The CERN Linac4 LLRF

LLRF 2013 / Lake Tahoe USA

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Abstract

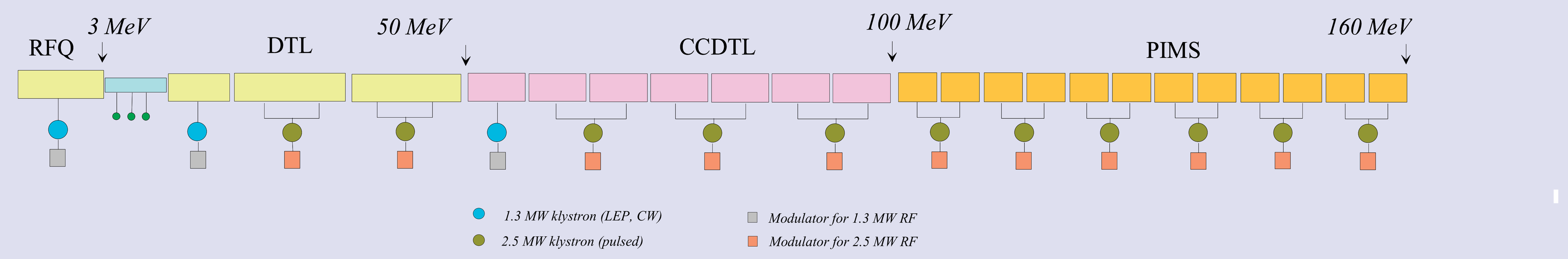
Linac4 is a new 76-m long normal-conducting linear accelerator that will provide 160 MeV H- to the CERN PS Booster, and replace the present 50 MeV proton Linac2. The commissioning in the tunnel of the RFQ starts in October 2013. The rest of the machine will be progressively commissioned between end of 2013 and 2015. The LLRF system has to control one RFQ, two choppers, three bunching cavities, twenty-two accelerating cavities and one debuncher in the transfer line to the booster. Tolerances in field control are one per cent in voltage amplitude and one degree in phase. The machine is PPM, "Pulse to Pulse Modulated" to accommodate multiple users which poses a particular challenge for the LLRF control with parameters and chopping pattern changing from one pulse to the next. To optimize the filling of the 1 MHz PSB bucket, the machine includes fast choppers (synchronized with the PSB RF) and a voltage modulation of the last two PIMS that will provide Longitudinal Painting for optimum filling. The LLRF is composed of one tuner loop per structure, and one field control loop per generator with one 2.8 MW klystron feeding two structures in some cases. Four different VME cards are being developed. For each generator, a single VME module generates all required clocks for up/down mixing and sampling the 352.2 MHz RF signals. The RF is mixed with an LO at f_{LO} = 15/16 f_{RF} = 330.1875 MHz and the resulting IF signal at 22.0125 MHz is sampled at four times this frequency, 88.05 MHz for IQ demodulation. After digital IQ demodulation the entire processing chain runs at 88.05 MSPS (Xilinx Virtex-5 Family). A dedicated high-speed gigabit serial link is used to transmit the essential signals for observation and diagnostic purposes to data storage and analysis hardware at an effective rate of 100 MWord per second (16 bits).

Linac 4 machine

Linac4 is an 160 MeV H– linear accelerator that will replace Linac2 as injector to the PS Booster (PSB). Thanks to the increased injection energy (160 MeV vs. 50 MeV) and the use of H- instead of protons, it is expected to increase the beam brightness out of the PSB by a factor of 2, making possible an upgrade of the LHC injectors for higher intensity and eventually an increase of the LHC luminosity.

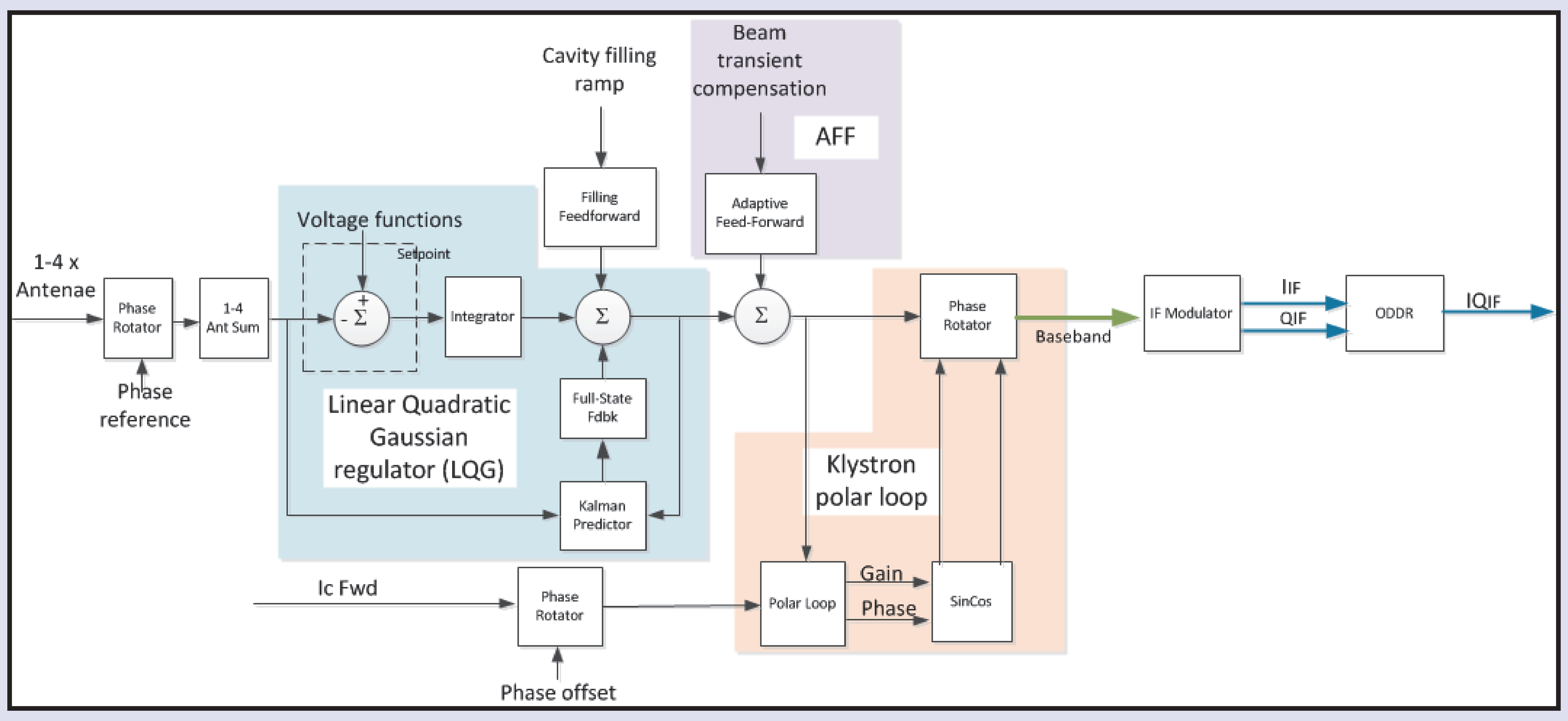
Main machine and beam parameters
Type of particle accelerated: H- ions
Output energy: 160 MeV
Maximum repetition rate: 2Hz
Beam pulse length: 400 µs
Mean pulse current: 40 mA
Overall machine length: 76.33 meters

Chopper @ 3MeV
The RFQ (3 MeV) is followed by a chopper line consisting of two electrostatic deflectors. It removes the head of the beam batch whose intensity is not well-controlled (rise time of the source pulsing). It then chops away the particles that would fall outside the 1 MHz bucket of the PSB (~65% duty factor). Chopper rise/fall times are < 2ns



PSB injection «painting» method
The H- beam will be injected by charge exchange injection allowing injecting several times into the same volumes of phase space. Thus, a large number of turns can be injected with high efficiencies and "painting" in order to shape the initial particle distribution for optimum performance becomes possible. In particular, a chopper makes longitudinal painting possible in addition to painting in transverse phase spaces. The slow synchrotron motion in the PS Booster (1.3kHz synchrotron frequency) implies an active longitudinal painting scheme, where the Linac4 output energy is modulated by modulating the accelerating field in the last two cavities. See C. Carli, R. Garoby, *Active Longitudinal Painting for the H- Charge Exchange Injection of the Linac4 Beam into the PS Booster*, CERN, AB-Note-2008-011 ABP.

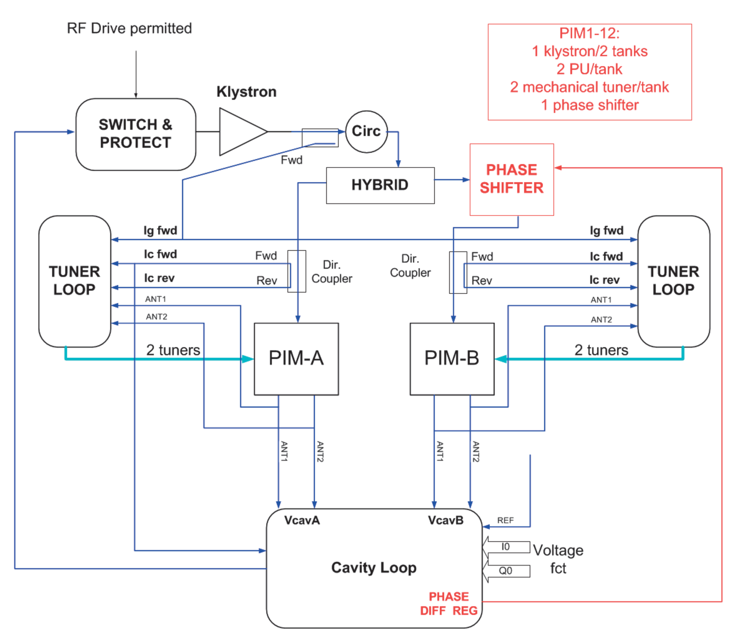
RF feedback & feedforward



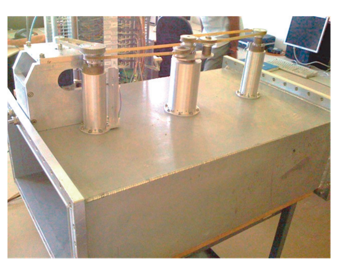
Kalman predictor
The overall loop delay is ~ 1.2 microsec. The Kalman predictor, clocked at 44.025 MHz, includes an (I,Q) model of the cavity (loaded Q and detuning) and a 53x2 taps delay line. The state vector has dimension (55x2). Using the cavity voltage measurement it updates the estimates of the present and past voltage in the cavity (1.2 microsec long history). The computational complexity is reduced by a factor of two for a cavity on-tune as the I and Q components decouple. This is a reasonable assumption for all cavities, except for the three bunching cavities and the single debunching cavity.
Feedback
A full-state feedback is implemented, using the Kalman predictor state vector. In order to track the reference input (desired cavity voltage set point), an integral feedback is added, using the difference between the measured cavity voltage and the set point. The integrator and full-state feedback gains are optimized using Linear Quadratic Regulator theory (LQR).
Adaptive feed-forward (AFF)
To compensate for the beam loading transient at the head of the beam batch (hopefully fairly reproducible from pulse to pulse), an Adaptive Feed-forward correction is added to the klystron drive. It is updated before every pulse, from measurements on past pulses. The computation is done off-line (in the VME CPU).

Single klystron feeding two cavities

Some cavities are powered by a private 1 MW klystron. But the PIMS (PI-mode structures) are paired, with a single 2.8 MW klystron powering two cavities via a power hybrid and two circulators. A power phase shifter is inserted in one branch to compensate for the difference in electrical delay and the possible phase imbalance. The Cavity Loops module receives signals from all antennas (both cavities) and regulates the klystron drive (high-bandwidth regulation correcting for the transient beam loading and klystron noise) and through the power mechanical phase shifter (very slow regulation correcting for temperature effects on waveguides and circulators).

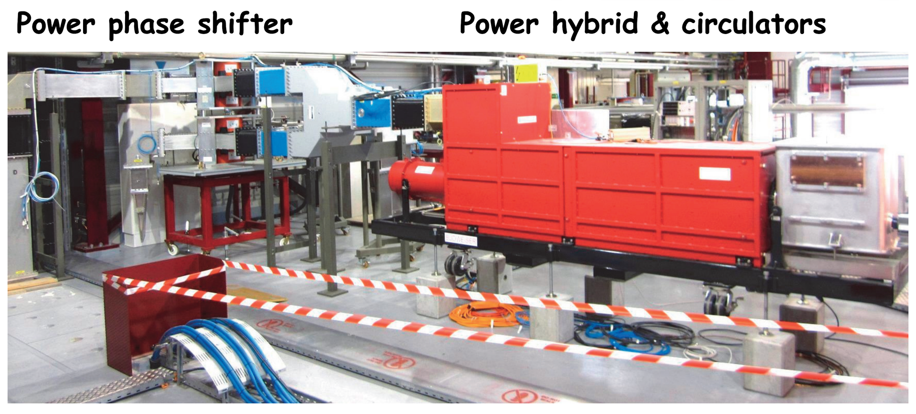


PIM 1-12 control system



Power phase shifter

Power hybrid & circulators

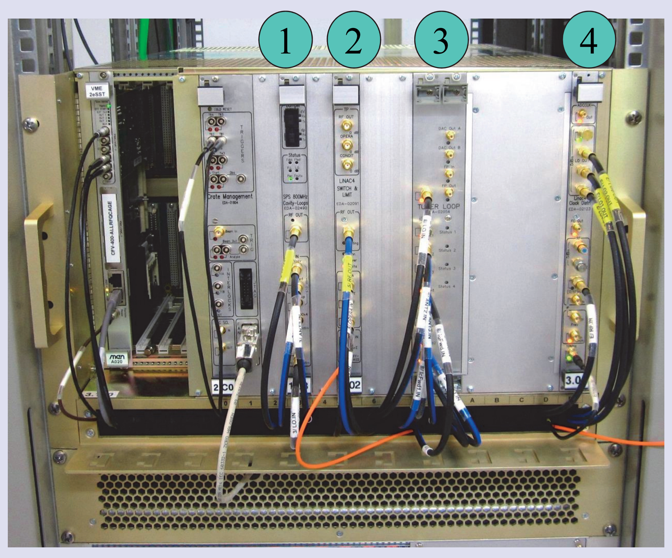


2.5 MW klystron

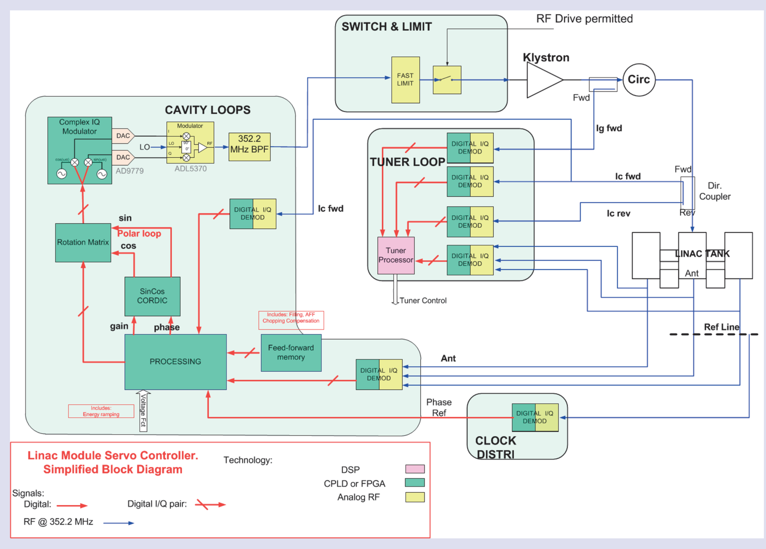
Overview of the Linac 4 LLRF system

The linac4 electronics consists in four VME modules

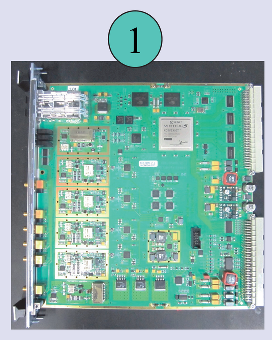
- ❑ The **Cavity Loops** module generates the klystron drive, regulated by three main loops. The Polar loop compensates the variation (droop and noise) of the klystron gain and phase shift caused by High Voltage (HV) supply fluctuations. The feedback and feed-forward loops keep the accelerating voltage at the desired value in the presence of transient beam loading and noise.
- ❑ The **Tuner Loop** module keeps the structure on resonance. It acquires the cavity antenna and the signal from a low-power coupler in the waveguide feeding the cavity main coupler. After extracting the phase difference, it controls the tuning via a PLC and a step motor acting on a plunger inside the cavity (or water circuitry acting on the cavity temperature - RFQ).
- ❑ The **Switch and Limit** module prevents driving the klystron over the saturation limit during loop transients. It also switches off the RF drive in nano-seconds when an interlock signal occurs, generated from other machine equipment (vacuum, HV, RF high power,..).
- ❑ The **Clock Distributor** module generates all necessary clocks for the acquisition and demodulation of the RF signals and for the generation of the RF drive.



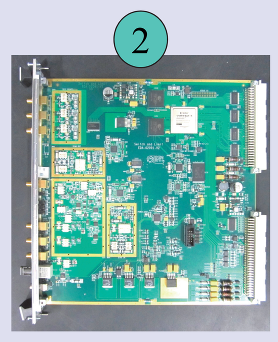
RF custom VME crate module



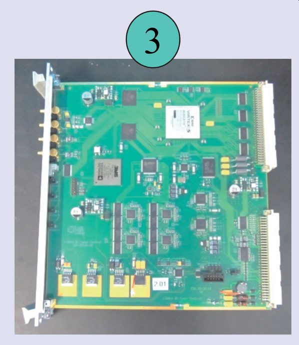
Functional block diagram of the Cavity Controller system



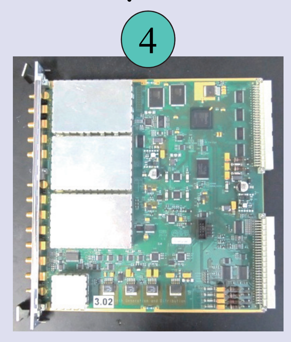
Cavity Loops module



Switch & Limit module



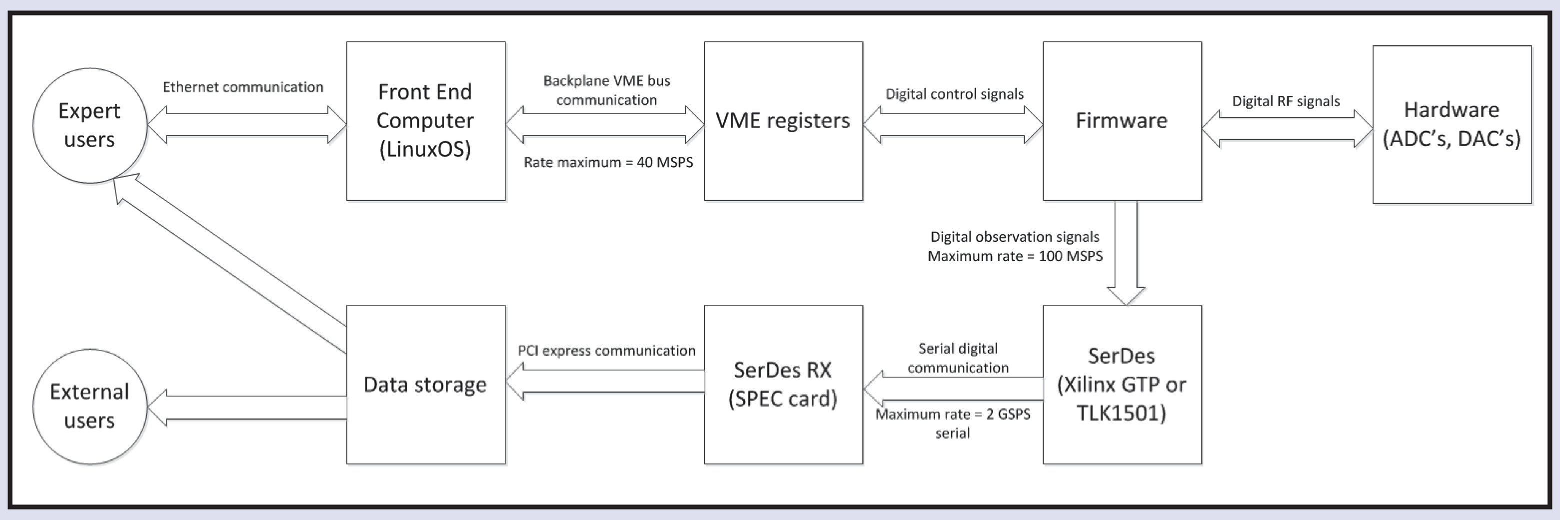
Tuner Loop module



Clock Distributor module

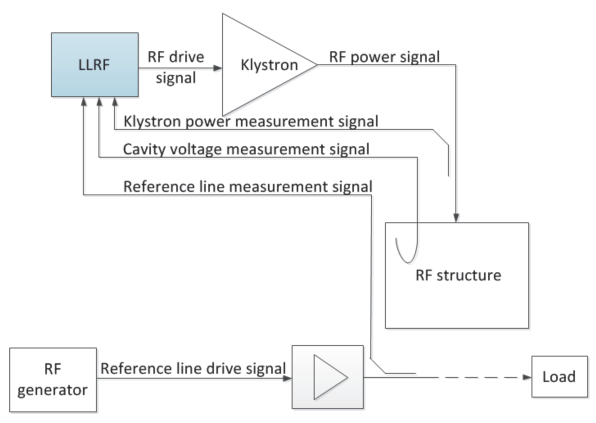
Observation and control data flow

As the embedded memory becomes bigger and bigger on the VME boards (each VME board has 4 M x 16 bits words), while the maximum transfer rate on the VME16 backplane is a modest 40 MSPS, the transfer of observation data to the CPU becomes an issue (it takes 100 ms per board). This would be a problem as we have several boards in a single VME crate. We have therefore added a dedicated channel for digital observation with an higher data rate. The best candidate is a high speed optical serial link that can run at 100 MSPS.

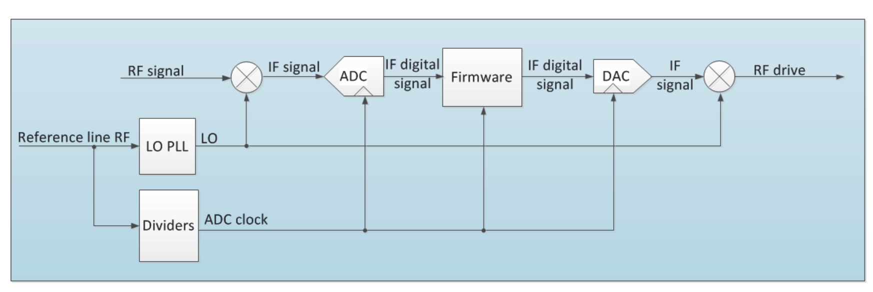


IQ demodulation and modulation

The IQ demodulation is done by mixing the 352.2 MHz signal down to an IF at 22.0125 MHz, followed by a sampling with an 88.05 MHz clock obtained by a division of the RF (RF/4 = 88.05 MHz). The digital IF signal is then de-multiplexed in an (I ,Q) pair. All clocks and LO are phase related as they are derived from the reference line RF signal. Antenna and reference line signals are routed in pairs to the LLRF, with cables coming from the same cable drum. Phase variations due to temperature are thus minimized.



Reference line and RF power generation



Demodulation and modulation principle

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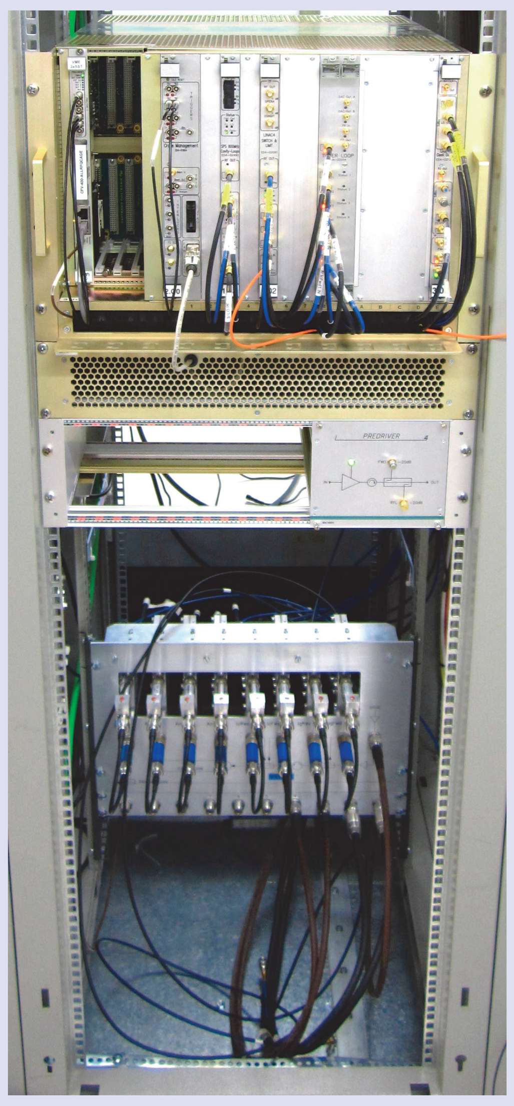
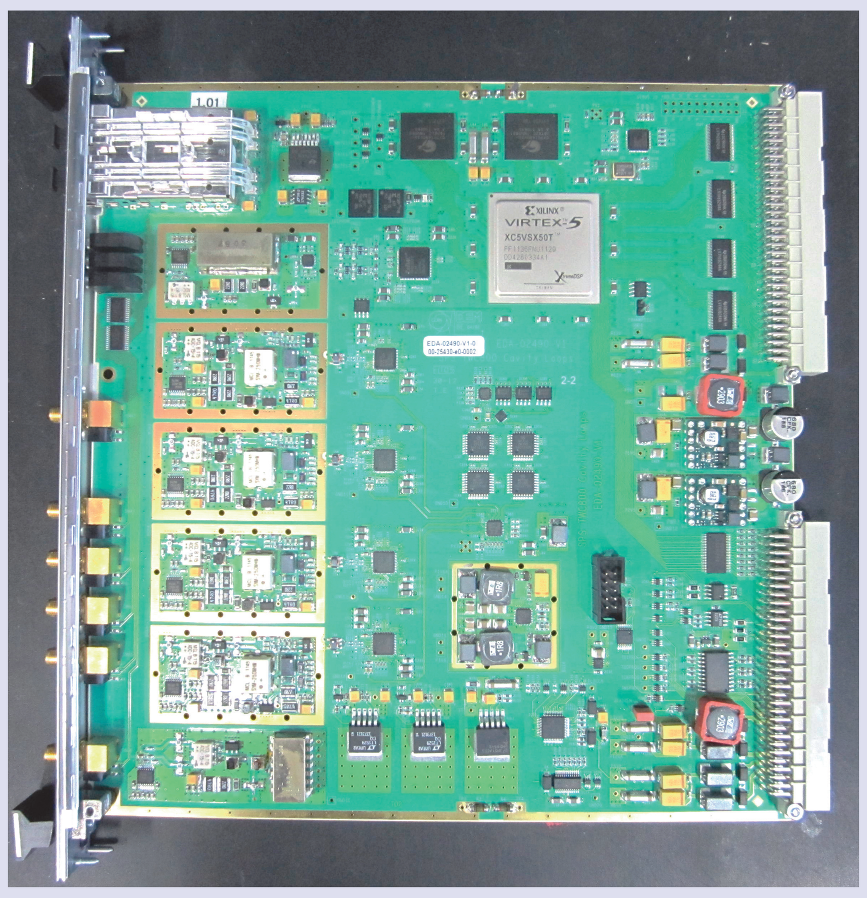
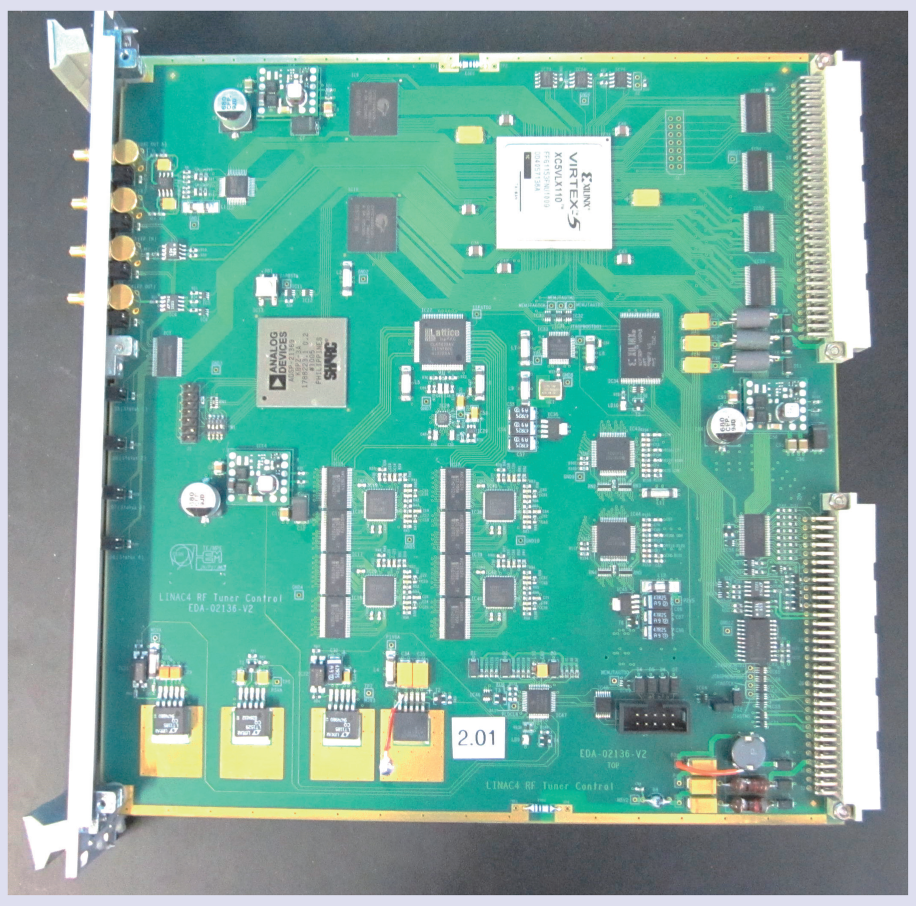
Linac4 low-level electronics



Low-level RF racks and RF signal distribution

- Klystron current forward
- Klystron current reflected
- Circulator current forward
- Four cavity voltage returns





Cavity Loops VME module

- Xilinx Virtex5, XC5VSX50T
- 4 x RF channels inputs
- 4 x Single ADI ADC, 125 MSPS, 14 bit
- 2 fast link optical tranceivers (2 GBps)
- 2 x 72 Mbit SRAM
- 1 x RF output(Quadrature modulator/BW 300-1000 Mhz)

Tuner loop VME module

- Xilinx Virtex-5, XC5VLX110
- ADI SHARC DSP, ADSP-21369, 400 MHz core clock
- 4 x Dual ADI ADC, 125 MSPS, 14 bit
- 8 x RF Front-end channels, ENOB 11.04 bits
- 2 x 72 Mbit SRAM
- 2 x SerDes transceivers, 1.5 GBps

Linac 4 RF Power structure

RFQ structure

Chopper and three bunching cavities

Two RF power circulators