

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

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Abstract

Real time monitoring of hadrontherapy beam intensity and profile is a critical issue for the optimisation of the dose delivery to the patient carcinogenic tissue, the patient safety and the operation of the accelerator complex. For this purpose an innovative beam monitor, based on the secondary emission of electrons by a non-perturbative, sub-micron thick Al target placed directly in the extracted beam path, is being proposed. The secondary electrons, accelerated by an electrostatics focusing system, are detected by a monolithic Silicon position sensitive sensor, which provides the beam intensity and its position with a granularity of 1 mm at 10 kHz frame rate. The conceptual design and the engineering study optimised for hadrontherapy, together with the results of the preliminary tests of the first system prototype, will be presented.

INTRODUCTION

The rationale for the SLIM project

Hadrontherapy is the use of hadron beams to irradiate tumours. In its most advanced form, the intense end-of-track Bragg ionization 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 that 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, considered that the therapeutic beam kinetic energies varies in the range (60 – 250) MeV for protons and (120 - 400 MeV/u) for carbon ions and that non-interceptive instrumentation is not sensitive enough to detect average beam intensities from few pA to few nA, with spill duration ~ 1 s. For this purpose an innovative beam monitor, named SLIM (Sem for Low Interception Monitoring), capable of providing beam intensity and profile during the treatment, has been conceived and developed in the framework of the SUCIMA (Silicon Ultra fast Cameras for electron and gamma sources In Medical Application) project. SUCIMA has been funded by the European Commission with the primary goal of developing a real time dosimeter based on direct detection in a Silicon substrate.

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SLIM beam monitor principle and requirements

A thin Al - Al₂O₃ - Al foil set at an angle to the beam serves both as a source of secondary electrons (SE) and as an electrode with electric field lines from the foil surface that guide the emitted electrons to a pixel/pad detector beyond the beam volume. A schematic layout of the beam monitor is shown in Figure 1.

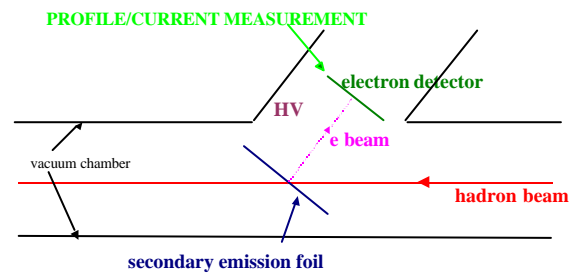


Figure 1: Schematic principle of the SLIM beam monitor.

The thin foils are produced following a technique consolidated at CERN [2] and consist of a support of 0.1 - 0.2 μm of Al₂O₃ coated on each side with 0.01 - 0.05 μm of Al for a maximum diameter of about 65 - 70 mm. As secondary emission is a surface phenomenon, it will concern just the most superficial aluminium layers. The emittance blow-up induced by the foil has been evaluated with a Monte Carlo programme for plural scattering [3] and goes from 2% to 10% according to the beam divergence at the foil for a 60 MeV proton beam (worst case). Experimental validation of the model results are foreseen during the first measurements on hadron beams.

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 base of the key requirements on the performances of the SLIM beam monitor summarised below:

- real-time (during the treatment of the patient)
 - stigmatic optics (demagnifying or proximity) to preserve the information on the beam profile
 - thin foil diameter $\Phi = 70$ mm (beam on 10×10 mm²)
 - profile granularity 1 mm
 - vacuum compliant ($10^6 \div 10^7$ Torr)
- and of the requirements specific for the SE detector and related electronics:
- active surface subdivided in cells (pads or pixels)
 - 5000 cells or more
 - sensitive to low-energy (~ 20 keV) electrons
 - large dynamic range ($3 \div 9 \cdot 10^3$ e⁻/pixel·100 μs)

- 10 kHz frame rate (to guarantee $\pm 2\%$ dose uniformity [4])
- no dead time

Last but not least, the monitor will be installed in a hospital-based facility: it should, therefore, be easy to operate and maintain, reliable and have a limited cost. Previous attempts to use the secondary emission from thin foils as a mean to measure the main beam parameters can be found in Refs. 5 - 8.

The secondary electron detectors

Two solid-state detectors (named PAD or pixel detector, according to the cells/sensor size) and a commercial detector (to test the performance of the focalization system) are foreseen for the SE detection:

- a commercial detector consisting of a micro-channel-plate (MCP effective diameter 32 mm) for SE amplification followed by a phosphor screen and a CCD camera;
- a Silicon PAD detector [9] with a sensitive area of 30.8 mm and a pitch of 1.4 mm for the first prototype and a sensitive area of 50 mm and pitch of 1 mm for the final prototype, bonded to a commercial integrating chip [10];
- a monolithic CMOS Silicon detector [11], developed in the framework of the SUCIMA collaboration, with a sensitive area of 17 mm and a pitch of 200 μm .

SLIM BEAM MONITOR DESIGN

Physics aspects of secondary emission

The main aspects of secondary emission necessary for the design of the SLIM in terms of SE energy and angular distributions and yields are summarised below. The low energy (below 50 eV) part of the SE spectrum does not depend on the primary beam kinetic energy. For proton on Al targets the distribution is peaked around 2.1 eV with a FWHM (that contains the 85% of SE) of 8.2 eV [12]. The integrated angular distribution, i.e. the number of SE with low energies emitted from the surface in the solid angle, follows a cosine-law peaked around the normal to the foil [13]. The number of SE emitted per impinging protons have been evaluated using Sternglass theory [14] with Borowski correction [15] for the C-ions and are summarised in Tables 1 and 2 (f and b refer to the forward and backward emission respectively).

Table 1: Calculated yields (proton beam)

p energy [MeV]	γ total [%]
60	4.4 (γ_b : 2.0, γ_f : 2.4)
250	1.6 (γ_b : 0.7, γ_f : 0.9)

Table 2: Calculated yields (C-ion beam)

C-ion energy [MeV/u]	γ total [%]
120	78
400	27

The energy and angular distributions illustrated above make possible the transport of the SE preserving the

information on the beam profile (see next Section). The number of electrons produced, evaluated on the base of the data of Tables 1 and 2, goes from 3 (0.3 if the 2 sigma beam edge is considered) to $9 \cdot 10^3 \text{ e}^-/\text{pixel} \cdot 100 \mu\text{s}$ for both proton and C-ion beams.

Focalisation system (FS) design

Different optics have been studied to match the electron detectors sizes and pitch. The final solution for the CMOS detector, simulated with SIMION 3D Ion Optics Programs [16], has been designed adapting the optical scheme of an image intensifier tube [17] to the beam monitor needs. Figure 2 shows the final prototype and its cross section inserted in the vacuum chamber. An arc of 60 degree of the cage cylinder is covered by 25 tungsten wires of 40 μm diameter (99% beam transparency) to allow the passage of the hadron beam. In blue are the SE trajectories and in red the electrostatic potential lines, while the green arrow represents the hadron beam. On the right are the values of the electrodes polarizing voltages.

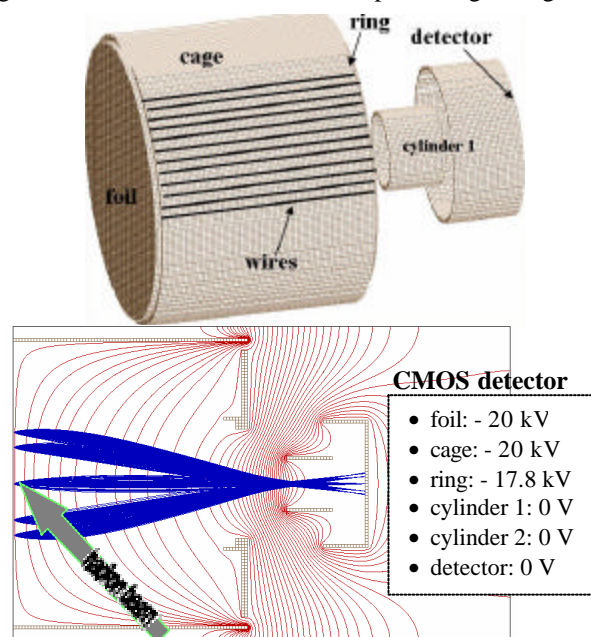


Figure 2 The final FS prototype (wire spacing 4 mm, wire diameter 40 μm , wires arc 60°).

As shown in Figure 2, the image is demagnified of a factor 5 to match the CMOS detector size. The flat emitting surface and the wider SE energy and angular spread in respect to photoelectrons causes aberrations larger than in the image intensifier tubes that inspired the FS design. Nevertheless simulations with a gaussian hadron beam proved that the spatial resolution is within the requirements also for off-centred beams.

Vacuum chamber (VC) design

Different vacuum systems with different geometries have been studied [18]. The final design is represented in Figure 3 where the green arrow on the right represents the hadron beam hitting the FS cage on the wire side (the flange-to-flange longitudinal occupancy is 460 mm). A

CCD camera is mounted on the right smaller flange to detect the light emitted in the interaction of the phosphor screen on the FS (see below) with the focalised SE.

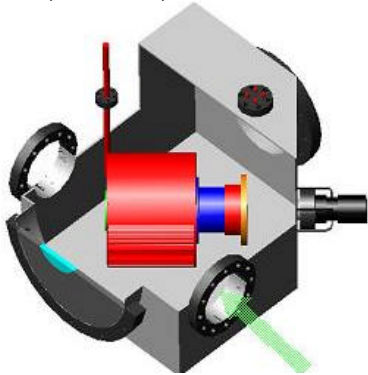


Figure 3: Inside view of the VC with the FS.

THE SLIM PROTOTYPE

A prototype of the SLIM beam monitor has been constructed and is shown in Figures 4 (focalisation system) and 5 (integrated system). In Figure 4 the detector mounted on the FS (left side) for the first tests is a phosphor screen (P47).

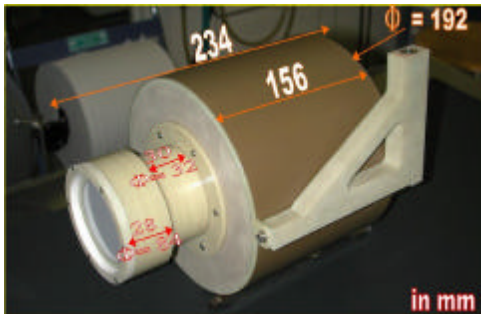


Figure 4: FS prototype (sizes in mm).



Figure 5: Integrated system in the laboratory.

Thermo-ionic electrons emitted from a biased tungsten wire replace the SE in the first laboratory tests of the FS performances. Results are qualitative (the CCD video signal was observed on a monitor), but promising. No discharges have been detected neither between FS and VC, nor between the FS electrodes for polarization voltages up to 30 kV and 5 ÷ 6 kV differences between the cage and ring electrodes at a residual gas pressure of $\sim 5 \cdot 10^{-5}$ Torr. A blue spot rising from the interaction of the thermo-ionic electrons with the phosphor P47 was clearly detected: it corresponds to a demagnified image of the tungsten wire (5:1) that changes size and position varying the FS polarization voltages. The first simulations indicate that a small shift (~ 2 mm) of the image can be ascribed to the tungsten wire magnetic field. Further tests with a MCP for electron amplification and lower wire currents (and therefore lower B-fields) and development of the frame grabber software for more quantitative measurements are in progress.

CONCLUSIONS

An innovative beam monitor based on secondary emission by a sub-micron thick foil for real time diagnostics in the extraction lines of a hadrontherapy centre has been constructed. A prototype, including thin foils, vacuum, focalisation and slow control systems, has been realised. Integration and laboratory tests are on progress: the preliminary results are qualitative, but promising. Test on hadron beams are foreseen by the end of 2003.

REFERENCES

- [1] U. Amaldi and B. Larsson (eds.), "Hadrontherapy in Oncology", Proceedings of the First International Symposium on Hadrontherapy, Como, Excerpta Medica, Elsevier International Congress Series 1077 (1994).
- [2] G. Molinari, CERN, private communication.
- [3] M. Pullia, TERA Foundation, private communication.
- [4] L. Badano et al., Proton-Ion Medical Machine Study – Part I, CERN/PS 99-010 (DI) (1999).
- [5] C. Fernandez-Figueroa, G. Molinari, Proceedings of the Third European Particle Accelerator Conference, EPAC92, Berlin (1992).
- [6] C. Chianelli et al., Nucl. Instr. and Meth. A237 (1988) 245.
- [7] R. W. Odom et al., Nucl. Instr. and Meth. B44 (1990).
- [8] J. Bosser et al., SPS/ABM/Note/87-06, CERN (1987).
- [9] A. Braem et al., Nucl. Instr. and Meth. A478 (2002) 400.
- [10] VA-SCM2, produced by IDEAs, www.ideas.no.
- [11] G. Deptuch et al., IEEE Trans. Nucl. Sci. 49 (2002) 601.
- [12] Hasselkamp D., Rothard H. et al., Particle Induced Electron Emission II, Springer-Verlag (1992) 63.
- [13] Abbot R.C., J. Appl. Phys. 30 (1959) 871.
- [14] Sternglass E.J., Phys. Rev. 108 (1957) 1.
- [15] Borovsky J.E., Nucl. Instr. and Meth. B36 (1989) 377.
- [16] David A. Dahl - SIMION 3D - Version 7.0 - Idaho National Engineering and Environmental Laboratory.
- [17] Illes P. Csorba, Image Tubes, Howard W. Sams (1985).
- [18] L. Badano, O. Ferrando, M. Pezzetta, Engineering Design Study for the SLIM Beam Monitor, SUCIMA Int. Note.