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

Academic year 2020/2021

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July 19, 2021

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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

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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 hadron therapy[2]. The strength of hadron therapy 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 hadron therapy. 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

Charged particles with mass greater than the one of the electron lose energy in matter through ionization. A classic calculation for the energy lost in ionization can be done taking

into account two assumptions:

- the speed of the atomic electron is negligible compared to the one of the incident particle;
- the mass of the incident particle is big in relation to the target mass. This means that the incident particle for each single hit receives a small amount of momentum and thus the direction of flight does not changes.

This hypothesis is valid keeping into consideration that the mass of the electron is 0.51 MeV, a muon has mass 105.6 MeV, for a proton it is 938.2 MeV and for a carbon ion ^{12}C it is 11177.9 MeV.
The classic calculation results in the Bethe-Block formula in equation 2.1 that describes the average energy loss in the target for unit of length, also called stopping power.

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

In equation 2.1:

- N_a: is the Avogadro number;
- r_e: is the classical radius of the electron;
- m_e: is the mass of the electron;
- ρ: target density;
- Z: target atomic number;
- A: target atomic mass;
- W: target average ionization energy;
- z: incident particle charge;
- W_{max}: maximum energy transferred in a collision;
- δ: polarization parameter in target
- c/z: core electrons shielding parameter
- $\beta = v/c$

The stopping power depends by the target mass, atomic number, density and average ionization energy (A, Z, ρ, W). To overcome and eliminate this dependence it was defined the massic stopping power in equation 2.2 that is measured in MeV/(g cm^2)

$$\delta = -\frac{1}{\rho}\frac{dE}{dx} \tag{2.2}$$

In figure it can be seen the trend of the massic stopping power of a μ^+ passing through a copper layer.

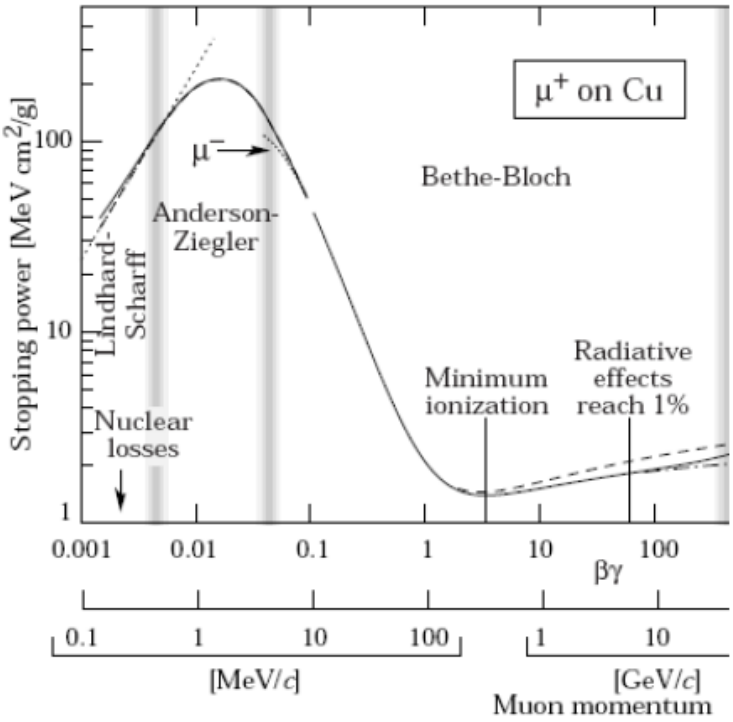

Figure 2.1: Massic Stopping power in function of the μ^+ momentum passing through a copper layer

In the trend of the stopping power in function of the momentum can be noted a de-growth for low momentum values that is due to the term $\frac{1}{\beta^2}$ in equation 2.1; the stopping power decreases until it reaches a minimum, and then slowly grows back.
The average path (range) of a charged particle can be calculated by integrating the stopping power along the "walk".

$$R = \int_{E_i}^{0} \frac{1}{\frac{dE}{dx}} dx \tag{2.3}$$

The range depends approximately on the A / Z ratio of the material and grows approximately with the square of the initial kinetic energy of the charged particle. The accrual of energy loss increases as the kinetic energy of the particle decreases with the depth of penetration, with a rapid ascent at the end of the path. The density of ionization of the charged particles along their path in the medium is therefore characterized by a plateau followed by a pronounced maximum towards the end of range, called Bragg peak, which is located at an energy-dependent depth initial kinetics of the incident particle, as shown in **Figure 1.2** If more particles are considered then it should be kept in mind the statistical fluctuations on the collisions of the particles and on the energy transferred for each collision: these fluctuations are well described by the Landau distribution **[2]**, generate uncertainty about the distance reached by the particles ("straggling"). Beyond all these considerations we must not neglect the possible interactions with the nuclear components of the matter crossed. One effect is enlargement lateral of the beam due to the interaction with the Coulomb fields of the nuclei that it is inversely proportional to the mass of the incident particle. The second effect it is due to the fragmentation of the primary bundle and/or of the nuclei of the material passed through due to nuclear interactions. The fragmentation cross section becomes relevant for ions heavier than the proton, such as carbon ions or heavier, and causes a decrease in the

number of particles incident along the path and the development of secondary fragments. The fragments produced deposit theirs energy deeper than the Bragg peak giving rise to a queue in the distribution.

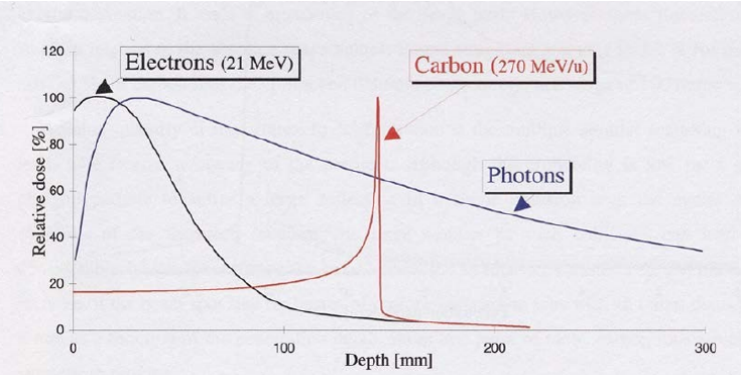

Figure 2.2: Dose profile for a 21MeV electron, 270MeV/u carbon ion and photon beam

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