FOOT (FragmentatiOn Of Target)

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1 Introduction

Hadrontherapy is a form of external radiotherapy that uses beams of protons (protontherapy) or heavier particles (ion therapy, mainly 12C) to treat tumors $^{1)}$. The typical energy range for therapeutic applications is 50–250 MeV for protons and 50–400 MeV/u for carbon ions. With respect to conventional radiotherapy with photons or electrons, the effectiveness of hadrontherapy is potentially improved by a better dose localization. However, nuclear interactions between the particle beams and the nuclei of the human body create ion fragmentation products $^{2)}$, $^{3)}$ ranging from protons to oxygen ions, with variable relative biological effectiveness (RBE) compared to conventional photon beams. A better understanding of the phenomena taking place during proton and hadrontherapy could improve the dose estimation in the treatment planning phase. In particular, target fragmentation in protontherapy causes the production of low energy, short-range fragments along the beam path in the patient $^{4)}$ which could explain the difference between the measured proton RBE and its predicted value. Projectile fragmentation of carbon ions produces long-range forward-emitted secondary ions that release dose in the healthy tissue beyond the tumor target. Some experiments have recently been dedicated to studying projectile fragmentation for 12C ions, such as the FIRST (Fragmentation of Ions Relevant for Space and Therapy) experiment $^{5)}$. However, only a few energies have been investigated $^{6)}$, $^{7)}$.

2 The FOOT experiment

The FOOT (FragmentatiOn Of Target) experiment was recently proposed to study the fragmentation processes that occur in the human body during hadrontherapy $^{8)}$, $^{9)}$, $^{10)}$. In the target fragmentation induced by proton beams, the fragments have ranges of the order of tens of μm $^{4)}$ and have a low probability of leaving the target and being detected. To overcome this difficulty, the FOOT experiment uses an inverse kinematic approach. Rather than accelerating therapeutic proton beams onto biological targets, FOOT studies the fragmentation of accelerated beams of ions composing the human body (e.g., carbon and oxygen) onto an hydrogen-enriched target. In the inverse reference frame, fragments have a boost in energy and thicker targets can be used. The incident beam flux will be set so as the projectile rate will be low enough (few kHz) to have only one particle at a time crossing the system. The FOOT apparatus is schematically shown in Fig. 1. The beam enters the left of the system and crosses the start counter, a plastic scintillator read by silicon photomultipliers (SiPMs) that provides the trigger information and the first timestamp of the time-of-flight (TOF) measurement. The beam profile is then reconstructed by means of the beam monitoring drift chamber that measures the direction and impact position of the ion beam on the target, necessary for an inverse kinematic approach. The vertex, trajectory and momentum of the fragments are measured after the target by a tracking system composed of a series

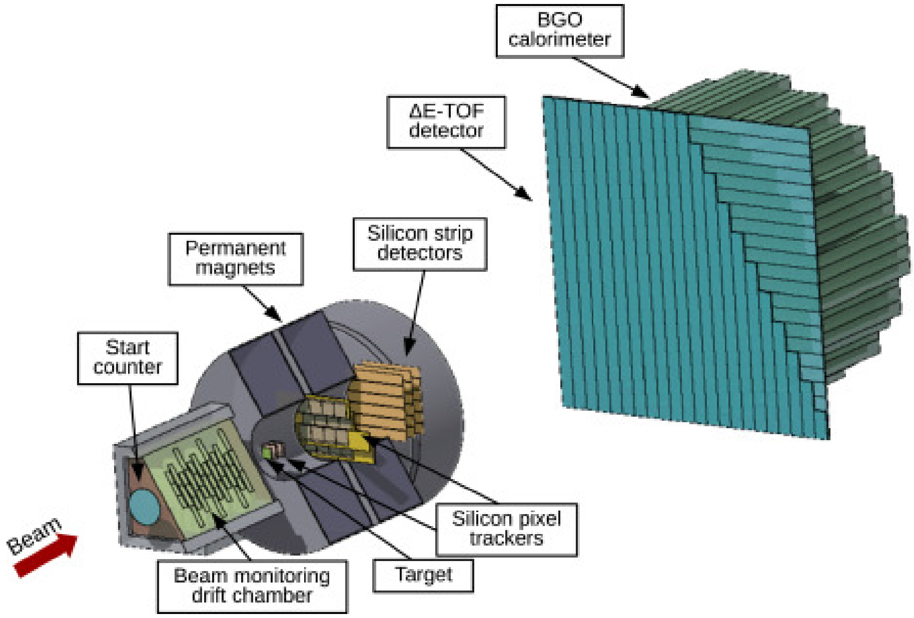

Figure 1: *Scheme of the final FOOT apparatus, obtained with FLAIR* [11]*, the FLUKA* [12], [13] *graphical interface.*

of silicon detectors around and inside a dedicated magnetic spectrometer. The tracking system allows matching the reconstructed tracks with the hits in the last two elements in the detection chain, a E-TOF detector and a calorimeter. The E-TOF detector measures the E, i.e., the energy deposited in a plastic scintillator, and the second timestamp of the TOF, i.e., the arrival time of the particle. The BGO calorimeter measures the kinetic energy of the fragments. The FOOT detector is optimized for the measurement of the heavier fragments mainly produced in the angular range of 10 degrees with respect to the beam direction. For the detection of the lighter fragments, the experimental setup changes completely, substituting all the apparatus after the drift chamber with an emulsion spectrometer divided in three sections, which measure the charge, energy and mass of the fragments, respectively.

3 Activity of the FOOT LNF group

The FOOT LNF group activity is focalized on the silicon pixel tracker. This part encompass the first two stations of the tracking system (Fig. 1): the Vertex detector and the Inner Tracker, both implemented with a monolithic pixel detector, the M28 Ultimate sensor designed and built by the IPHC In2p3 Pixel group in Strasbourg [14]. All sensors used, to minimize the refragmentation probability, are thinned at $50\mu m$ thickness. Ultimate is the final sensor chip designed for the upgrade of STAR inner layer of the vertex detector. Its architecture integrates main functions of Mimosa28, a Monolithic Active Pixel Sensor (MAPS) with fast binary readout and zero suppression logic. The sensor consists of a matrix composed by 928 (rows) by 960 (columns) pixels of $20.7\mu m$ pitch for a size of the chip of $20.22mm$ by $22.71mm$ and then cover an area of about $2cm$ by $2cm$. It is implemented using the microelectronic process Austria Micro System AMS-C35B4/OPTO that uses 4 metal and 2 poly layers. The thickness of the epitaxial layer stretches out up to $15\mu m$ in Hi-Resistivity substrate (400 Ohm.cm).

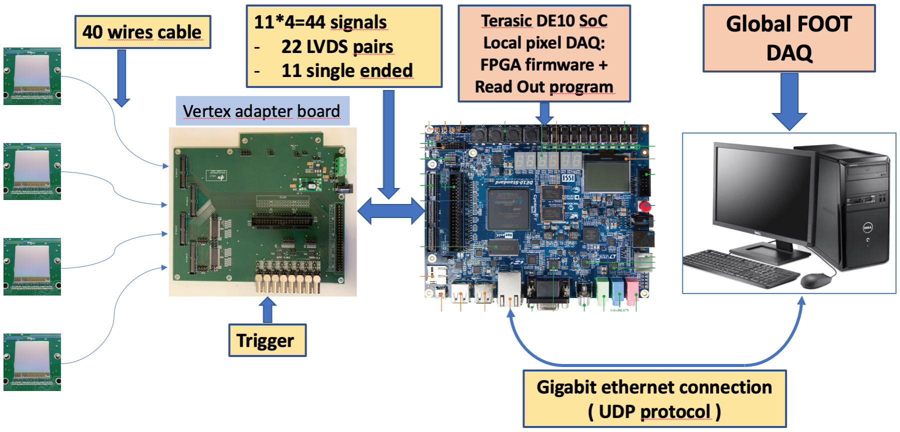

Figure 2: *Vertex DAQ chain*

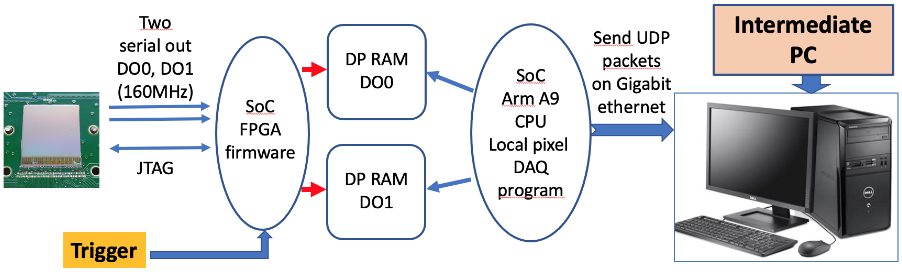

Figure 3: *Vertex DAQ logic*

3.1 Vertex detector

The Vertex detector is made by a stack of four equal specifically designed and constructed PCB (Printed Circuit Board) used to house one M28 sensor each. Those four stations allows to track the fragments coming from the target closely placed near the first sensor of the stack. This sytem has been already tested in laboratory, at the BTF facility of the INFN LNF and used for the first FOOT data taking at the GSI laboratory in Darmstadt in spring 2019. The main work done by the group is the design of the already mentioned PCB and of the entire data acquisition chain (hardware and software) schematically shown in Fig. 2. All electrical signals (data lines, control signals and power) are converted and dispatched by the specifically designed Vertex adapter board and are then managed by the commercial FPGA SoC (System On Chip) Terasic DE10 board (Fig. 2). The two data serial line running at 160 MHz producing the data from each of the four M28 sensors are processed by one DAQ board where are deserialized and decoded by the firmware in the FPGA, stored in a Dual Port Memory that is accessed by the on board data acquisition program that sends them trough the Ethernet connection, using a UDP protocol, to the intermediate PC. The logic of the acquisition system is depicted in Fig.3.

3.2 Inner Tracker

The basic idea of the Pixel part of the tracker is to have four tracking stations close to the fragmentation point in the target before the magnetic field, then after the first magnet an intermediate

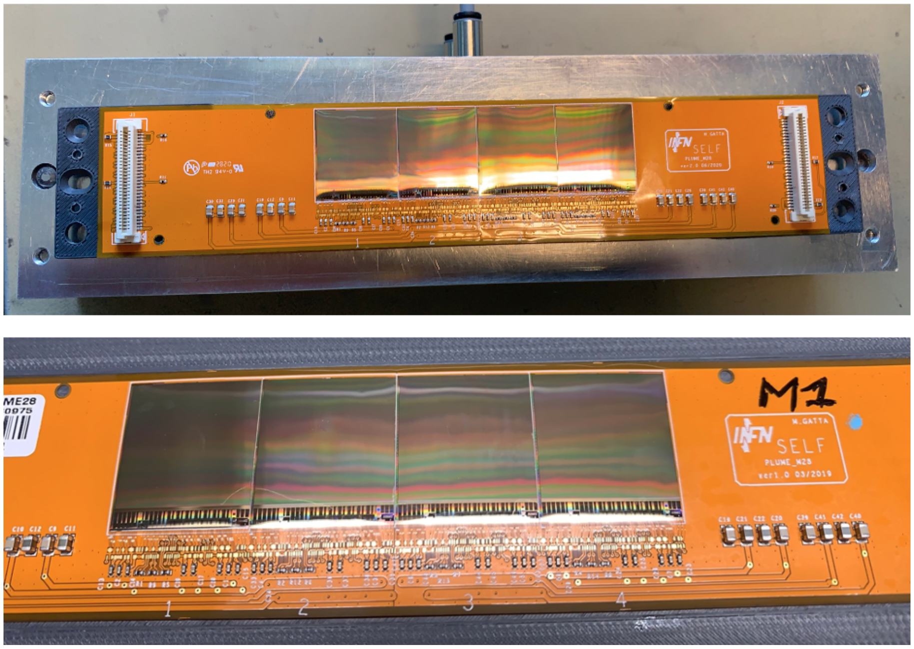

Figure 4: *First Inner Tracker assembled module*

station able to provide two more impact points in the track. Then after the second magnet the last tracking station is implemented by silicon strip sensors. The two pixel layers in the second tracking station are implemented by four ladders, each ladder is composed by two modules glued back to back on a $2mm$ thick Reticulated Vitreous Carbon (RVC) foam sheet 15). Each ladder houses 4 plus 4 sensors and has an overall acceptance area of about 2x8 cm. Staggering four ladders on the two side of a metallic frame (Fig. 5) the complete acceptance area is about 8x8 cm covering together with the Vertex an angular acceptance of ±10 degrees.

The first implemented module with real sensors is depicted in Fig. 4. The PCB used to assemble a module has been designed and produced by the FOOT Frascati group and is made by $100\mu m$ thick Printed Flex cable housing at the ends two connectors serving two M28 sensors each. The remaining assembly work of gluing and bonding of the sensors on each module and finally the gluing of the two modules in a ladder is made by the already mentioned In2p3 Strasbourg group. The complete data acquisition chain, hardware and software has been designed and implemented by the LNF FOOT group, it includes a chain, of two different adapter boards, serving two M28 sensors each that converts and dispatch the electrical signals to a common Terasic DE0 nano SoC board that reads half ladder. Eigth of such readout boards, using practically the same code used to readout the Vertex, send the data on eigth ethernet links that are connected to a common readout PC that concentrate the data and send the assembled packets to the experiment general data acquistion system. All needed software to manage remotely from the intermediate PC has also been implemented in Frascati.

To minimize the magnetic field reduction the distance from the two magnets has been fixed at $5cm$. In this space the inner tracker needs to be accomodate, then the overall layout: ladders distance and placement, way of fixing them to the frame to avoid all possible mechanical stresses,

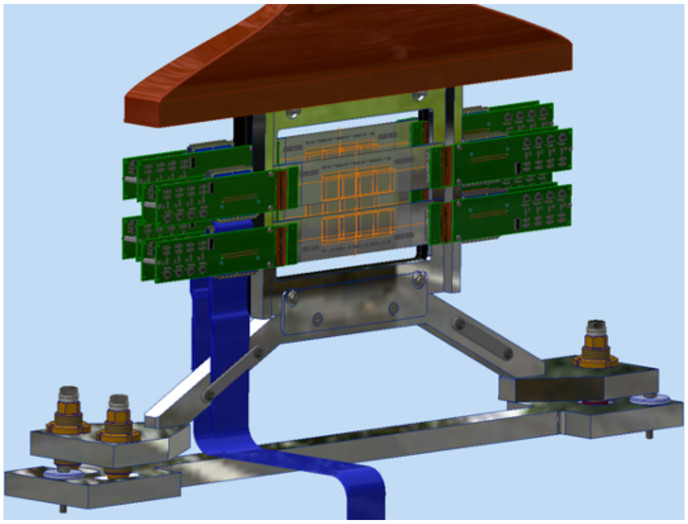

Figure 5: *Inner Tracker layout*

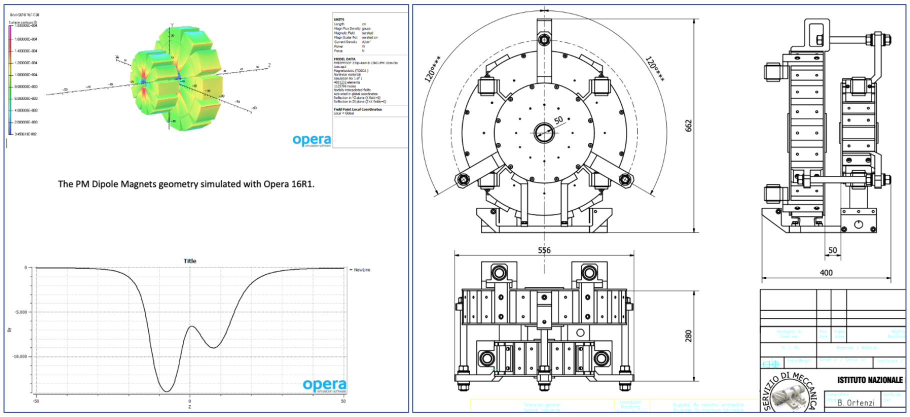

Figure 6: *Inner Tracker layout*

placement of the adapter board to read the two side of each module and the carefull placement and routing of the cables have been defined and designed by the Frascati group.

3.3 Magnetic system

The Frascati FOOT group has also realized the design of the system of two permanent magnets in Halbach configuration $^{16)}$, their magnetic configuration and mechanical structure is depicted in Fig. 6. Being the availabilty of the beams needed for those kind of measurument at different laboratories the experimental setup needs to be transportable, then an heavy electromagnet would have been too heavy and complex to manage and a solution with permanent magnets has been choosen. The implemented design will have an overall weigth of less than $200Kg$ and is actually under production at Sigmaphi company.

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