Physics Department of Turin
Master's degree course in physics

Development and test of FPGA firmware for the readout of the ABACUS chip for beam monitoring applications in hadron therapy

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Chapter 1

ABSTRACT

Hadron therapy is a particular type of oncological radiotherapy for the treatment of solid tumors that uses proton or ion beams instead of conventional X-rays. The usage of hadron particles allows a better control on the energy release, improving the precision of the treatment and the conservation of healthy tissues around the target. Particle beams are obtained by means of dedicated accelerators, requiring a precise control of particle flux and beam profile. Thus beam-monitoring systems become of primary importance, demanding the usage of fast particle sensors and readout electronics to monitor real-time the particle beam reaching the patient.

In this context the Medical Physics group at University of Torino and INFN (the Italian National Institute for Nuclear and Particle Physics) is participating to the MoVeIT (Modeling and Verification for Ion beam Treatment planning) research project, which aims to develop new and innovative models for biologically optimized Treatment Planning Systems (TPS) using ion beams in hadron therapy. As part of the project the Torino group is involved in the development of solid state detectors and readout electronics for measuring with high precision the characteristics of the hadron beam for irradiation, such as number of particles delivered per unit time, energy and beam profile.

Low-Gain Avalanche Diode (LGAD) thin silicon sensors segmented in strips have been selected as a promising choice for the implementation of the final beam-monitoring system. Thanks to the internal gain mechanism in fact, this sensor technology allows to obtain a large signal-to-noise ratio (SNR) for very low amounts of deposited charge, thus allowing to detect and count single beam particles.
Silicon strips are read out by a full-custom and optimized Application Specific Integrated Circuit (ASIC) designed by Torino INFN. The chip, named ABACUS (Asynchronous-logic-Based Analog Counter for Ultra fast Silicon strips), has been designed using a commercial CMOS 110 nm and integrates 24 readout channels. Each channel includes a low-noise preamplifier and a fast discriminator. The data acquisition system uses commercial Field Programmable Gate Array (FPGA) boards that receive the data from up to six readout chips.

This thesis presents my personal contributions on the upgrade of the FPGA firmware used to characterize the second version of the ABACUS chip and measurement results. The FPGA used to readout the chip is a Kintex-7 KC705 board by Xilinx programmed using the VHDL Hardware Description Language. The FPGA is responsible for both the chip configuration and sensor data readout.

The first part of my work describes the upgraded VHDL firmware, which includes several new features such as: i) the creation of a debugging tool for malfunctioning channels on the board; ii) the complete rewriting of the internal Digital to Analog Converter (DAC) configuration system for the new ABACUS chip, which now uses an address-based system instead of a serial method; iii) the addition of a timestamp in the data packets for a more accurate calculation of the particle rate; iv) the implementation of a latch for internal counters; v) firmware modifications that allow the usage of LVDS (Low-Voltage Differential Signaling) signals instead of CML (Current Mode Logic) ones.

The second part of the thesis presents experimental results for the characterization of the second version of the ABACUS chip. Measurements include DAC-linearity studies and threshold scans to quantify the threshold dispersion between channels

Chapter 2

Hadron Therapy

2.1 Introduction

The National Cancer Institute define a tumor[1] as "an abnormal mass of tissue that results when cells divide more than they should or do not die when they should." In a healthy body, cells grow, divide, and replace each other in the body. As new cells form, the old ones die. When a person has cancer, new cells form when the body does not need them. If there are too many new cells, a group of cells, or tumor, can develop. A tumor develops when cells reproduce too quickly. Tumors can vary in size from a tiny nodule to a large mass, depending on the type, and they can appear almost anywhere on the body. There are three main types of tumor:

- **Benign**: These are not cancerous. They either cannot spread or grow, or they do so very slowly. If a doctor removes them, they do not generally return.
- **Premalignant**: In these tumors, the cells are not yet cancerous, but they have the potential to become malignant.
- **Malignant**: Malignant tumors are cancerous. The cells can grow and spread to other parts of the body.

Radiation therapy is the medical use of ionizing radiation to treat cancer. In conventional radiation therapy, beams of X rays (high energy photons) are produced by accelerated electrons and then delivered to the patient to destroy tumour cells. Using crossing beams from many angles, radiation oncologists irradiate the tumour target while trying to spare the surrounding normal tissues. Inevitably some radiation dose is always deposited in the healthy tissues. When the irradiating beams are made of charged particles (protons and other ions, such as carbon), radiation therapy is called hadrontherapy[2]. The strength of hadrontherapy lies in the unique physical and radiobiological properties of these particles; they can penetrate the tissues with little diffusion and deposit the maximum energy just before stopping. This allows a precise definition of the specific region to be irradiated. The peaked shape of the hadron energy deposition is called Bragg peak and has become the symbol of hadrontherapy. With the use of hadrons the tumour can be irradiated while the damage to healthy tissues is less than with X-rays.

2.2 Interaction between matter and charged particles

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta 2\frac{C}{Z}\right] \tag{2.1}$$

2.3 Effects of radiations on biological systems

2.4 Dose distribution systems in hadron therapy

2.4.1 Passive dose distribution systems

2.4.2 Active dose distribution systems

2.4.3 Treatment Planning System

2.5 Beam monitoring

2.5.1 Silicon detectors

Bibliography

[1] www.medicalnewstoday.com/articles/249141

[2] enlight.web.cern.ch/what-is-hadron-therapy