Chapter 1

The LIP e-CRLab

The activities of LIP in the domain of cosmic ray research justified the creation of an electronics laboratory devoted to this field. A proposal to FCT (Fundação para a Ciência e Tecnologia) provided the necessary funds to equip the laboratory. I was deeply involved in this proposal and in the definition of the requirements of the equipment to be installed. The selection and negotiation of the equipment to be bought and the installation of the laboratory were mainly my responsibility.

The Laboratory is named e-CRLab that stands for "Electronics for Cosmic Rays LABoratory. In this section its installation and activities are presented.

1.1 Requirements

Cosmic rays reaching the Earth's atmosphere interact and produce Extensive Air Showers (EAS). EAS produce fluorescence and Cherenkov light that can be detected by UV-Telescopes. The shower front can be sampled at ground by using particle detectors. Most common particle detectors generate light through scintillation or Cherenkov effects which is then collected. Thus many modern cosmic rays experiments rely on the detection of light.

The most commonly used device to detect light produced by the EAS is the PMT. The PMT converts light into photo-electrons that are multiplied to produce an analog output signal. This output signal is usually amplified, filtered and then digitised. From this point onward all the electronics chain is digital. This electronic chain includes memory for the acquired signal and trigger algorithms to reject the noise and background. At some point the electronics must communicate with a computer where data is stored for off-line analysis.

Digital electronics plays thus an important role in data acquisition systems.

Recent technological developments allow the implementation of all-digital logic in a single electronic chip. The FPGA (Field Programmable Gate Array) contains a high number of programmable logic components and programmable interconnections between the logic components. Such devices allow the implementation of complex logic operations using a Hardware Description Language such as Verilog or VHDL. The firmware of such chips can be downloaded to the FPGA using a computer or it can reside in a memory that programmes the FPGA when a reset occurs. The FPGA can even be reprogrammed remotely at run time. Such versatility makes these devices ideal for the implementation of trigger, memory and other digital modules of Data AcQuisition (DAQ) systems.

A digital electronics laboratory is thus justified by the importance that digital logic has been acquiring in DAQ systems. Such laboratories must provide facilities to all development of firmware and to test it in hardware for the correct operation and timings of the devices. A digital electronics laboratory must also make it possible to develop the tools necessary for the testing of the correct operation of digital systems.

The e-CRLab was planned and designed so that the Cosmic Ray groups of LIP could acquire competence in the digital electronics domain. The laboratory was also thought to provide the necessary conditions for teaching and training activities.

Research

The e-CRLab gives support to the LIP group that develops its activities in cosmic rays experiments, namely in the Pierre Auger Observatory (PAO) and in the Gamma Air Watch (GAW) project. The activities in this domain are now centred in the development of firmware for the different components of the DAQ systems and the test, in hardware, of the firmware developed. However, in specific cases, it is also necessary to develop PCB boards for, e.g., the interface of testing equipment with the DAQ boards.

The DAQ systems being developed use fast digital devices with operating frequencies of the order of hundreds of MHz. Technological advances are pushing the operational frequencies of devices even higher. It should be foreseen that, in the near future, DAQ systems will be designed to work at GHz frequencies . Thus the laboratory must be able to cope with the frequencies used nowadays but should, where and when possible, be designed for GHz operating frequencies.

High-density PCB boards developed for high frequencies require complex production equipment. It also requires competence on the most advanced techniques of PCB production which fall outside the scope of the laboratory. However the design of such boards must be within the competence of the laboratory. Thus a requirement was the availability of a CAD software able to deal with the design of high frequency PCB boards and with the simulation of the circuits. The fabrication of complex boards will be outsourced but, when viable, the assembly will be performed in the laboratory. Thus, it is imperative to have equipment for manually assembling and repairing such boards. The complexity of these boards make it obligatory that the equipment is adequate for assembling components with a high density of pins and small pitch.

In complex digital systems the firmware needs to be optimised and tested through simulation. These features must be present in the development software. The development software was required to be able to deal with high-density FPGA devices and allow for incremental compilation so that design blocks can be created and optimised independently while preserving the blocks already implemented. In complex designs it is also convenient to be able to use off-the-shelf IP cores. Moreover the software should have a timing analyser for the assurance of the different timings through the device. It is also desirable to be able to have an embedded logic analyser and support for integration with external logic analysers.

The test and measurement activities performed in the e-CRLab require equipment both for functional tests and for performance evaluation that is able to work in the hundreds of MHz (preferably in the GHz range). The main items considered were: a logic analyser to deal with many digital channels; a highly performant oscilloscope to characterise the analog signals acquired by ADCs; a signal generator for testing the functionality of the systems; a spectrum analyser for the study of the components of signals and their behaviour on the various part of the electronics systems.

Digital development kits were also required as a test-bench for the development of firmware. Being used to interface some of the DAQ boards, these kits should be highly performant. Preferably these kits should be able to deal with operating frequencies in the range defined previously

Education

The laboratory was planned to give support both to cosmic ray outreach projects and to specific laboratory courses for students of the second cycle of higher education, as defined in the Bologna process. Presently the Cosmic Ray Telescope (TRC) project, an outreach project, and the cosmic ray laboratory, a course of IST, are supported by the e-CRLab. In the second semester of 2008/2009 and in the context of the Master degree in Physics Engineering from IST, a course in digital electronics named "Projecto e Controlo em Electrónica Digital" will be held at the e-CRLab.

Activities for first cycle students were also foreseen within the research integration of university-level students program supported by FCT. Such activities give the students the opportunity to perform small projects, embedded in a research environment and having an early contact with electronics and FPGA devices. The electronics projects are usually developed in three phases: design; prototyping and testing. Some activities are centred in the development of firmware modules.

The design process of such projects implies no special requirements since optimisation and simulation is not required at this level.

The prototyping to test the adopted solutions can be achieved using bread-boards in an early stage. However the laboratory was designed to have the capability of producing PCB for the prototypes and final versions of the projects. The availability of a CAD software and production machinery was then set as a requirement.

The laboratory needed also to assure the necessary conditions for testing and validating of the prototypes produced. In the education environment emphasis is given to the functionality of the systems developed rather than to the precision and accuracy. The technical requirements for the test and measurement equipment used in education environment were less stringent and a good value for money had to be found.

The existence of a test bench for the development of firmware was also set as a requirement so that such work could be decoupled from hardware development. Such a test bench should be composed by commercially available generic development boards. These boards must have a FPGA implemented and control and display devices to allow the quick development of firmware and functional testing. It was also considered the need for the associated software.

1.2 Installation

1.2.1 Premises

The e-CRLab was physically installed in a space located in the basement of the building where LIP-Lisbon is located. The space is composed by two rooms: one with 18 m^2 and the other with 15 m^2. There is also a small storage room with 2 m^2. The adaptation of the space required small civil work. The works were mainly concentrated in painting and electrical and network installation. Special care was taken with the power installation, namely with the grounding and insulation of

(a) (b)

Figure 1.1: Photographs of the e-CRLab.

the different workstations. A separate electrical ground was installed to reduce the electrical noise present in the electrical network of the laboratory. Groups of power sockets were created, one for each workstation, protected and isolated from each other in the main switch board. The laboratory was installed with workbenches and shelves.

The first space is dedicated to education activities, figure 1.2(a), where up to three groups of two students can be installed. In this space it is also installed the PCB production equipment taking advantage of the existing water and sewer installation. The second room is dedicated to research activities, figure 1.2(b). In this room four workstations are available.

1.2.2 Equipment

One of the key points of the installation of the e-CRLab was the selection of the equipment to be bought. The laboratory was installed from scratch and a whole set of equipment had to be acquired. For more expensive equipment, a preliminary market research was made followed by a budget submitted with the project proposal. Afterwards the items were negotiated directly with the manufacturers. A compromise between the performance and price of the equipment had to be found. A total budget of 80 000 Euro was available. The equipment installed in the laboratory can be grouped as generic, mid-range equipment and state of the art equipment.

The set of generic equipment is composed by mechanical tools, power supplies, a digital workstation for bread board prototyping, a memory programmer, multimeters, a signal generator and 100 MHz digital oscilloscopes. A system for PCB production was installed and is composed by an UV exposure unit, heated processing tanks and a spray etching station (Rota-Station from Mega electronics). The suite Altium Designer was chosen as the PCB design software allowing to design the schematic diagram, route the board, simulate and export to standard format for fabrication. This suite has also the capability for the development of FPGA firmware which is not currently being exploited.

Several digital development kits based on Altera FPGAs were bought. The DE2 (Development and Education Board) from Terasic is a good development platform with a huge set of devices attached to the FPGA. This board will be the standard workbench for education activities. Thus several of these kits were acquired. More performant and specific development boards were bought: Digital Signal Processing (DSP) development kit, Nios Development kit and the PCI development kit. Most of the kits provide already the software from Altera for programming FPGA - QUARTUS II - as well as libraries with IP cores.

The highest performance equipment is exclusively dedicated to research activities and is composed of a 300 MHz bandwidth oscilloscope, an arbitrary function generator with a maximum frequency output of 240 MHz, a spectrum analyser for frequencies up to 3GHz with tracking generator, a 64 channel logic analyser capable of acquiring state data at 235 MHz and has a timing resolution of 125 ps. An oscilloscope with 1GHz bandwidth and a sample rate of 5 GS/s.

A probing system for compact PCB boards is also available in the laboratory. The system is composed of a 32× stereo microscope and four probe heads. The probe heads are fixed to any surface using vacuum and are suitable for probing pads with dimensions down to hundreds of micrometre.

1.3 Research

The research activities are centred on the development and test of firmware for FPGAs. A new version of LIP-PAD is being developed, LPV3. The firmware of GAW data acquisition boards is also being developed and tested in the laboratory

1.3.1 LPV3

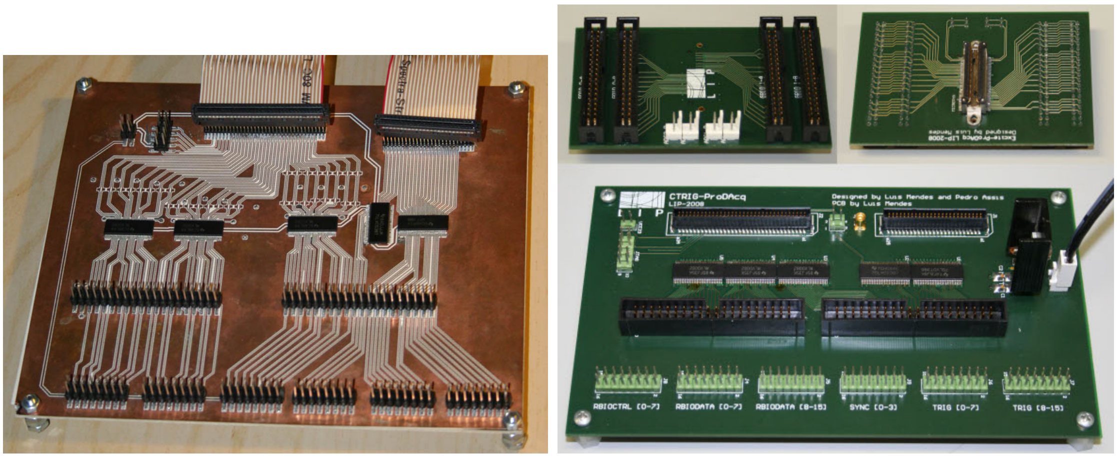
The LPV3 is a multipurpose DAQ board with the capability of acquiring six analog signals and perform time synchronisation with an accuracy better than 10 ns. The LIP-PAD and the LPV3 are described in detail in chapter ??. The LPV3 is currently in the development phase. This new board is thought as a completely independent acquisition system capable of acquiring data by itself and send it via network. Many new features had then to be introduced in the board design. An upgrade of the DAQ part of the board is being carried out to increase its performance. A preliminary design of the LPV3 board was done at the e-CRLab. The work in the e-CRLab was centred in the schematic design of the board and the test of the solutions for the different functionalities introduced. The solutions adopted were tested in simulation and also some components of the system were tested in the development kits available. It is a responsibility of the laboratory to implement the LPV3 firmware and to test the prototype board both for its functionality and performance. The performance test of the DAQ and synchronisation parts of the board assumes critical importance as the operation frequencies of such modules should reach 200 MHz.

1.3.2 GAW boards

Currently one of the activities at the e-CRLab is the development of firmware for the GAW experiment. Namely, the firmware for the digital acquisition board is being developed and tested. This board, named ProDAcq and the electronics of GAW are described in detail in section ??. For the interface of ProDAcq with the testing equipment it was necessary to develop a small interface board (LIP-CTRIG) for reading and control of the board. It was also necessary to develop an excitation source and interface (ProDAcq-Excite) for testing the response of the board and firmware to all the possible configurations of the digital data entering the ProDAcq. A first prototype of CTRIG was designed and produced in the laboratory for functionality tests. However the final version of the interface boards were designed at LIP, taking into account the constraints imposed by the high frequencies involved, and produced elsewhere for increased performance. In figure 1.2 a photograph of the prototype (left) and of the final versions (right) are shown.

The LIP group has also taken the responsibility to design and test the firmware for GAW triggering boards. The e-CRLab is prepared to start the test on the boards as soon as they became available.

The laboratory will have a complete acquisition set, provided by IASF-Palermo, composed by a PMT, a FEBrick, a ProDAcq and a trigger generation board. This system will serve as a test bench for a complete test of the acquisition system of GAW. An optical system to stimulate the PMT pixels and test the response of the electronics to different configurations of noise and signal is being studied.



(a) (b)

Figure 1.2: Photographs of the prototype of LIP-CTRIG (left) and final version of LIP-CTRIG and ProDAcq-Excite (right).

1.4 Education

1.4.1 Training programs in Digital Logic

Training programs on advanced digital electronics are being organised in the e-CRLab for first cycle students within the FCT program to integrate students in research activities. These activities allow the students to have contact with digital electronics and FPGAs in the first years of their higher formation. Most programs consist on the development of a small project that incorporates the use of an FPGA.

One of the projects that already started with a third year student consists on the development of a display of fluorescence events recorded by the Pierre Auger Fluorescence Detectors. The display consists on a grid of 440 LEDs, emulating the FD camera pixels. Each LED will be lit with an intensity proportional to the signal recorded by the corresponding pixel. The display will be able to show the development of the event in the camera in a time scale perceptible to the human eye. The LED matrix will be controlled using an FPGA development kit. Raw data from selected FD events will be pre-processed to produce film strips. Each frame will contain the signal intensity of each pixel in the matrix. This data will then be loaded in a memory. The FPGA will be programmed to read data from memory and light up the corresponding LEDs. The system should also have a mode in which is shown the integrated pixel signal for an event. One of the open questions still remaining is the emulation of the full geometry of the camera (hexagonal pixel, mercedes, support, etc.) due to its complex geometry.

Another project planned is to develop a PC-based digital oscilloscope using an FPGA and an ADC. For this project the DE2 development kit will be coupled to a data sampling module that will consist on a signal conditioning stage followed by an ADC. The FPGA will then have to be programmed to execute the basic functions of an oscilloscope (acquire ADC data and perform trigger) and communicate the acquired data to a PC. This project will also introduce students to the techniques used in data acquisition systems, namely in the LIP-PAD, a PCI acquisition board developed by LIP.

1.4.2 Course in digital electronics

In the second semester of 2008/2009 a course in digital electronics named "Projecto e Controlo em Lógica Digital" will start in the e-CRLab. The course will be given to fourth and fifth year MEFT students from IST that have already a background on digital electronics.

The course will cover mainly digital systems design using FPGA devices. The course will use the Verilog HDL for describing and implementing logic designs. Students will get acquainted with FPGAs and its programming languages. Logic designs will be developed and implemented in FPGAs and its implementation and performance compared to traditional implementations in bred-board. Students will also explore advanced functionalities of FPGAs and the techniques used for validation and performance tests of the solutions implemented. Namely students will learn how to use simulations and internal and external logic analysers to validate their designs.

Abbreviations

ADC Analog to Digital Converter

CAD Computer Aided Design

CAMAC Computer Automated Measurement And Control

CLF Central Laser Facility

CNR Consiglio Nazionale delle Ricerche, Italy

CTRIG Control and TRIGger; an interface board for GAW

DAQ Data Acquisition

DE2 Development and Education Board

DSP Digital Signal Processor

e.g. exempli gratia (for example)

EAS Extensive Air Shower

e-CRLab Electronics for Cosmic Rays Laboratory

FCT Fundação para a Ciência e Tecnologia (Foundation for Science and Technology)

FD Fluorescence Detector

FEBrick Front End Brick

FPGA Field Programmable Gate Array

GAW Gamma Air Watch

GS/s Giga Sample per second

HDL Hardware Description Language

I2C Inter-Integrated Circuit (Serial communications protocol)

IASF Istituto di Astrofisica Spaziale e Fisica Cosmica CNR, Italy

IASF-Palermo IASF-CNR at Palermo, Italy (formerly IFCAI)

IP Intellectual Property

IST Instituto Superior Técnico

LIP Laboratório de Instrumentação e Física Experimental de Partículas, Portugal

LIP-PAD LIP - Placa de Aquisição de Dados (LIP - data acquisition board)

LPV3 LIP-PAD Version 3

MEFT Mestrado em Engenharia Física Tecnológica (Master in Physics Engineering)

NIM Nuclear Instrumentation Module

PAO Pierre Auger Observatory (as ACRO)

PCB Printed Circuit Board

PCI Peripheral Component Interconnect

PMT Photo Multiplier Tube

ProDAcq Programmable Data Acquisition

RS232 Recommended Standard RS-232; A standard for serial binary data signals

SD Surface Detector

TRC Telescópio de Raios Cósmicos (Lisbon Cosmic Ray Telescope)

UV Ultra Violet

VHDL VHSIC Hardware Description Language

Bibliography