A REAL-TIME BEAM MONITOR FOR HADRONTHERAPY APPLICATIONS BASED ON THIN FOIL SECONDARY ELECTRON EMISSION AND A BACK-THINNED MONOLITHIC PIXEL SENSOR*

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Abstract

A novel, non-disruptive beam profile monitor for low intensity light-ion beams has been constructed and tested. The system is designed for use in medical hadrontherapy centers where real-time monitoring of the beam intensity profile is of great importance for optimization of the accelerator operation, patient safety and dose delivery. The beam monitor is based on the detection of secondary electrons emitted from a submicron thick Al_2O_3 foil placed in the beam at an angle of 45 degrees. The present paper reports the latest results achieved with a customized back-thinned monolithic active pixel array, which provides the beam intensity and position with a precision of better than 1 mm at a 10 kHz frame rate. The monitor performance has been tested with a patterned beam, produced with a multi-hole collimator, with the results indicating that the system performs according to its design specifications.

INTRODUCTION

Hadrontherapy is a radiotherapy technique using highly accelerated light ion beams (usually protons or carbon) to irradiate tumours. The intense end-of-track Bragg energy deposition peak, together with variations in beam profile and energy, are used to deliver an optimized dose to the tumour minimizing the damage to nearby healthy tissues [1]. Patient safety, accelerator operation, and dose delivery would all benefit if the beam intensity and profile could be continuously monitored in the extraction line during the treatment. An effective device for on-line beam monitoring must produce negligible effects on the few nA clinical beam, featuring a spatial resolution not exceeding 1 mm, a beam current measurement resolution of few percent and a frame rate of the order of 10 kHz [2].

Up to present this has not been possible, since existing interceptive monitors interfere with the beam, causing significant beam disruption for therapeutic kinetic energies (60 MeV to 250 MeV for protons and 120 MeV/nucleon to 400 MeV/nucleon for carbon ions). At the same time non-interceptive instrumentation is not sensitive enough to detect average beam intensities from a few pA to a few nA, with extracted beam durations of the order of 1 s. To overcome this limitation an innovative, non disruptive beam monitor, named SLIM (Secondary emission monitor for Low Interception Monitoring) [3, 4], capable of providing beam intensity and profile measurement during the treatment has been proposed, constructed and tested. The device has been developed in the framework of the SUCIMA (Silicon Ultra Fast Cameras for electrons and gamma sources In Medical Application) project [5] funded by the European Commission. In-beam testing has been carried out at the Cyclotron Laboratory of the European Commission (EC) Joint Research Centre, Ispra, Italy.

Previous attempts to use the secondary emission from thin foils as a mean to measure the main beam parameters can be found in [6, 7, 8, 9]. The devices illustrated in [6, 7] concern only beam intensity measurements, while the detectors described in [8, 9] do not fulfill the hadrontherapy requirements either in terms of beam acceptance (70 mm), or in terms of spatial (1 mm) and time resolution (100 μs).

BEAM MONITOR WORKING PRINCIPLES

The proposed monitor is based on the secondary electron emission from a thin Al foil intercepting the hadron beam path at 45° as shown in Figure 1. The Al foil has a diameter of 65 mm to 70 mm and consists of a support of 0.1 - 0.3 μm of Al_2O_3 coated on each side with 0.01 - 0.02 μm of Al. Ionization of the Al atoms by the hadron beam can result in electrons receiving energy and momentum sufficiently large to escape from the foil surface. Electrons with a kinetic energy below 50 eV are conventionally called secondary electrons (SE). These are the predominant component (85%) of the emission spectrum [10]. An electrostatic field accelerates the SE and focuses them onto an imaging device with a final electron energy in the 10 - 30 keV range and a flux in the 1 - 10^4 e^-/pixel/100 μs range[1]. The op-

* Work supported by the European Commission under the contract G1RD-CT2001-00561.

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[1] The number of electrons/pixel is independent on the pixel size that is fixed by the required resolution and optical system demagnifying factor; 100 μs corresponds to the required frame rate.

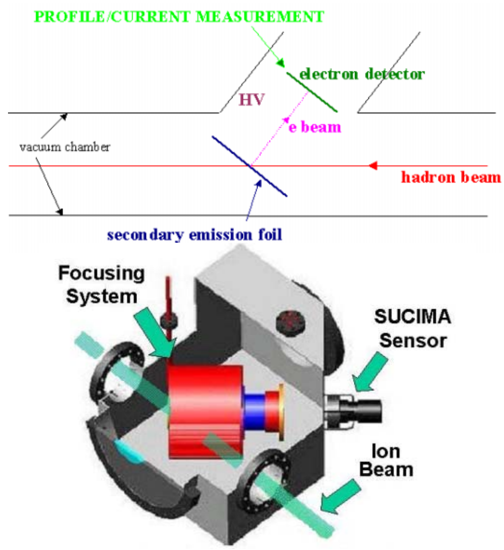


Figure 1: *(a) Schematic drawing of the SLIM (Secondary electron emission for Low Interception Monitoring) beam monitor working principle and (b) of the focusing system prototype inside the vacuum chamber; an arc of the cylindrical cage electrode is covered with 40 μm wires, 4 mm spacing for a 99% transparency to the hadron beam.*

tics for the collection of the SE, the type, the size and the pitch of the electron detector, the front-end electronics and the readout system have been designed to fulfil the beam monitor requirements [11].

The SUCIMA collaboration developed a dedicated CMOS silicon detector, named MIMOTERA (see Table 1) with an area of $17 \times 17\ \mathrm{mm}^2$ and a pixel pitch of $\sim 200\ \mu\mathrm{m}$ assuming a focusing system demagnifying factor of about 5. Due to the short range ($3\ \mu\mathrm{m}$ in silicon) of low energy electrons, their detection with a CMOS sensor is a challenging task that can be accomplished with a complete substrate removal. In addition to the MIMOTERA tests, a before commercially available system, that does not feature the required frame rate, has been used to measure the electrostatic lenses optical properties. It consists of a MCP (micro-channel plate) coupled to a phosphor screen and a CCD (charged coupled device) [3].

Table 1: *MIMOTERA main characteristics*

Size [pixels]	112×112
Pixel pitch	$153 \times 153\ \mu\mathrm{m}^2$
Frame rate	10 kHz
Parallel analog output	4 channels
Technological process	$0.6\ \mu\mathrm{m}$ AMS CUA
Epitaxial (sensitive) layer	$\sim 14\ \mu\mathrm{m}$
Dynamic range (20-keV e^-)	$1 - 10^4 e^-$/pixel/100μs

Low energy electron detection in a silicon sensor has been demonstrated as follows:

- sensitivity to beam current variations has been measured with a hybrid, moderate granularity pad sensor [12] read out with a high dynamic range charge integrating ASIC [13];
- profiling capability has been investigated relying on the dedicated monolithic CMOS sensor.

This paper refers to the first results obtained with the MIMOTERA sensor mounted in the SLIM monitor on the Ispra cyclotron beam line, using a 17 MeV proton beam.

EXPERIMENTAL RESULTS

Preliminary tests of the electrostatic focusing system were first performed using thermionic emission from a hot tungsten wire as a source of electrons [14]. The experimental results confirm that the optical properties are in good agreement with the computer simulations and fulfill the SLIM beam monitor requirements [3, 11].

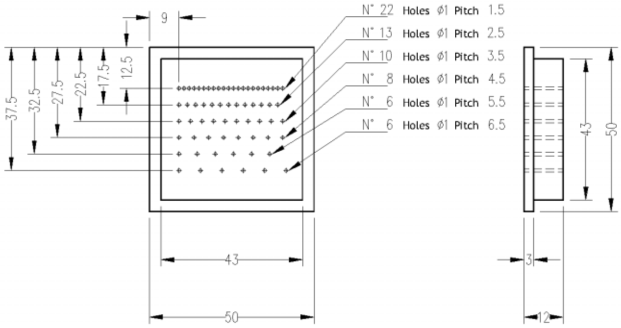
The full system testing is being carried out at the Scanditronix MC40 cyclotron of the EC Joint Research Centre located in Ispra (Italy). The cyclotron is capable of accelerating various light ions up to an energy of 39 MeV (for protons) with a beam intensity in 5 nA - 50 μA range. With no loss of generality and considerable cost saving, initial tests were performed with a standard Al sheet about $10\ \mu\mathrm{m}$ thick[2]. The SLIM was initially tested on beam with the commercial MCP, phosphor and CCD system. Following the commissioning, the pad sensor was integrated to assess the sensitivity to beam current fluctuations [3].

As a second stage spatial granularity and sensitivity of the system were studied integrating the backthinned MIMOSA CMOS sensor MIMOTERA. Images of 17 MeV proton beams with 10-nA intensity were acquired and analyzed. The beam energy was chosen for the most efficient use of the beam time slots in between commercial radioisotope production without the need of readjusting the accelerator parameters. The secondary emission efficiency with 17 MeV primary proton is expected to be at $\sim$10% [11].

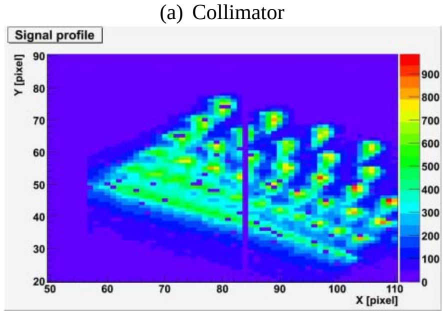
The data acquisition was based on a custom developed DAQ system [15]. The response of the SLIM was studied by inserting in the beam path a 12 mm-thick Al collimator with six rows of 1 mm-diameter holes and pitches from 1.5 up to 6.5 mm as shown in Figure 2(a). During the test with the MIMOTERA, the secondary electrons were accelerated to 10 keV giving to a sharper image on the on-line display. The recorded image on the CMOS sensor is shown in Figure 2(b).

The image is the average of 500 frames (100 μs/frame readout time) after pedestal subtraction and the color scale represents the signal intensity for each pixel. The image appears tilted by about 210° in agreement with the mounting scheme of the sensor on the focusing system. Hot spots corresponding to the collimator holes are clearly visible.

[2] Since the secondary emission is a surface effect, the replacement of the Al foil will not modify the secondary emission yield and energy and angular spectra.



(a) Collimator



(b) Contour image

Figure 2: *(a) Schematic drawing of the collimator placed in the beam path, consisting of a 12 mm-thick aluminium block with 6 rows of holes of 1 mm diameter. The hole pitches range from 1.5 up to 6.5 mm. (b) An image of the beam profile on the SLIM monitor as detected by the CMOS sensor. According to the mounting scheme of the sensor on the focusing system the image appears tilted by* 210°. *The gray scale on the right represents the mean analogue signal stored in each single pixel.*

The demagnifying factor was measured by comparing the peak separations on the sensor with the real pinhole separations - the resulting value was 4.3. The discrepancy with respect to the nominal value of 5 might be due to a shift in the detector position with respect to the simulated focal plane, due to mechanical constraints. It might be also due to aberration effect since the image is off-centered with respect to the sensor centre.

Different explanations for the high level of signal in between the adjacent hot spots have been envisaged, such as background ionizing radiation field in the extraction line beam pipe, divergence of the proton beam after passing through the collimator, together with forward scattering of the beam from the front edges (incident beam side) of the holes in the collimating block or thermionic electron emission from the Al foil caused by primary beam heating.

Tests and calculations demonstrate that none of the above effects can account for the observed signal. Since the blooming effect is certainly present, to exclude an electronics misbehaviour of the sensor due to an oversaturating secondary electron flux or a distortion of the electrostatic field due to charge-up of the insulating parts of the focusing system, beam tests with the collimated beam and the commercial detector are scheduled as well as further studies of the background signal origin.

CONCLUSIONS

A beam monitor, innovative in terms of beam acceptance, spatial and time resolution for real time diagnostics of charged particle beams in the extraction lines of a hadrontherapy centre has been designed, developed and tested. The laboratory tests with thermionic electrons have demonstrated that the focusing system optical properties fully satisfy the requirements in terms of linearity, demagnifying factor and resolution. The results of the first measurements on a cyclotron proton beam with both the phosphor screen viewed with a CCD camera and a pad sensor for the secondary electrons detection were successful. The latest experiment using as a detector the dedicated ultra-thin back-illuminated CMOS sensor sensitive to 20 keV electrons has been performed with promising results. Further tests to identify the origin of the observed background signal are underway.

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