“QBeRT: an Innovative Instrument for the Real-Time Qualification of a Particle Beam”

This paper describes an innovative beam diagnostic and monitor system, QBERT (Qualification of Beam Real Time) composed of a position sensitive detector (PSD) and a residual range detector (RRD). The sensitive area of PSD is composed of four layers of scintillating fibers (SciFi) arranged to form two planes that are orthogonal to each other. The fibers of 500 µm (nominal) square section are optically coupled to two Silicon Photomultipliers arrays following a channel reduction system patented by the Istituto Nazionale di Fisica Nucleare. Sixty parallel layers of the same fibers used in the PSD form the sensitive area of RRD. The various layers are optically coupled to a Silicon Photomultipliers array by means of wavelength shifting fibers. The sensitive area of the two detectors is 9×9 cm². In both PSD and RRD, the output signals from the SiPM modules channels are read-out and processed by an electronic acquisition chain articulated on two main levels. The first level consists of front-end electronics that operates the analog-to-digital signal conversion. The output signals of the front-end are sent to a SoM (System-on-Module) for decoding and filtering. The SoM, via gigabit Ethernet communication, sends filtered signals to a PC for filtered data to be displayed in real time, and stores raw data (unfiltered) for later analysis.

The unique feature of these detectors is the possibility to work in imaging conditions (e.g. a particle at a time up to 10⁶ particles per second) and in therapy conditions up to 10¹⁰ particles per second. The combined use of the two detectors, in imaging conditions, as an example of application, allows the particle radiography of an object. In therapy conditions, in particular, the system measures the position, the profiles, the energy and the fluence of the beam.

The performance of the prototypes was tested in different hadron-therapy facilities:

- CATANA proton therapy facility (Laboratori Nazionali del Sud, INFN, Catania, Italy) where proton beam with energy up to 62 MeV and rate of about 10⁶ particles per second are available.
- CNAO (Centro Nazionale di Adroterapia Oncologica, Pavia, Italy) where carbon and proton pencil beams with energy up to 400 AMeV and 250 MeV, respectively, and rate up to 10¹⁰ particles per spill, are available.
- TIFPA Proton Irradiation Facility, where proton beam with energy up to 230 MeV and current up to about 300 nA are available.

The comparison between simulations and the measurements confirms the validity of the described system. The measured spatial resolution of the tracker is about 170 µm and the range resolution is about 170 µm.

In figures below, some of the most important experimental results achieved with the described system.

**PSD - Fluence measurement**

The PSD performs a fluence measurement by counting each particle that crosses the sensitive area of the detector up to 108 per fiber. A typical pencil beam spot covers at least ten 500 µm fibers, then, the maximum measurable fluence is about 10⁹. In practice, the SciFi have an efficiency of about 80%, which is slightly dependant on the beam energy. A fluence measurement has been performed at CNAO treatment room. The results are reported in figure and compared to the dose delivery log. Comparison between the fluence measured by the PSD in each direction (left) and that measured by dose delivery system of CNAO (right).

**RRD Range vs Energy**

A proton, which crosses the RRD, passes through a number of layers proportional to its input energy, before stopping. The dose released by the proton in each layer has an inverse profile, which increases with depth up to the Bragg peak. The Bragg peak is in the layer in which the proton produced more scintillation light, which for the protons corresponds roughly to the point where they stop in the medium. After the calibration of the response to the energy deposited in the detector, it is possible to measure the initial energy of the particle by observing the layer in which it deposits the higher dose.

(Left) Comparison between experimental data (CATANA) and simulation values of the residual range, with their respective fit.