SLIM (Secondary emission monitor for Low Interception Monitoring) AN INNOVATIVE NON-DESTRUCTIVE BEAM MONITOR FOR THE EXTRACTION LINES OF A HADRONTHERAPY CENTRE

P.N. Gibson[a], U. Holzwarth[a], K. Abbas[a], L. Badano[b], O. Ferrando[b], G. Molinari[c], T. Klatka[d], M. Koziel[d], A. Bulgheroni[e], and M. Caccia[e]

[a]Institute for Health and Consumer Protection, Joint Research Centre, European Commission, Ispra, Italy
[b]Fondazione TERA, Milan, Italy
[c]CERN, Geneva, Switzerland
[d]AGH - University of Science and Technology, Krakow, Poland
[e]Universita' degli Studi dell'Insubria, Como, Italy

Abstract

Real time monitoring of hadron therapy beam intensity and profile is a critical issue for the optimisation of dose delivery to carcinogenic tissue, patient safety and operation of the accelerator complex. For this purpose an innovative beam monitor, SLIM (Secondary electron emission for Low Interception Monitoring) is being developed in the framework of the EC-funded SUCIMA (Silicon Ultra-fast Cameras for electrons and gamma sources In Medical Application) project. The detector system is based on the secondary emission of electrons by a non-perturbative, sub-micron thick Al foil placed directly in the extracted beam path. The secondary electrons, accelerated by an electrostatic focusing system, are detected by a monolithic silicon position-sensitive sensor, which provides the beam intensity and its position with a precision of 1 mm at a 10 kHz frame rate. The results of the laboratory tests of the first system prototype with thermoionic electrons emitted from a hot Tungsten wire are presented together with the measurements performed on a low intensity hadron beam at the Cyclotron of the Joint Research Centre in Ispra.

INTRODUCTION

Hadrontherapy is a radiotherapy technique using light ions (usually protons or carbon) to irradiate tumours. The intense end-of-track Bragg ionisation peak, together with variations in beam profile and energy, are used to deliver an optimum, shaped dose to the tumour that minimizes the damage to nearby normal tissues [1]. Patient safety, accelerator operation, and optimum dose delivery would all benefit if the beam intensity and profile could be continuously monitored during treatment, rather than just during the set-up. This has not been previously possible, since existing interceptive monitors interfere with the beam, causing a non-negligible beam scattering or a beam disruption for therapeutic kinetic energies (60 to 250 MeV for protons and 120 to 400 MeV/nucleon for carbon ions). Available non-interceptive instrumentation is not sensitive enough to detect average beam intensities from few pA to few nA. To overcome this limitation an innovative non-interceptive monitor, named SLIM (Secondary emission monitor for Low Interception Monitoring) [2, 3], capable of providing beam intensity and profile measurement during the treatment without degrading the hadron beam, has been proposed. The device has been developed in the framework of the SUCIMA (Silicon Ultra Fast Cameras for electrons and gamma sources In Medical Application) project [4] funded by the European Commission with the primary goal of developing a real-time dosimeter based on direct detection of secondary electrons in a silicon substrate (contract: G1RD-CT2001-00561).

WORKING PRINCIPLES

The operation of the beam monitor is based on the secondary electron emission. A thin Al foil is placed in the hadron beam path at 45 degrees to the beam direction as shown in Fig. 1.

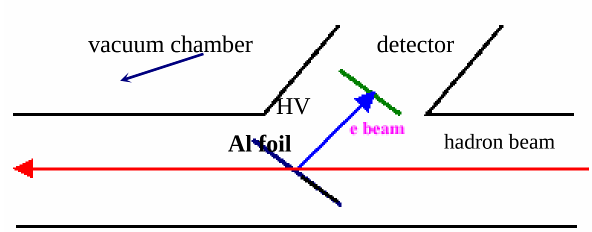

Figure 1: Schematic layout of the SLIM beam monitor.

The Al foil has a diameter of 65 to 70 mm and consists of a support of 0.1 to 0.3 μm of Al_2O_3 coated on each side with 0.01 to 0.02 μm of Al. The energy lost by the hadron beam in the foil is transferred to the electrons of the medium. Those that receive a sufficient impulse to be ionized and escape from the foil surface can be classified into high energy electrons (δ-rays) and electrons with a kinetic energy below 50 eV, conventionally called secondary electrons (SE). The latter are the predominant component in the spectrum of the escaping electrons [5] and are, therefore, the most important for this application. The field of the electrostatic lenses accelerates the SE and focuses them on the detector with a demagnifying factor of about 5 to match the size (17x17 mm^2) and pixel pitch

(200 μm) of the CMOS monolithic active pixel sensor [6]. The optics for the collection of the SE, the type, size and pitch of the electron detector, the front-end electronics and the read-out system have been designed on the basis of the key requirements. The design and construction of the first prototype are described in [2] and [3].

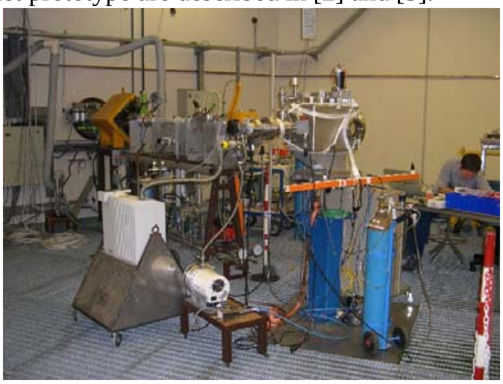

Figure 2: The SLIM beam monitor installed on a JRC Cyclotron bea line.

BEAM MONITOR TESTING

Laboratory tests with thermionic emission

Tests of the focusing lenses have been performed using thermionic emission from a hot tungsten wire as a source of electrons [7] and are analyzed in detail in [3]. The experimental results confirm that the optical properties of the focusing system are in good agreement with the computer simulations and fulfil the SLIM beam monitor requirements. In particular, the optical system is linear with small aberration effects for distances from the symmetry axis of the focusing system larger than 20 mm, as predicted by theory. The deviation between theoretical and experimental demagnifying factors is within 3 %. Moreover experimental resolution values are in agreement with those obtained from the computer simulations [8].

First beam tests of the SLIM beam monitor

Complete tests of the SLIM with a 100 nA intensity hadron beam are in progress at the cyclotron of the Joint Research Centre (JRC) at Ispra, Italy. The SLIM installed on one of the beam line of the Cyclotron is shown in Fig. 2. The detector used for the first beam tests was a micro channel plate (MCP) with a phosphor screen (P47) observed by a CCD (charge coupled device).

The preliminary results with a 17 MeV proton beam, of intensity in the range 90 to 140 nA are shown below. After the setting up of the line, as soon as the fluorescent beam monitor was taken away from the beam path, the signal was clearly detected on the SLIM. Fig. 3 shows the beam profile measured with the JRC Cyclotron reference beam monitor (a 3 mm granularity scintillating screen observed with a TV camera and a video monitor). Fig. 4 shows the beam profile measured with the SLIM, where the CCD signal is displayed either with a video monitor (left) or digitised with a frame grabber (right).

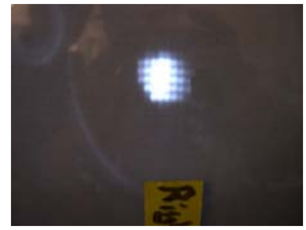

Figure 3: Beam profile measured with the JRC Cycloton reference beam monitor.

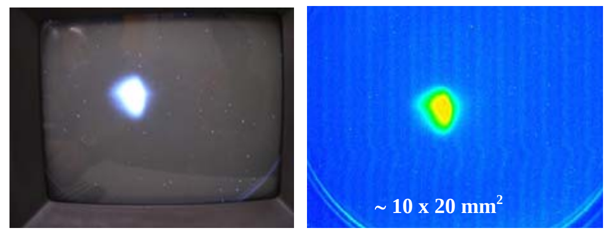

Figure 4: Beam profile measured with the SLIM; left, the CCD signal on a video monitor, right, digitised with a frame grabber.

As expected, the beam changed shape and position, by varying the values of the voltages of the electrodes of the focusing system. Changes in the measured beam shape due to variations of the current in the extraction line quadrupole magnets were also measured in real time.

After these encouraging results, a position sensitive silicon detector integrating 22 x 22 pads with 1.4 mm pitch was mounted on the focusing system, as shown in Fig. 5, and integrated in the beamline.

The sensor is read out by 4 VASCM2 ASICs chips of the VIKING family [10], via a dedicated data acquisition system [11]. Due to wire bonding problems, only one pad every two could be connected to the readout chips. Moreover, one of the chips was not working correctly and it was not possible to detect the signal of one quarter of the sensor. Nevertheless chip and sensor behaved as foreseen and the results with the first prototype proved that a silicon detector with shallow backplane is sensitive to 20 keV electrons and can be used for realtime beam imaging.

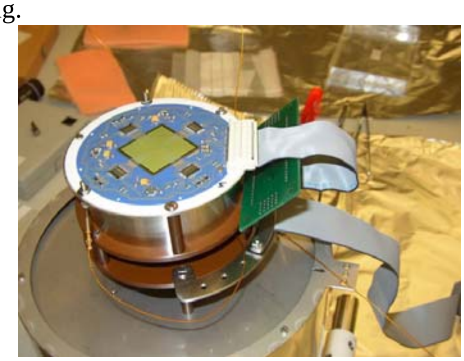

Figure 5: Pad detector hybridized on ceramic and mounted at the end of the SLIM focusing system.

During these latter tests, the beam was delivered to the SLIM beam monitor through a collimator with three holes, a central one (5 mm diameter) plus two smaller satellites (2 mm diameter), as shown in Fig. 6.

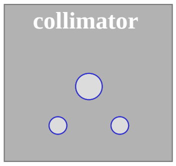

Figure 6: Schematic view of the Al collimator with the three central holes.

The average beam intensity was below 5 nA and the integration time was set to 1 ms. Changing the extraction line quadrupole settings, the beam position was swept from the larger hole to one of the secondary holes as clearly distinguishable in Fig. 7. The upper left of Fig. 7 refers to the case where the beam was illuminating the central and left holes. On the right is represented the symmetric situation while, on the bottom part, is the superposition of the two images. The horizontal and vertical scale refers to the number of the pad.

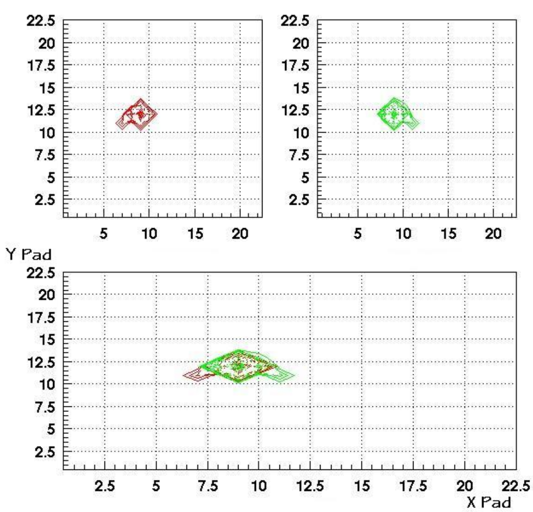

Figure 7: First record of SLIM images with the pad silicon sensor.

Position and intensity measurements are planned on a short time scale after the implementation of a time scheme of the chip to reduce the integration time and avoid saturation for the typical beam intensities of the Ispra cyclotron. Further tests with the dedicated CMOS monolithic active pixel sensor designed in the framework of the SUCIMA collaboration to provide 1 mm spatial resolution at the foil (200 μm at the detector) and 10 kHz frame rate are in progress.

CONCLUSION

A beam monitor, innovative in terms of beam acceptance, spatial and time resolution, based on secondary emission by a sub-micrometer thick foil for real time diagnostics of charged particle beams in the extraction lines of a hadrontherapy centre has been developed. 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 hadron beam with both the phosphor and CCD camera and the pad sensor for secondary electrons detection in the JRC Cyclotron look very promising. Further beam tests with the pad sensor and a new time scheme of the chip to avoid saturation and with the dedicated CMOS monolithic active pixel sensor designed in the framework of the SUCIMA collaboration are in progress. Tests with high intensity (up to 1 mA) beams to evaluate the possibility to use the SLIM beam monitor for the real time control of radioisotope production beams are also foreseen.

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