FINAL REPORT

Student name: **Stefano Pavinato**

Cycle: **XXX**

Curriculum: **ICT**

Supervisor name: **Matteo Bertocco, Marco Bellato**

Thesis title (final): **Design and development of a digital Radio Frequency control system for linear accelerators**

PART 1 - COURSES, CONFERENCES AND MOBILITY

Courses for Ph.D. students

- Applied linear algebra.
- The FFT and its use in digital signal processing.
- Real-Time Systems and applications.
- Digital Processing of Measurement Information.
- Internet of things (Doctoral Course "Brain, Mind and Computer Science").

Summer schools, short courses, tutorials

- “Seventh I.N.F.N. International School on Architecture, tools and methodologies for developing efficient large scale scientific computing applications”, Bertinoro (FC), 25-31 October 2015.
- “RF Superconductivity for Particle Accelerators”. USPAS school, Lisle (IL), 12-23 June 2017.

Participation to International Conferences and Workshops

- IEEE-NPSS conference in Padova 5-10 June 2016
- LINAC16 conference in East Lansing 25-30 September 2016
- ICALEPCS17 conference in Barcellona 8-13 October 2017

PART 2 - RESEARCH ACTIVITY

The research activity was carried out at Legnaro National Laboratories (LNL) one of the four national labs of the Italian Institute of Nuclear Physics (INFN). At LNL there is a superconducting particle accelerator (ALPI), formed essentialy by 96 Radio Frequency (RF) cavities. They are resonators that store electromagnetic energy to accelerate the beam of particle. In order to ensure an optimum energy gain of the accelerated beam the stabilization of RF electromagnetic field in the cavity is crucial. In particular with respect to its phase, its amplitude and its frequency.

The most important project supported by INFN at Legnaro is SPES (Selective Production of Exotic Species). It is a new radioactive ion beam (RIB) facility which aims to produce radioactive nuclei of interest for nuclear astrophysics and to human health. The RIB is boost through ALPI and sent to the three experimental halls for the physical experiments. So that ALPI be suitable as an RIB accelerator some upgrades have to be done. In this scientific context my research activity is inserted.

The subject of this PhD thesis is indeed the development of a fully digital RF control system; focusing on the validation of the Low Level RF (LLRF) controller, its programming and its integration in the particle accelerator control system. The LLRF controller interacts directly with the cavities and it works in a real-time closed loop. It stabilizes the phase, the amplitude and the frequency of RF field cavity. To guarantee a correct acceleration a phase stability from 0.1° o to 0.5° and a gradient stability from 0.005% to 0.05% rms must be kept.

At the beginning of my Phd the LLRF controller was already designed and the first prototype was just produced. The controller is basically formed by three boards in-house developed. The boards are: the RF Input/Output Control (RF IOC), the RF Front End (RFFE) and the Power Monitor (PM) boards. RF IOC undersamples the signals picked-up from the cavities, implements the control algorithms through an FPGA and then the elaborated signals are reconverted in analogue form by DACs. It represents also the port to interface with the particle accelerator control system. RFFE adapts the power level between cavities and RF IOC and between RF IOC and power amplifiers and hence the cavities. PM is used to measure the forward and the reflected power from the cavities.

The particle accelerator control system is based on EPICS (Experimental Physics and Industrial Control System) framework. It is an open-source software environment used to develop and implement distributed control systems in large experiments as particle accelerators.

The three board previously listed, require configuration before operating. Tha main Integrated Circuit (IC) to program is the FPGA. Its firmware was written in VHDL language. The firmware has been written connecting entities that implement specific functionalities. I have contributed to write some blocks of the firmware. In particular, I dealt with the :

- IPbus : the interface between the accelerator control system and the internal registers of the FPGA;

- the JESD204b interface : the ADC and DAC communicates with the FPGA with the high speed serial link based on JESD204b protocol;
- some blocks of the digital signal processing. Essentially a PI controller is implemented.

All the other ICs requires to be configured. They feature an SPI slave interface or I2C to access their internal registers. Each register consists of one or more fields which control the device functionality. They communicate with the FPGA that represent the SPI or I2C master. They are configured from the control accelerator control system.

Once the boards were configured the hardware qualification stage began. In order to evaluate the performance of the LLRF controller, there were performed a set of measurements focused at determining some critical parameters in the RF IOC and in the RFFE boards. In the RF IOC board the clock jitter, the ADC ENOB and the signal integrity of the high speed serial link between FPGA and converters were assessed. While in the RFFE board the crosstalk between adjacent channels and the distortion introduces by the input channels were evaluated.

The LLRF controller is a sub-system of the particle accelerator control system. Therefore part of the work done, during the research activity, was the development of an EPICS driver support in order to allow the understanding of the cards by the clients. This is the lowest EPICS software layer between the control system and the RF IOC board. In order to control each LLRF controller the users from a remote console set and get some working parameters. These parameters can be divided, based on how and where they access the FPGA internal registers, in two groups:

1. loop control parameters;
2. configuration and reading ICs registers;

The hardware, firmware and software above described were finally used to boost a real beam. The RF control system was in charge to control eight cavities, for a couple of days. The results of the test were excellent. The beam was successfully accelerated. The measurements shown very good agreement of phase and amplitude field stability requirements for a modern linear accelerators.

PART 3 - PUBLICATIONS

List of publications on conference proceedings

C1. "Custom Hardware Platform Based on Intel Edison Module", ICALEPCS 2015, 17-23 October 2015, Melbourne.

C2. "New LLRF control system at LNL", IEEE-NPSS Real Time Conference (RT) 2016, 5-10 June 2016, Padova;

C3. "An I/O controller for real-time distributed tasks in particle accelerators", IEEE-NPSS Real Time Conference (RT) 2016, 5-10 June 2016, Padova;

C4. "Development of a digital LLRF control system at LNL", LINAC16, 25-30 September 2016, East Lansing (IL);

C5. "Upgrade of the LLRF control system at LNL", ICALEPCS17, 8-13 October 2017, Barcellona; [**submitted**]

C6. "New RF Cavity Tuning System at LNL", ICALEPCS17, 8-13 October 2017, Barcellona; [**submitted**]

Padova, 29/09/2017

Student signature

Supervisor signature