COMMISSIONING OF THE 400 MHZ LHC RF SYSTEM

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Abstract

The installation of the 400 MHz superconducting RF system in LHC is finished and commissioning is under way. The final RF system comprises four cryo-modules each with four cavities in the LHC tunnel straight section round IP4. Also underground in an adjacent cavern shielded from the main tunnel are the sixteen 300 kW klystron RF power sources with their high voltage bunkers, two Faraday cages containing RF feedback and beam control electronics, and racks containing all the slow controls. The system and the experience gained during commissioning will be described. In particular, results from conditioning the cavities and their movable main power couplers and the setting up of the low level RF feedbacks will be presented.

OVERVIEW OF THE 400 MHZ RF SYSTEM

The system consists of eight single-cell SC cavities per beam. Four cavities are housed in a single cryo-module, operating at 4.5 K. Each cavity has a high-power variable RF coupler to optimize the requirements from injection to top energy. Each cavity supplies 1 MV at injection and 2 MV at top energy. The four cryo-modules, two per beam, were extensively tested and RF conditioned to 1.5 times their nominal operating voltage and the couplers to full power prior to installation in LHC. [1, 2]

Figure 1: RF Cryo-modules in the LHC tunnel at IP4.

Each cavity is powered by its own 300 kW klystron. The klystrons are housed in the nearby UX45 cavern and each is connected by waveguides via a circulator and load to its cavity coupler. Four klystrons share a high-voltage power supply installed on the surface. The klystrons have a modulating anode to set optimum DC current. Tetrodes driving the modulators, fast protection (crowbar) and other high-voltage equipment are located in fireproof concrete bunkers near the klystrons, one per group of four klystrons.

Figure 2: Klystrons, Power Equipment and Control Racks in the UX45 Cavern**.**

The control system is based on commercial PLCs, but with dedicated hardware for functions such as fast RF interlocks and RF power measurement. The control system interface is provided by CERN's "Front-End Software Environment" (FESA) and applications for operation and expert use are written in JAVA or LabView.

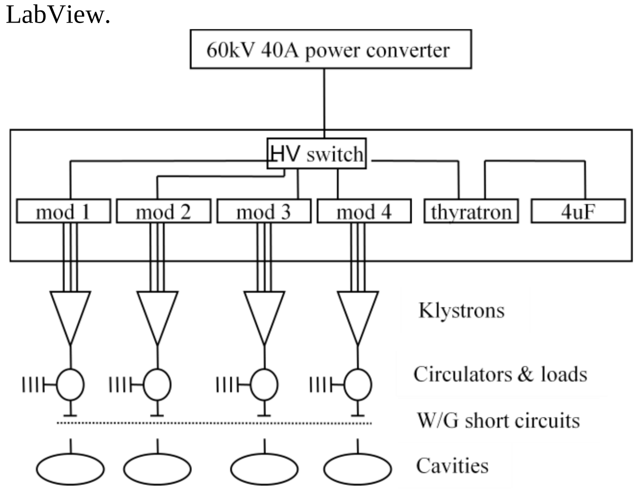


Figure 3: Layout of Klystrons, HV Equipment, Cavities and Power Converter.

Sophisticated low level RF and beam control systems are needed in a high intensity proton storage ring like LHC. Each cavity has two VME based Cavity Controllers, containing cavity tuner loop, RF feedback loop, klystron feedbacks to minimise noise and ripple, as well as ramp function generator and timing interfaces [3]. These systems are housed in Faraday Cages in UX45, close to the klystrons. Additional beam control loops and fast timing and synchronization systems are housed in a surface building. FESA is also used to for these systems, with applications in JAVA or LabView.

Figure 4: Cavity Controllers in UX45 Faraday Cages.

"WARM" COMMISSIONING

Before cool-down of the cavities all systems were fully checked out. Waveguide shorts were mounted in front of the cavities and klystrons and high power RF equipment taken to full power and RF calibrations done.

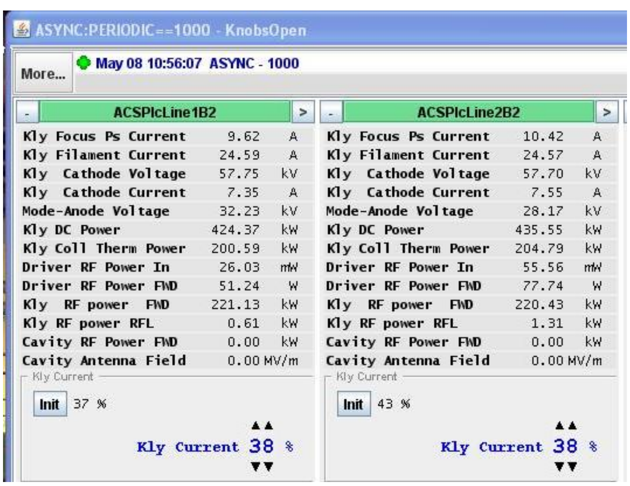


Figure 5: RF Power Calibration Checks.

RF power readings from directional couplers mounted near the klystrons were cross-checked with DC and collector power measurements. The complex signal distribution and monitoring systems were calibrated and the cavity controller loops set up. This included setting up special clamping circuitry in the klystron drive chain to prevent overdrive of the klystron which would otherwise cause instability in the RF feedback loops.

"COLD" COMMISSIONING

Cryogenics

The cavities share the same Cryogenic Distribution Line (QRL) that supplies the magnets. The RF cryo-modules are grouped around the centre of Point 4; two of them are supplied by the distribution lines of Sector 3-4 and the other two by Sector 4-5. These lines are high pressure systems, the supply line operates at up to 3 bar, but both it and the return can rise to very high pressures (<20 bar), in the event of multiple cavity quenches. The cavities and their helium tanks are low pressure devices (2 bar maximum) and must be fully protected under all abnormal conditions. This is provided by the process control, but there are also automatic pressure operated shut off valves and, in addition, a non-return valve in the return line.

Cooling down of the cavities had to follow the general hardware commissioning schedule which saw only limited operation periods in each of the sectors. Efficient use of RF commissioning time was therefore essential.

Sector 4-5 was the first to be cooled down, a period of roughly 12 weeks was available for RF work, from around the end of 2007, continuing into early 2008.

During this first cool-down, special attention was paid to setting up of the cryogenic system, in close collaboration with the cryogenics team. Once the cavities were full and stabilized at 4.5 K, measurements were done on the cavities using a low power generator. These included verification of the cavity tuning limits and the range of Q_{ext} provided by the variable couplers.

Cavity Conditioning and Powering

With the waveguides connected, RF power was carefully applied to the cavities and conditioning done with pulsed RF to bring them to a sufficient level to allow calibration of the cavity signals used for monitoring and in the feedback loops. Automated conditioning systems are built into the cavity controllers. These have their own local synthesizer and contain fast vacuum loops, with slower software controlled loops to optimally moderate the conditioning process [2]. This proved very effective, allowing simultaneous conditioning of several cavities, under remote supervision. The control application is shown in Figure 6. RF Pulse length, modulating envelope parameters and vacuum threshold and sensitivity can be set. Histories of vacuum, cavity voltage and applied RF power are displayed.

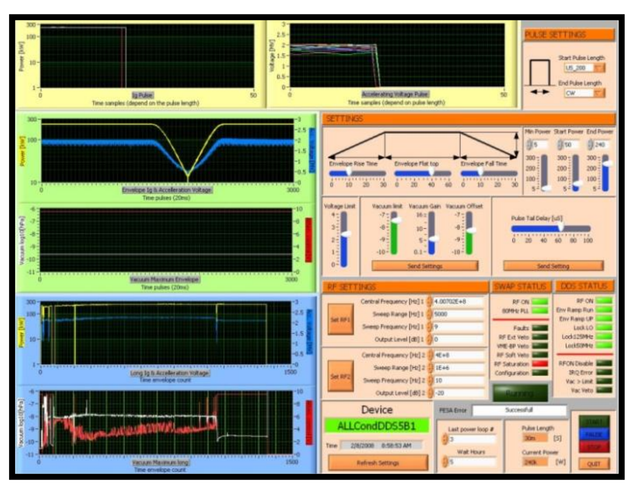


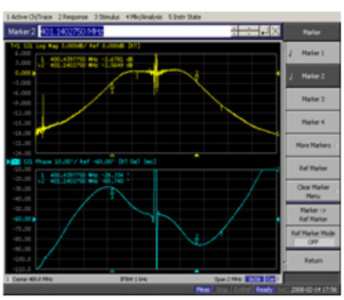
Figure 6: Operator's View of Cavity Conditioning

Conditioning itself proved to be straight-forward, the time needed was not significantly increased by transport and installation of the cavities and over one to two years without having seen RF. In spite of the inevitable interruptions due to various faults and tunnel accesses, all cavities were successfully brought to nominal RF gradient of 5.5 MV/m, or 2 MV per cavity, the values needed for LHC operation. Maximum forward power was also taken to 250 kW cw, with the variable couplers at full coupling. Radiation levels in the tunnel were low at these power and field levels, as were the levels induced in the neighbouring UX45 cavern. Further conditioning to 8 MV/m, which would allow a 50 % reserve in available RF voltage, is envisaged at a later stage.

CAVITY CONTROLLER AND FEEDBACK SYSTEMS COMMISSIONING

The main cavity controller loops are the tuning loop, the RF feedback on the cavity voltage and also the klystron polar loops - the phase and amplitude loops operating around the klystron to minimize the effects of power converter ripple on the RF. The RF feedback and klystron polar loops are absolutely essential for good beam lifetime. in LHC. While operation of all these systems has been tested in the SM18 test stand, full operation of all together was only attempted for the first time during commissioning.

RF Feedback



200 kHz/div.

Upper: Amplitude 3 dB/div.

Lower: Phase 10 deg/div.

Figure 7: Cavity Response with RF Feedback,

The feedback systems were fully set up on three cavities. The loop delays were as expected, around 600 to 650 ns. Figure 7, the loop response with the RF feedback loop closed, shows a bandwidth of 700 kHz, and Q of 600. RF feedback reduced the impedance at the centre frequency from 2.7 MΩ to 27 kΩ.

Very importantly, strong reduction was observed with RF feedback on in the 50 Hz. harmonics in the power spectral density of the klystron output, e.g. 47 dB reduction of the 600 Hz component.

Klystron Polar Loops

These gave the same dramatic reduction in the 50 Hz ripple harmonics in the klystron output obtained in SM18.

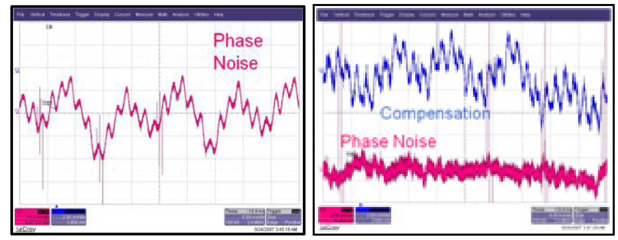


Figure 8: Klystron Phase Ripple (10mV/deg): Left Polar loop off, scale 10mV/div. Right: Loop on, scale 2mV/div.

A level of 3.5 deg p.p. was reduced to 0.2 deg p.p., i.e. a factor of almost 20. With RF feedback and Polar loop together the total reduction observed was around 60 dB.

CONCLUSIONS

A major part of hardware commissioning for the LHC RF system has been successfully completed. Power systems have been fully tested for all 16 cavities, as have controls systems and software. The eight cavities cooled by the Sector 4-5 cryo-plant have been conditioned to nominal RF voltage and near full power. Cryogenics for the RF was tested and safety systems validated. Availability was satisfactory and pressure stability good.

The tuner, RF feedback and klystron loops have been fully tested on three cavities.

Cooling down of the two modules on the Sector 3-4 side has now started; conditioning and commissioning of the rest of the system will follow, then remaining work will be completed on the Sector 4-5 side. Overall completion of commissioning is expected in August 2008.

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