnetic field to
compensate for the ferrite temperature variations, keeping optimum input matching and isolation at all forward power levels.

For better performance and to reduce the size, 330 kW ferrite loaded waveguide absorbers will be used as the port 3 terminations, instead of water-loads. Other advantages of these ferrite loads are higher bandwidth and low variation in reflected phase with absorbed power.

*Protection and Interlocks*

The circulators must be protected against high reflected cavity power that may result under certain fault conditions and would cause arcing between the ferrite plates. This is done using fast interlocks (see section 6.6.3) on cavity reflected power and arc detection in the waveguides, to switch off RF power within several microseconds. Short transients with reflected power peaks considerably higher than the installed power but less than a few microseconds long will however occur during injection damping. These would not result in circulator arcing and must be tolerated by the interlock system. There are also fast interlocks on klystron reflected power to act in the event of circulator malfunction. Klystrons and high-voltage equipment are protected by the slower PLC based interlock system that acts on the power converter.

6.2.5 System Tests Before Installation

The installation of the RF system comes relatively late in the planning and the time for RF system testing before beam is very limited. A full system for the powering of one cavity will therefore be assembled in SM18. It will resemble the final machine installation as closely as is reasonably possible and will be used to test the operational reliability of all major components and the overall performance of the system. Particular attention will be paid to the RF power interlock system and to the operation of the low-level RF systems.

6.3 STAGED 200 MHZ CAPTURE SYSTEM (ACN)

6.3.1 Specification of the Staged Capture System.

If the injected bunch emittance from the SPS approaches 1 eVs, the resulting bunch length given by the maximum available voltage in the SPS, combined with the phase and energy errors expected, leads to unacceptable losses from the 400 MHz buckets in the LHC. Various schemes to cope with this have been studied: more voltage in the SPS, or a higher harmonic RF system in the SPS etc. but the solution retained is a separate 200 MHz capture system in the LHC. Studies and simulations [10] have shown that by installing 3 MV/beam, capture losses can be significantly reduced. Again transient beam-loading is the major issue and determines the installed power of 300 kW per cavity.

A full RF system using four standing-wave cavities has been designed [3], space has been reserved at IR4, basic civil engineering work has been undertaken and a complete power chain for one cavity will be tested, but due to the significant improvements in the longitudinal emittance of the beam from the SPS the 200 MHz system will not be installed in the machine for initial commissioning. Only later, at higher intensities than nominal when the beam emittance approaches 1 eVs, will the capture system be installed. In operation the system is used for both capture and injection damping. The beam is “transferred” to the 400 MHz RF system just before ramping, the 200 MHz voltage being reduced to zero and the cavities damped.

6.3.2 The Cavities

The cavity design is based on the SPS SWC 200 MHz standing-wave cavities. The nominal frequency is 200.210 MHz. The main constraints on the design were the reduced diameter imposed by the 420 mm separation between the two beams and the necessity of keeping essential monopole HOM frequencies away from multiples of the 40 MHz bunch frequency. These constraints result in slightly higher shunt impedance and lower quality factor. With \( R/Q = 192 \, \Omega \) and \( Q_0 = 30,0000 \) the power dissipated at a nominal field of 0.75 MV is 69 kW. Particular attention was therefore paid to the design of the cooling channels to evacuate this large amount of power. Components such as the four HOM couplers, the tuner (200 kHz range) and the two fundamental mode dampers will be recuperated from the SPS SWC cavities and refurbished. A new
power coupler, based on the new SPS TWC one, will be used. A low-power version has been built to validate the geometry and a full-power one will be built in 2004.

6.3.3 ACN Vacuum

Four ion pumps (400 l/s) are used, mounted underneath the cavities. A Penning gauge, also installed below the cavity, monitors the pressure. The pumps provide hardware interlocks to the RF system. The bake-out temperature of the cavities will be limited to 150 °C due to the use of conical flanges (SPS type). Heating is obtained by circulation of hot water in the cooling circuit of the cavity, the body being thermally insulated by an insulation film. These cavities will be isolated from the other equipment by two all-metal DN100 sector valves.

The second beam will pass very close to the cavity body. The length of the chamber, standard diameter NEG coated Cu tube (ID80/OD84 mm), is chosen to avoid conflict between the interconnecting bellows and the body of the cavities. Special supports will be used to support the second beam tube, their positioning taking into account the free space required to exchange a tuner.

6.3.4 RF Power

The cavity is connected to the power amplifier via a circulator, which directs the reflected wave to a terminating load. This configuration not only leads to the minimum RF installed power for a given cavity voltage and beam current, but also opens up the possibility of easily combining (in a 50 Ω matched system) several RF power amplifiers.

The solution chosen to provide the 300 kW per cavity is to recuperate four SPS-LEP SWC amplifiers (60 kW CW, up to 90 kW for 1 s) and use two stages of combiners to give the final power (three hybrids per cavity, each hybrid the same as those used with the SPS TWC systems) [11]. The driver amplifier will be the same with some modifications of the output circuitry. A pre-amplifier of 50 W and pre-driver of 1 kW are needed.
The amplifiers, combiners, circulator and load will be installed in the old LEP klystron gallery (UA). The reflected power from the cavity implies that the circulator must take 240 kW average with a peak of 400 kW during 1 s. The overall RF loop delay must be kept below 700 ns, as with the 400 MHz system.

Four existing HV power supplies (10 kV, 1.1 MVA each) will be re-used for the ACN (one for two ACN cavities) and installed in building SR4.

### 6.4 TRANSVERSE DAMPING AND FEEDBACK SYSTEM (ADT)

The LHC transverse feedback system (ADT) combines three principal functions: it damps transverse injection errors, prevents transverse coupled bunch instabilities (dipole modes) and can excite transverse oscillations for beam measurements [12,13,14,15].

#### 6.4.1 Specification

There are four independent systems, one per plane and per ring. Each system comprises two modules, each consisting of two kicker units. Each kicker unit has one power amplifier with two tetrodes installed directly under the kicker vacuum tank. The horizontal kickers and power amplifiers for ring 1 are installed left of the IP4 and the vertical kickers and power amplifiers for ring 1 are to the right. The installation for ring 2 is asymmetric with respect to ring 1. Kickers and power amplifiers of ring 2 are interleaved with those of ring 1, as shown in Fig. 6.12. This arrangement optimizes the beta functions to maximize kick strength. Space has been left for a future upgrade of one extra module per ring and plane to boost the total system capability by 50%.

![Figure 6.5: Block Diagram of an LHC Damper System.](image)

Fig. 6.5 shows a schematic diagram of one system. Tab. 6.3 summarises the performance calculated for a $\beta$ function of 100 m at the kicker and gives related hardware parameters for the four systems [5,14,15]. The ADT systems resemble the SPS damper for which considerable experience exists [16].

The systems work in base band, from below 3 kHz up to > 20 MHz. The lower frequency limit is given by the choice of fractional tune, $0.25 < Q_{\text{frac}} < 0.75$. The upper cut-off frequency is given by the necessary bandwidth to damp coupled bunch dipole oscillations at a bunch spacing of 25 ns. The lower frequency cut-off is limited in the hardware by the driver amplifier [17], and the upper frequency by the RC characteristics of the kicker-amplifier combination. LHC optics version 6.4, see Tab. 6.4, gives improved performance due to the higher $\beta$ values at the kicker locations. Consequently in the vertical plane, damping times can be reduced easily to 2/3 of the values of Tab. 6.4. Note that the injection kicker in the LHC acts vertically.
Table 6.3: Nominal Performance and Hardware Parameters of LHC ADT Systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection beam momentum</td>
<td>450</td>
<td>GeV/c</td>
</tr>
<tr>
<td>Static injection errors (β=183 m)</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>Ripple (β=183 m)</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>Resistive wall growth time</td>
<td>27.4</td>
<td>ms</td>
</tr>
<tr>
<td>Tolerable emittance growth</td>
<td>2.5</td>
<td>%</td>
</tr>
<tr>
<td>Overall damping time</td>
<td>4.1</td>
<td>ms</td>
</tr>
<tr>
<td>Standard bunch spacing</td>
<td>25</td>
<td>ns</td>
</tr>
<tr>
<td>Minimum gap between batches</td>
<td>995</td>
<td>ns</td>
</tr>
<tr>
<td>Lowest betatron frequency</td>
<td>&gt; 2</td>
<td>kHz</td>
</tr>
<tr>
<td>Highest frequency to damp</td>
<td>20</td>
<td>MHz</td>
</tr>
<tr>
<td>Aperture of kickers</td>
<td>52</td>
<td>mm</td>
</tr>
<tr>
<td>No. of kickers per plane &amp; ring</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Length of kickers (electrodes)</td>
<td>1.5</td>
<td>m</td>
</tr>
<tr>
<td>Nominal voltage up to 1 MHz</td>
<td>± 7.5</td>
<td>kV</td>
</tr>
<tr>
<td>Kick / turn at 450 GeV/c (1 MHz)</td>
<td>2</td>
<td>µrad</td>
</tr>
<tr>
<td>Rise time 10-90%</td>
<td>350</td>
<td>ns</td>
</tr>
<tr>
<td>Rise time 1-99%</td>
<td>720</td>
<td>ns</td>
</tr>
<tr>
<td>Frequency range (gain)</td>
<td>0.001-20</td>
<td>MHz</td>
</tr>
<tr>
<td>Noise</td>
<td>&lt; 1 LSB</td>
<td>with 10 Bit/2σ</td>
</tr>
</tbody>
</table>

Table 6.4: Performance with Optics 6.4, compared to β = 100 m (at 450 GeV/c), assuming 7.5 kV maximum kick voltage.

<table>
<thead>
<tr>
<th></th>
<th>β=100 m performance</th>
<th>Optics 6.4 performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kick per turn in σ</td>
<td>Kick per turn in σ @ β in m</td>
</tr>
<tr>
<td>ADTH beam 1</td>
<td>0.23 σ</td>
<td>0.360 σ at β = 169 m</td>
</tr>
<tr>
<td>ADTH beam 2</td>
<td>0.23 σ</td>
<td>0.326 σ at β = 197 m</td>
</tr>
<tr>
<td>ADTV beam 1</td>
<td>0.23 σ</td>
<td>0.356 σ at β = 228 m</td>
</tr>
<tr>
<td>ADTV beam 2</td>
<td>0.23 σ</td>
<td>0.380 σ at β = 273 m</td>
</tr>
</tbody>
</table>

6.4.2 Kickers and Power Amplifiers

Kickers and power amplifiers, as well as their supports, form part of a contribution to the LHC by the Joint Institute for Nuclear Research (JINR), Dubna, Russia [18,5]. The kicker plates are directly coupled to the power amplifier tetrode anodes. They present a capacitive loading to the tetrode at low frequency in parallel with the anode resistor. At higher frequencies the distributed nature of the kicker capacitance behaves like a TEM line connected at the centre and open circuited at the ends [19]. Simulations, using a mathematical model developed for the kicker and the power amplifier circuit including the tetrodes [20] agree well with prototype measurements [20,15]. With 12 kV of anode voltage, 10.5 kV deflecting voltage is achieved at 100 kHz. The amplifier can be run with anode voltages of up to 15 kV DC further boosting the kick strength at low frequencies. At 1 MHz, however, the kick strength is limited by the capacitance of the kicker in parallel with the anode resistor. Not much more than the nominal 7.5 kV can be obtained beyond 1 MHz. The reserve kick strength at low frequencies is interesting for narrow band applications such as a beam exciter, for example as an ac dipole as demonstrated in the SPS [21]. At 15 kV anode voltage a maximum kick strength of around 4 µrad can be obtained at the lower frequencies for about 100 ms, limited by the power dissipation in the anode resistor. The feedthroughs are designed to withstand these high voltages [22]. Tab. 6.5 shows the maximum capabilities of the systems at different frequencies. These maximum values are only available in pulsed mode (50 ms at a duty cycle of 50%). In continuous mode about 50% of these values can be reached.
Table 6.5: Estimated Maximum Capabilities in Pulsed Mode ($\beta=100$ m)

<table>
<thead>
<tr>
<th></th>
<th>100 kHz</th>
<th>1 MHz</th>
<th>10 MHz</th>
<th>20 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADTH</td>
<td>0.47 $\sigma$</td>
<td>0.43 $\sigma$</td>
<td>0.14 $\sigma$</td>
<td>0.05 $\sigma$</td>
</tr>
<tr>
<td>ADTV</td>
<td>0.47 $\sigma$</td>
<td>0.43 $\sigma$</td>
<td>0.14 $\sigma$</td>
<td>0.05 $\sigma$</td>
</tr>
</tbody>
</table>

The auxiliary high-voltage equipment, including the anode voltage power converter, screen grid and control grid voltage converters, will be installed on the surface. All must be interlocked and remotely controlled. A distributed PLC system will be used for controls, slow interlocks and alarms. PLCs installed in UX45 and SR4 will communicate via a private bus for this purpose. They will also control the driver amplifiers in UX45 and monitor the power amplifiers in the tunnel. A fast hard-wired interlock chain is foreseen between SR4 and UX45.

Tab. 6.6 shows the most important higher order longitudinal modes contributing to the machine impedance with an estimate of their damped Q values.

Table 6.6: Higher-Order Longitudinal Modes in Kicker Structure (per Kicker); Estimates from Prototype Measurements.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>R/Q in $\Omega$</th>
<th>Q (damped)</th>
</tr>
</thead>
<tbody>
<tr>
<td>89</td>
<td>2</td>
<td>256</td>
</tr>
<tr>
<td>176</td>
<td>3</td>
<td>110</td>
</tr>
<tr>
<td>296</td>
<td>&lt;0.1</td>
<td>47</td>
</tr>
<tr>
<td>357</td>
<td>9</td>
<td>46</td>
</tr>
<tr>
<td>436</td>
<td>13</td>
<td>104</td>
</tr>
<tr>
<td>488</td>
<td>11</td>
<td>42</td>
</tr>
</tbody>
</table>

There are some modes above 500 MHz including a cluster of modes at 800 MHz, but precise estimates of impedance require measurements on the final kicker. Damping is achieved using two capacitively coupled 50 $\Omega$ HOM couplers, one per plate (coupling capacity 2 pF). They can extract 500 W each, estimated to be sufficient even for ultimate beam intensities. The most critical case is when a mode falls exactly on a bunch frequency line (multiple of 40 MHz for 25 ns standard bunch spacing), and some modifications to the final geometry can be foreseen to push modes away from these dangerous lines.

6.4.3 ADT Vacuum

The dampers will be baked in situ at 250°C for 24 h. Each damper pair has two 30 l/s ion pumps, one at each end. A Penning gauge installed on each pair will provide a hardware interlock to the damper control system. The dampers and longitudinal pickups are between the same sector valves.

6.4.4 Damper pickups and RF Front End

Dedicated sets of two pickups per ring and plane will be used. These pickups are equipped with both buttons and strip-lines (See Sec. 13.11, Beam Position Monitors). The length of the strip-lines, short-circuited at one end, is 150 mm, giving a first transfer function maximum at 500 MHz. Hybrids in the tunnel provide the sum and difference signals, which will be transmitted via high quality 7/8" RF cables to the surface building SR4 where the signal processing is located.

6.4.5 Signal Processing and Interface with Computer Control

Signal processing will consist of an RF front end to down convert the pickup signals from a suitable harmonic of the revolution frequency to base-band, with a minimum bandwidth of ±20 MHz. Subsequent digital signal processing will be done with >80 MHz sampling rate and a minimum resolution of 12 bits for analogue to digital conversion. The main functions of the digital signal processing are to adjust the feedback phase [23,24] and adjust the overall delay to match the beam time of flight (1-turn delay). The processing is complemented by a post-mortem facility and a possibility for feedback gain adjustment. Correct system functioning can be tested by injecting a test-signal at the start of the signal processing and following it
through the chain up to the power amplifiers in the tunnel. Beam excitation signals can be added to the analogue part of the feedback loop or programmed in the digital part and triggered by timing.

6.4.6 System Operation and Limitations

At injection of a batch of proton bunches the dampers can be operated at the highest possible gain to achieve rapid damping of the lower frequency part of the injection error. During some tens of turns the systems can be operated in saturation, further reducing the damping time [25]. After initial damping the gain should be reduced to stay in a linear regime to provide feedback gain over the entire bandwidth of 20 MHz. Simulations show that the lower frequency part of the injection errors up to 1 MHz can be damped in the specified time, but small ripples in the strength of the injection kicks along the batch, both from the SPS extraction and LHC injection elements, which extend in frequency up to about 12 MHz, are damped more slowly and consequently lead to some emittance blow-up. Errors in timing of the kicker firing can also produce large bunch oscillations at the extremities of the batches.

Special care must be taken to limit noise injected by the ADT systems. Excess noise leads to emittance blow-up, the amount depending on the feedback gain and the betatron frequency spread [25]. Operation of the feedback in presence of strong non-linearities, such as octupoles, must be avoided. Stabilisation during the ramp and the flat top before colliding can be done by the feedback. Octupoles may be used instead; the overall strategy is described in Sec. 5.4 of this design report.

6.5 LOW-LEVEL RF

The low-level RF system comprises four sub-systems, the Cavity Controller, the Beam Control, RF Synchronization and the Longitudinal Damper. It also uses the longitudinal pickups (APW). The system described below is for the 400 MHz RF system. The requirements for the low level of the 200 MHz system are similar in many respects and the design will closely follow this system.

6.5.1 The Cavity Controller

There is one cavity controller for each individual cavity. It has two main functions; to provide adequate control of the phase and amplitude of the voltage in the cavity and to keep the power demanded at acceptable levels. To achieve this it comprises a number of separate loops (Fig. 6.6).

The Different Controller Elements

The Klystron Polar Loop keeps the gain and phase constant from the RF modulator input to the cavity main coupler input. It compensates the large change in phase shift when the klystron beam voltage is changed (~30°/kV) [29], the smaller phase shift variation with circulator temperature and the gain and phase modulation caused by power supply ripples (50 Hz, 600 Hz), on the power supply (~35° RF peak to peak measured on the second klystron). The loop bandwidth is approximately 1 kHz.

The RF Feedback Loop reduces the effects of the cavity impedance by compensating variations in the beam-induced voltage. The loop delay is ~650 ns. A 20 dB impedance reduction (open loop gain of 10) is specified at the exact RF frequency, reducing to zero at 1 MHz. The 1-Turn Feed-forward loop provides an extra 10-15 dB reduction of the beam loading at the RF frequency. In addition, a 1-Turn Feedback provides 20 dB gain on the revolution frequency sidebands to control transient effects. It reduces the impedance in a band extending to ~1 MHz on each side of the RF frequency.

The Tuner Loop maintains a given phase between incident power and cavity field. It has to be controlled in such a way that power transients due to the passage of batches and gaps are minimised (half-detuning).

The Set Point defines the desired voltage in the cavity. It should ideally be constant. However, some bunch-to-bunch variation is allowed as a compromise between an ideal voltage and the ability of the klystron to deliver transient power spikes. In addition to this function, the Set Point module also injects the drive from the Longitudinal Damper (see below).
Technology

All RF signals are first demodulated to generate base band I and Q signal pairs. The achievable range of impedance reduction with RF feedback depends on the overall loop delay and to minimize this a fast analogue path is used. Digital technology, inherently slower, is used to provide high precision control of 1° phase and 1% amplitude at the exact RF frequency. Digital I/Q Demodulators are used [30], implemented in Field Programmable Gate Arrays (FPGAs) or Complex Programmable Logic Devices (CPLDs). FPGAs are also used wherever bunch-by-bunch processing at 40 MHz is required (1-Turn Feedback, 1-Turn Feedforward and Set Point Generation).

Diagnostics

All signals used in the loops are logged in two different memories, one for observation and one for post-mortem. For slow signals 6 s of data are kept with one sample /100 μs, whereas fast signals are logged at a rate of 40 MHz to observe the effects on each bunch, the last ten turns (~1 ms) being stored. In addition a base band network analyzer is included: an arbitrary function can be injected into the loops and the corresponding outputs at various points enable the transfer function to be obtained, as is done in PEPII [31]).

Layout

The cavity controllers are installed on a platform in UX45 on the opposite side of the tunnel from the klystrons to minimize the risk of signal contamination. There are four racks common to all cavities plus one rack per cavity. The latter contains the RF Feedback crate and the Klystron and Tuner Loop crate. A small pre-driver amplifies the 400 MHz output and sends it across the tunnel to the klystron driver amplifier.
6.5.2 Beam Control

The main functions of the beam control are to generate the beam centred RF reference, stabilize the beam against dipole oscillations and minimize noise effects - mainly phase noise - to optimize lifetime in coast. There is one separate system per ring, as shown in Fig. 6.7, but one single dual-frequency program, common to both.

The dual frequency program pilots two Direct Digital Synthesizers (DDS) that generate the 400 MHz RF for each ring. The frequency is computed from the instantaneous value of the integrated B field, defined by a function, not a measurement, and the desired radial steering. The two rings can be ramped independently, but for physics to take place they will be ramped synchronously.

The Beam Control Loop module implements the classic three loops: phase, radial and synchronization. The last two are exclusive. If required, acceleration can be done with the radial loop. For physics, however, the frequency of each ring is locked in phase to the reference via the synchronization loop and both DDS have, at all instants, the same frequency. Acceleration with a synchronization loop is also used for LHC beams in the SPS [32].

The phase loop input is the phase error between the total cavity voltage and the beam phase, measured with a pickup. The Phase Discriminator Module measures the phase for each bunch and computes an average for the Beam Control Loop. The Beam Control thus deals with the beam as a whole, updating the RF frequency at each turn.

The dynamics of the synchronization loop must be adjusted as the synchrotron frequency changes [33]. The Beam Parameter Module computes the synchrotron frequency and passes the value to the Beam Control Loop module.

Technology

The processing is slow (update rate at the revolution frequency of 11 kHz) so that DSPs can be used. The Phase Discriminator uses a Digital I/Q Demodulator and transforms the cartesian coordinates (I,Q) into
(phase, amplitude) using the COordinate Rotation DIgital Computer (CORDIC) algorithm implemented in an FPGA. This is also used at RHIC [34]. The modules will reside in a VME crate.

**Layout**

The Beam Control system is installed in the Faraday Cage in SR4. It generates the Master \( f_{RF} \) and the revolution frequency and these are sent on fibres to the RF cavern in UX45.

**6.5.3 RF Synchronization**

The three main functions are the synchronisation of the SPS to LHC “bunch into bucket” transfer - with diagnostics of transfer faults, generation of beam synchronous signals (40 MHz bunch frequency, revolution frequency and injection kicker pulses) for users (experiments, Beam Instrumentation, Beam Transfer etc.) and fine re-phasing of the two rings before physics.

The method used for synchronizing the transfer is now classic at CERN, (PSB to CPS, CPS to SPS and also SPS to LEP [32, 35]). The LHC is the master machine, sending to the SPS a fiducial frequency train at the frequency \( f_c = \frac{SPS}{27} f_{rev} = \frac{LHC}{7} f_{rev} \) and a phase shifted LHC 400 MHz RF. The SPS locks its beam to these two signals. A delay box allows selection of the buckets to receive the SPS batch. The phase of the 400 MHz sent to the SPS can be fine adjusted to centre the received beam in the middle of the LHC bucket. All these adjustments are transparent to the SPS.

**Layout and Distribution**

The RF Synchronization systems will be installed in the Faraday Cage in SR4. The two signals sent to the SPS (BA3) go via thermally compensated fibre-optic links (re-used from LEP). Three pairs of bunch frequency plus revolution frequency references are also generated in SR4. There is one pair per ring for beam instrumentation equipment and one pair for the experiments. The links are under the responsibility of the AB Controls group. The LHC RF also generates pulses for the LHC injection kickers (transmitted on fibres). For fail-safe operation two dedicated fibres transmit the revolution frequency signals to the beam dump systems. The transmission is the responsibility of the AB Beam Transfer group.

When the LHC is ramped for physics, the two rings are locked from injection and the two DDS shown in Fig. 6.7 receive the same control word for their frequency register at all times. Before physics the relative phase of the two rings can be fine-adjusted by simply changing the control word of the phase register of one DDS.

**6.5.4 Longitudinal Damper**

The longitudinal damper reduces emittance blow-up due to filamentation following phase and energy errors at injection. This is important in the SPS-LHC transfer because the SPS bunch almost fills the LHC bucket [10]. The damper can also fight against slow longitudinal coupled-bunch instabilities but this should not be a concern [4,36]. It tries to damp the longitudinal oscillation of the bunch centre of charge (dipole mode) or the oscillations of the bunch shape (quadrupole and higher modes). Dipole mode damping is achieved by injecting a correction into the 400 MHz system to generate a cavity field in quadrature with the main accelerating field. Quadrupole damping, foreseen as an upgrade, can be achieved by varying the amplitude of the main accelerating field to modulate the bucket size.

**Implementation and layout**

The dipole mode damper will be similar to that proposed in [37]. Filtering will be done with a Finite Impulse Response (FIR) filter clocked at 40 MHz and implemented in an FPGA. The hardware will be located in the Faraday Cage in SR4 and will produce a signal in base band (momentum kick) extending from dc to a few MHz. This signal will be sent via a fibre-optic link to the RF cavern UX45, and hence to the Set Point module shown on Fig. 6.6.
6.5.5 Longitudinal Pickup (APW)

Two longitudinal monitors per beam will be installed. They are of the wall current type and are based on the coaxial-line designs used in the SPS and PS [38,39]. They will be used for the beam phase reference for the low level loops and also for longitudinal bunch and beam diagnostics. Their transfer impedance is \( -8 \Omega \) and their bandwidth \( \sim 170 \text{ kHz} \) to \( \sim 3.7 \text{ GHz} \). As the pickups contain ferrite materials, they will be baked *in situ* at \( 250^\circ \text{C} \) for 24 h and each pickup will have a 30 l/s ion pump at both ends. Before installation the ferrite will follow a special out-gassing procedure, presently being defined. No specific pressure hardware interlock is needed for these pickups.

6.6 EQUIPMENT CONTROLS

6.6.1 Hardware and Layout

Equipment controls for the LHC RF ACS, ADT and ACN systems will make extensive use of Programmable Logic Controllers (PLC), and industrial components. The ACS power system and SC cavities will be controlled by 20 midrange PLCs having 192 remote interface modules in total. Altogether the ACS control system will have to treat approximately 3400 signals, 1000 interlocks and 1100 alarms. The ADT and ACN systems will each use eight PLCs. While commercial remote interface modules will mainly be used, a number of special signal conditioners have been developed, in industry-compatible form. These include a multi-sensor Pt100/Allen Bradley/CERNOX temperature conditioner, a liquid helium level measurement interface and a dual threshold level detector. The remote interface modules will be grouped near the equipment and connected to the PLCs via a field bus network (FIPIO). Special equipment, including that recuperated from LEP, e.g. RF amplifiers, power supplies and vacuum conditioners etc. will be fitted with this FIPIO. The PLCs will exchange data with each other and communicate with the supervision layer by Ethernet, over standard structured cabling. The layout for the ACS system is shown in Fig. 6.8.

![Ethernet Distribution](image)

Figure 6.8: ACS Equipment Controls for a) One Klystron Cavity Line and b) One Cryomodule

There is one PLC for each cavity/klystron line and one for each SC module and HV system. The PLCs and remote interfaces for each system are distributed at the various equipment locations in UX45, SR4 and
machine tunnels so that cabling cost and complexity are minimized and problems with passing signals over long cables are avoided.

6.6.2 Software

The control software has been structured in an object-oriented manner right down into the PLC, as shown in Fig. 6.9. In the PLC each hardware device has its software counterpart. Global software devices have been defined allowing higher levels of abstraction. The software device contains properties (command, status code, values) that are the image of the hardware device parameters. The individual devices are controlled by a “sequencer” for automatic operation. The PLC devices are remotely accessible through an OPC server and a middleware gateway is used to implement Remote Device Access (RDA) based on Common Object Request Broker Architecture (CORBA), following the Common Middleware (CMW) approach. The “IOScan” mechanism is used to exchange predefined blocks of data between PLCs.

6.6.3 Interlocks

Fast interlocks (< 2µS) are treated by an independent hardware system based on that used in LEP. An interlock crate contains up to eight modules that can be interrogated by a local controller over an internal serial bus (I²C). This is shown in Fig. 6.10. Information on the first fault in each module and the first active module in the crate is returned to the PLC over the fieldbus. A particular feature is that interlocks can be software inhibited by the PLC through a special command sequence. Crates and modules are chained to realise the full interlock system. In the ACS system there will be two chains: one for RF interlocks and one for HV interlocks. For the ADT, with interlock inputs in both UX45 and SR4, the HV chain is split into two parts.

6.6.4 Slow Interlocks and Alarms

Each PLC will generate an alarm code in the form of a coded integer (the ‘code’ property of each device) with an update period of <10 ms. The device codes are grouped to form a macro summary code used to toggle the PLC interlock output bit. A first fault detection mechanism is implemented in the PLC and fast interlock data and device codes are latched. An external reset is needed to restart. The supervision has full access to all alarm and interlock data.
6.6.5 Machine Protection

Simulations have shown that with nominal intensity the trip of one klystron will cause the beam to be lost. The RF systems will supply interlock signals to the Beam Interlock Controller (BIC) to provoke beam dump when serious fault conditions arise. Under certain conditions when there is no risk of damage to the machine, i.e. pilot beam, they will be inhibited by the BIC. Signals for the protection of the SC cavities will also be supplied to the BIC: these include HOM coupler temperatures, helium tank levels and pressures and insulation vacuum.

6.6.6 Low-Level RF Controls

The LHC low-level RF, damper feedback and beam control systems will make extensive use of digital technology in the form of FPGAs and DSPs. This allows the direct integration not only of all necessary remote control functionality but also of extensive diagnostics facilities.

6.6.7 Front End and Application Software

The local intelligence required for sequencing of complex equipment actions will reside where possible in the PLCs. Where non-PLC equipment is involved, such as in the RF low-level, damper feedback and beam control systems, the sequencing will be done in the front-end computer. There will be one front-end computer per ring for each system, which will be responsible for overall equipment control and will provide the interface to the accelerator control software via the Controls Middleware. The front-end computers will be AB/CO standard hardware, running software built on the standard AB/CO Front End Software Architecture (FESA). FESA is also being evaluated as the software platform for the VME crates housing the low-level system electronics.

Application software for the test stands and for expert diagnostic purposes in the LHC is being developed in Java, using tools provided by AB/CO such as the GUI Platform for user interfaces and CMW for communication.

The low-level RF, damper feedback and beam control systems represent a particular challenge. Many measurement and analysis tasks traditionally done with external instrumentation such as oscilloscopes and network analyzers will be done directly inside the systems themselves. Extensive software will be needed for setting up these facilities and for subsequent data acquisition, analysis and presentation.

6.6.8 Signal Observation and Post-Mortem

Since the RF equipment in UX45 will not be accessible when beam is circulating, operation of the RF systems will require remote observation of a number of signals. These signals fall into three categories: fast (RF) signals at and above 400 MHz, bunch frequency signals at 40 MHz and slow signals, below 100 kHz.

Many of these signals will be available directly from the RF low-level and damper feedback VME systems. The remaining signals will be acquired using commercial off-the-shelf digitizer and multiplexer modules based on Compact PCI, following the nAos replacement standard (OASIS). Data for the post-mortem system will be stored in circular buffers inside the digital parts of the low-level and feedback systems, as well as in the external Compact PCI acquisition crates. The arrival of a post-mortem trigger event will freeze the buffers, making the data available for readout via the control system. A second set of buffers will operate in parallel to provide data for non-post-mortem observation purposes. All diagnostics systems and systems containing diagnostics will be powered by Uninterruptible Power Supplies (UPS).

6.7 LAYOUTS AND INFRASTRUCTURE

Following the changes introduced by Optics version 6.4, all RF systems are now positioned closely around IR4, in UX45, RB44/46 and UL44/46. The 4800 kW power plant with its 16 klystrons, circulators and loads for the 400 MHz superconducting cavity RF system (ACS) is located in the cavern UX45, together with its HV equipment, auxiliary power supplies and control racks. The layout of the equipment is shown in Fig. 6.11.
The two accelerating modules for Beam 2 are positioned directly on either side of the centre of IR4, followed by the modules for Beam 1. This is to permit passage of the cryogenic line (QRL) which joins the bottom of the cavern UX45 after the Beam 2 modules.

While waveguides connecting the cavities to the klystrons are now more accessible than they were in the original layout, installation and access remains particularly difficult for the two modules of Beam 1, these being partly situated inside RB44 and RB46. The entrances into RB44 and RB46 cannot be enlarged, as they are steel-reinforced supporting structures for the cavern.

The machine tunnel crossing the cavern is shielded with 1200 mm thick concrete walls and an 800 mm thick concrete roof. Openings for the cryogenic lines and the 16 waveguides would allow passage of radiation from the tunnel into the cavern. While there is no access to UX45 for operation with beam, access to the control racks and the klystrons is necessary during RF conditioning which produces intense gamma radiation. An additional shielding wall (800 mm thick concrete) must therefore be installed. Simulations have confirmed that this wall reduces the radiation to safe levels.

Figure 6.11 Layout of ACS and equipment in UX45

The other RF equipment is located in the tunnel areas symmetrically on either side of the IR. The layout on the right hand side is shown in Fig. 6.12. Equipment on the left hand side is identical. The RF pickup stations (APW) are at about 16 m, the transverse damper system (ADT) at about 23 m and the 200 MHz system (four cavities per beam) at about 24 m from the centre.

Although the 200 MHz system (ACN) is staged, it forms a normal part of the integration studies. Six holes for passing the coaxial power lines from the galleries UL44/46 and UA43/47 to the cavities in RB 44/46 have already been drilled.

The total dissipation of all RF systems into air is 490 kW (300 kW without the 200 MHz system). The existing ventilation plant in UX45 (100 kW), complemented by several additional local chilled water
ventilation units, is used to remove this heat. Two doors will separate the air volume of the RF areas from the machine tunnel.

The cooling of all RF systems requires 1300 m$^3$/hour water flow (930 m$^3$/hour without the 200 MHz system), supplied by two pumps, one for the left and one for the right side of Point 4.

The surface building SR4 is dedicated to RF. It houses the five 4 MW klystron power converters for the 400 MHz cavities and the power converters for the 200 MHz system and the transverse dampers. There will also be a Faraday cage for beam control equipment.

Figure 6.12: Layout of RF Systems on right-hand side of IR4

About 1100 cables of different kinds, totalling 160 km, connect the equipment in the machine tunnel, the power plants and the control racks. The cables for the 400 MHz modules are routed via two openings in the floor of the tunnel to the low level racks and the klystrons.

Most of the low-level and feedback electronics (20 racks) are located in the part of UX45 next to the cryogenic equipment, US45. This location has been chosen in order to reduce the lengths of the feedback cables as much as possible, and also to minimize possible cross-talk with the high-power RF installation (klystrons, circulators, power loads, and waveguides). Simulations indicate that the radiation level at the feedback electronics is 100 times lower than in the RRs where power converters and electronics will be installed. Nevertheless, there is a risk of single event perturbations and the susceptibility of the electronics is under study.

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