Chapter 4

The RF systems and beam feedback

4.1 Introduction

The injected beam will be captured, accelerated and stored using a 400 MHz superconducting cavity system, and the longitudinal injection errors will be damped using the same system. This choice defines the maximum allowable machine impedance, in particular for higher order modes in cavities [23]. Transverse injection errors will be damped by a separate system of electrostatic deflectors that will also ensure subsequent transverse stability against the resistive wall instability [24]. A new capture system at 200 MHz to reduce injection loss and ease operation has been proposed and designed. It will be installed at a later stage, if the injected emittance increases when intensities much higher than nominal are reached. All RF and beam feedback systems are concentrated at 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. Point 4 is already equipped with klystron power converters to be reused from LEP.

The beam and machine parameters that are directly relevant to the design of the RF and Beam Feedback systems are given in table 4.1. 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 as a result, an RF system in the LHC of 400.8 MHz can be used to capture the beam with minimal losses, accelerate, and finally store it at top energy. Higher frequencies, while better for producing the short bunches required in store, cannot accommodate the injected bunch length.

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 [23].

The final emittance at 7 TeV (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 ($\sim$ 1 A) combined with the long beam

Table 4.1: The Main Beam and RF Parameters.

	Unit	Injection 450 GeV	Collision 7 TeV
Bunch area (2σ)*	eVs	1.0	2.5
Bunch length (4σ)*	ns	1.71	1.06
Energy spread (2σ)*	10^{-3}	0.88	0.22
Intensity per bunch	10^{11} p	1.15	1.15
Number of bunches		2808	2808
Normalized rms transverse emittance V/H	μm	3.75	3.75
Intensity per beam	A	0.582	0.582
Synchrotron radiation loss/turn	keV	-	7
Longitudinal damping time	h	-	13
Intrabeam scattering growth time - H	h	38	80
- L	h	30	61
Frequency	MHz	400.789	400.790
Harmonic number		35640	35640
RF voltage/beam	MV	8	16
Energy gain/turn (20 min. ramp)	keV	485	
RF power supplied during acceleration/ beam	kW	$\sim$ 275	
Synchrotron frequency	Hz	63.7	23.0
Bucket area	eVs	1.43	7.91
RF (400 MHz) component of beam current	A	0.87	1.05

* The bunch parameters at 450 GeV are an upper limit for the situation after filamentation, $\sim$100 ms after each batch injection. The bunch parameters at injection are described in the text.

gap ($\sim$ 3 μs) due to the abort gap dominates the design of the LHC RF system and leads to the choice of SC cavities with a 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(HOM) 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 is 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 is increased in the RF region to 420 mm by means of special superconducting dipoles. With the increased separation and also by staggering the cavities longitudinally, the "second" beam can pass outside the cavity. It must still, however, pass through the cryostat.

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4.2 Main 400 MHz RF Accelerating System (ACS)

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 superconducting cavities. A large tuning range is required to compensate the average reactive beam component. Each RF system has 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 [25]. 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_{ext}) but the higher field in coast demands a high Q_{ext} to limit the power needed. The power coupling must therefore vary during the ramp. The variable coupler has a range of $Q_{\mathrm{ex}} = 10{,}000$ to $Q_{\mathrm{ext}} = 200{,}000$. To control the transient beam-loading, the installed power is 300 kW — the average RF power being much lower. Simulations [26] 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 HOMs 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. To couple to the different polarities of the multi-pole modes, two wide-band HOM couplers are used placed at 120° around the circumference. The wideband couplers have a notch filter at 400 MHz which causes reduced coupling to these modes. Two dipole modes at ~500 MHz (TE_{111}) and ~534 MHz (TM_{110}) respectively 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 use of niobium sputtering on copper for construction of the cavities 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, as 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

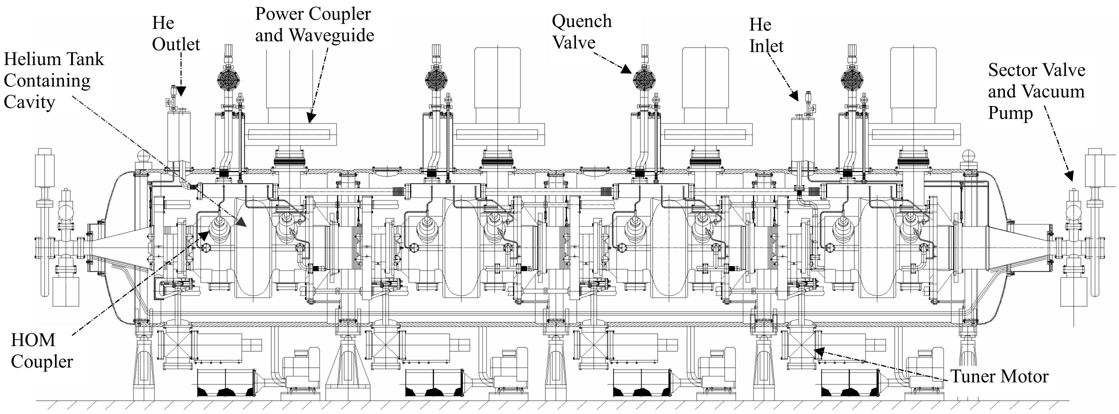

Figure 4.1: Four-cavity cryomodule.

a single cryomodule, see figures 4.1 and 4.2. 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 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.

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 $\pm$15 mbar. The operation of the cavities will be 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.

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 chambers are made of

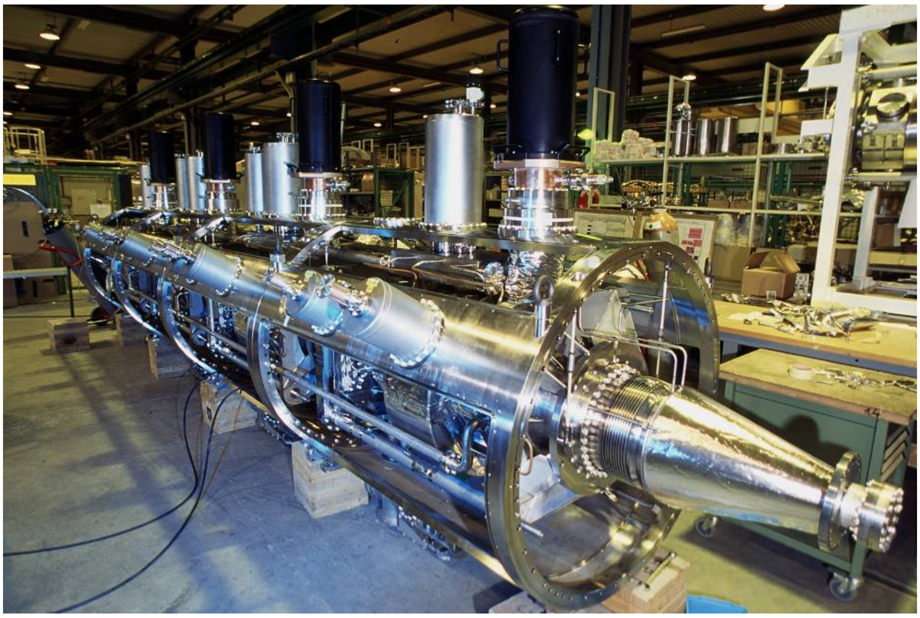

Figure 4.2: Four-cavity module during assembly.

stainless steel tube (ID 67 mm, 1.5 mm thick), coated by electro-deposition 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 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.

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. 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 table 4.2. 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.

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 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.

Table 4.2: Characteristics of the RF power equipment.

Klystron:	
Output power	300 kW
Operating frequency f_0	400.8 MHz
DC to RF conversion efficiency	$\geq$ 62%
Operating voltage	$\leq$ 54 kV
Maximum beam current	9 A
Gain	$\geq$ 37 dB
Group Delay at $f_0 \pm$ 1MHz and 1 dB below rated output power	$\leq$ 120 ns
1 dB bandwidth	$\geq \pm$1 MHz
Circulator:	
Operating frequency f_0	400.8 MHz
Type	3-port junction circulator
Ports	WR2300 half-height waveguide
Maximum CW forward power	300 kW
Maximum CW reflected power	330 kW, at any phase
Insertion loss at rated forward power	$\leq$ -0.1 dB
Isolation: a) within frequency range $f_o \pm$0.25 MHz b) within frequency range $f_o \pm$12 MHz	 $\leq$ -28 dB $\leq$ -20 dB
Group delay at $f_o \pm$ 0.25 MHz	$\leq$ 30 ns

4.3 Staged 200 MHz Capture System (ACN)

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 [26] 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, space has been reserved at Point 4, 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.

The 200 MHz standing-wave cavity design is based on the SPS SWC cavities, see figure 4.3. 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

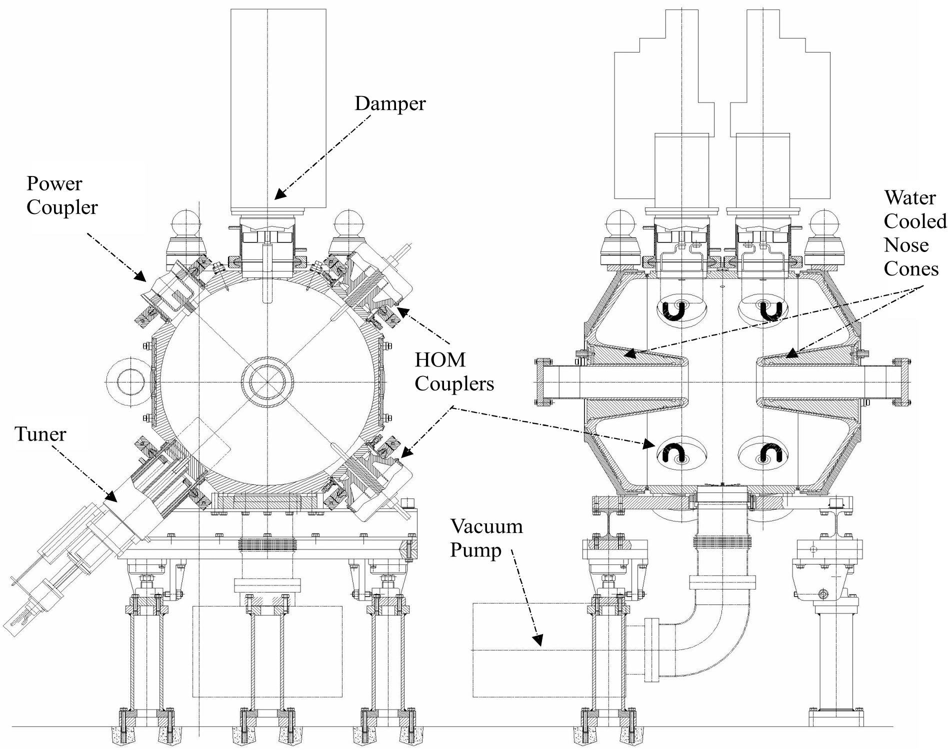

Figure 4.3: ACN 200 MHz cavity mounted on its support.

constraints result in slightly higher shunt impedance and lower quality factor. With R/Q = 192 Ω and Q_0 = 30'000 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.

4.4 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 [27]. 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. 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%. The systems work in base band, from below 3 kHz up to $>$ 20 MHz.

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4.5 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. 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, see figure 4.4. 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 ($\sim$30°/kV), the smaller phase shift variation with circulator temperature and the gain and phase modulation caused by power supply ripples (50 Hz, 600 Hz), on the power supply ($\sim$ 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 $\sim$ 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 $\sim$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.

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 ($\sim$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 [27]).

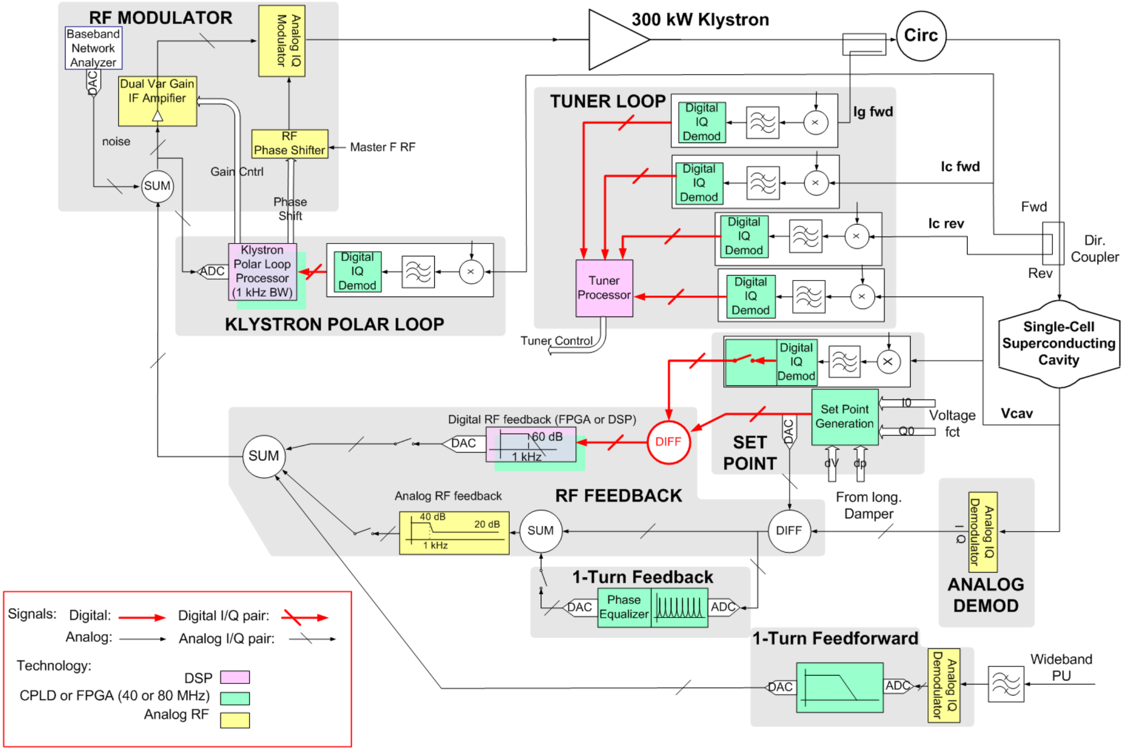

Figure 4.4: The cavity controller (one per cavity).