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FIRST RESULTS OF PEPITES
A NEW TRANSPARENT PROFILER BASED ON SECONDARY ELECTRON EMISSION FOR CHARGED PARTICLE BEAMS

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Abstract

The PEPITES project* consists of a brand new operational prototype of an ultra-thin and radiation-resistant profiler capable of continuous operation on mid-energy (O(100 MeV)) charged particle accelerators in the vacuum of the beamline. Secondary Electron Emission (SEE) is chosen for the signal because it requires a small amount of material and is very linear. The monitor is made of segmented electrodes (strips), generating the SEE signal when crossed by the beam. Signals from the strips are carried outside the beamline and are read by a dedicated low-noise and high-dynamic electronic. A demonstrator is installed at ARRONAX and has been successfully operated on a wide dynamic. Its permanent installation will allow a long-term feedback.

INTRODUCTION

Protontherapy dose delivery requires a continuous and accurate measurement of beam properties, intensity, position and profile during patient treatment. The beam monitors must be thin enough to limit the effects of scattering to a submillimeter lateral spread of the beam at the patient. For monitors located a few meters upstream of the patient, this translates into a material budget of less than 15 μm water equivalent thickness (WET). Good resistance to radiation is also necessary, as the long exposure time results in integrated doses of some 10^6 to 10^8 Gy per year.

To fulfil these requirements, PEPITES [1,2], a new type of transparent beam profiler (< 10 μm WET) has been developed. It equips the beam line of the ARRONAX cyclotron [3] and will be used daily to monitor the beam during radiobiological and preclinical experiments [4]. The profiler will measure the lateral beam shape in a broad range of energy (15 – 70 MeV) and a wide range of intensity (100 fA – 10 nA), for alpha, proton and deuteron particles.

PRINCIPLES

PEPITES uses secondary electron emission (SEE) for the signal as it requires only a minimal thickness of material (~10 nm); very linear, it also offers a great dynamic.

The SEE yield is proportional to the dE/dx of the beam particles [5,6] and is independent of the beam intensity up to current far beyond expected needs both for medical use and radiobiology needs. The lateral beam profile is sampled using segmented electrodes, constructed by thin film methods. Gold strips, as thin as the electrical conductivity allows (50 nm), are deposited on an as thin as possible insulating substrate which, in contrast with conventional systems like ionization chambers, are free from mechanical constraints and can be as thin as achievable. Polyimides (PI), such as Kapton® or CP1™, are chosen as polymer substrates because of their insulating properties and the presence of aromatic cycles in their structure that make them extremely resistant to radiation [7]. When crossing the gold, the beam ejects the electrons by SEE, the current thus formed in each strip allows the sampling.

The thinness of the monitor disturbs very little the incident beam, which can then be delivered to the patient while keeping the profiler in the line, ensuring continuous monitoring. Also, it makes the energy deposit very small allowing the monitor to tolerate higher currents than existing systems without suffering from overheating problems. Besides, the absence of mechanical efforts on the membranes makes radiation damages of less consequence than with classical systems like ionization chambers allowing to extend the operation duration of the system.

Detector Layout

The layout of the prototype is shown in Fig. 1. It consists of four electrodes: two segmented cathodes each facing an anode (with a 15 mm gap) biased at 100 V to ensure the collection of secondary electrons emitted by the strips. The four electrodes are made of 50 nm thick gold deposited by chemical vapor phase on polymer membranes: 32 strips for cathodes and fully metallized anodes. The membranes are made of 1.5 μm thick CP1™, a colorless polyimide produced by the NeXolve company[1]. Initially developed for

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solar sails, its availability in very small thickness make it a key aspect to meet the 10 µm WET budget.

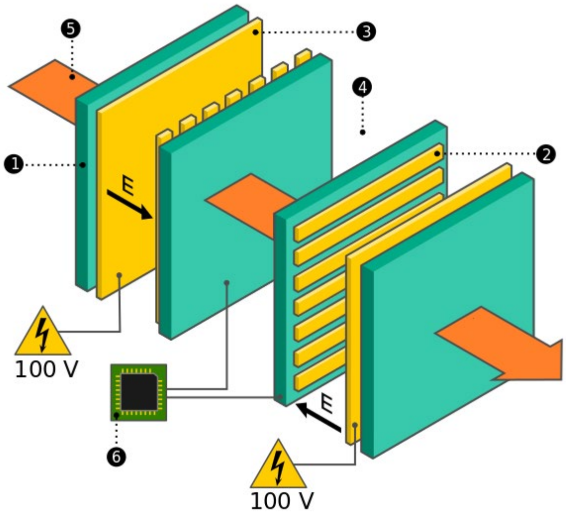

Figure 1: Schematic layout of PEPITES prototype. CP1^{TM} membranes (1) sustain 50 nm thick gold strips (2) or are fully metallized (3). They stand in vacuum (4) where the beam (5) crosses the strips and produces secondary electrons. The signals coming from each strip are read by a dedicated readout chip (6). The actual prototype is made of 32 strips cathodes (2).

The profiler is divided into two mechanically independent blocks for the measurements of the beam position and lateral shape in the two directions (X and Y). The signals from the strips can be rather low as resulting from SEE (about 10% yield) and spreading of the beam over several strips. A dedicated low-noise and high dynamic Application Specific Integrated Circuit (ASIC) has been developed at CEA. One ASIC per block reads each strip individually. The whole system operates in the vacuum of the beamline and can be put on and off the beam path by a translation movement device.

PROTOTYPE

Figure 2 shows the realization of the project. The sensitive area (golden part) is mounted on an arm, itself bound to a flange that ensures the vacuum-air interface. The strip plans are 70×70 mm, with 32 strips, as simulation shows this ensures an at least 1 mm precision on beam position and width. High quality thin connectors (2×32 cables) carry the signal from the strips through the flange, up to a connector, on the air side of the flange. On this picture, the BNC cables, for voltage application to the anodes, are also visible.

The SEE rate depends on the Z of the material. We chose to use gold as we targeted proton beam currents down to a fraction of pA. Gold is in addition easy to handle and does not oxidize (which would result in an alteration of SEE rate). To have strips and anodes conductive, the deposit must be at least 30 nm thick so that the metallic structure materializes; this is thick enough for the SEE. A 50 nm deposit is made for safety, which represents ~0.5 µm WET. The 1.5 µm CP1^{TM} corresponds to ~2.1 µm WET.

Figure 2: PEPITES sensitive area (gold) mounted on its support tool (see text).

The radiation tolerance of the system results from two sources: the intrinsic tolerance of the materials and the minimal mechanical stress applied to them. As a polyimide the CP1^{TM} has an excellent radiation tolerance compared to other thermoplastics such as Mylar or PEEK. Since no mechanical stress is applied to the films that are in the vacuum of the beamline, damage is of lesser consequence than in a stressful case, which is favorable with respect to detector lifetime.

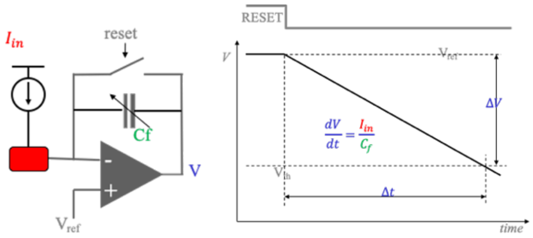

Figure 3: Current measurement principle used in the dedicated ASIC and based on a current to time conversion. Details are provided in the text.

The ASIC current measurement principle is illustrated on Fig. 3. The continuous signal current I_{in} charges the capacitance C_f making the output tension V to evolve at the rate $\mathrm{d}V/\mathrm{d}t = I_{in}/C_f$. The time Δt needed to range the predefined tension interval ΔV is then proportional to I_{in} -which provides the measurement- and inversely proportional to C_f

-which is used to define several gains of the system using a programmable capacitance.

The complete system is installed on site, the beam line AX3, at ARRONAX (Fig. 4). A vacuum chamber is mounted on the beamline and a translation system allows the sensitive area to be moved in or out the beam path. On this picture, PEPITES is in the "in beam" position. The sensitive area (Fig. 2) is visible through the vacuum chamber porthole. At the top of the flange, the readout system is visible as a metal box.

Figure 4: Complete system on AX3 beamline in ARRONAX.

Studies of the material tolerance to radiation and associated damage have been carried out to anticipate the detector lifetime and identify possible weaknesses: with gammas from ^{137}Cs and 68 MeV protons at ARRONAX [8], 2 MeV and 160 keV protons at CSNSM ("Centre de Sciences Nucléaires et de Sciences de la Matière", IJCLab, Orsay, France), and 2 MeV electrons at LSI ("Laboratoire des Solides Irradiés", Ecole polytechnique, Palaiseau, France). None of them showed significant defects of the sensitive parts of the detector and could not call into question the principle of operation of the PEPITES detector in the long term [1,8].

A more stringent test for CP1^{TM} was performed on samples with gold strips, irradiated in air at ARRONAX with a 300 nA and 68 MeV proton beam for ~2.5 h. Around a 10^{16} H^+/cm^2 fluence, the CP1^{TM} became fragile (samples were not destroyed but became sensitive to direct contacts). The estimated dose in CP1^{TM} was 2×10^7 Gy. It is interesting to note that similar strip plans tolerated much larger doses with 2 MeV electrons at LSI (up to 10^8 Gy with no effect, and 10^9 Gy with CP1^{TM} becoming fragile) and 2 MeV and 160 keV proton at CSNSM (10^8 Gy, with no effect), with the irradiations done with the samples in vacuum. There could be two possible interpretations (which are not mutually exclusive): one concerns the presence of nuclear interactions formed in the 68 MeV proton irradiations, generating fragments with high LET, and the other the damage increased by chemical reactions in the air.

Finally, a study of irradiation on material aging was carried out. In order to mimic the standard operating conditions of the detector, a sample was mounted on a Faraday cup (in the vacuum of the beam line) and moved in and out of the beam. The sample received O(10^{17}) protons for a dose of O(10^8) Gy, including a high intensity period of ~45 s at O(6 µA), and no noticeable degradations was observed.

RESULTS

The prototype has measured its firsts beams at the end of May 2022 and has been able to operate smoothly the monitor with proton beams from 1 pA to 20 nA. Beam spots can be seen on Fig. 5, where the measured signal current peaks at 35 fA for the 1 pA beam.

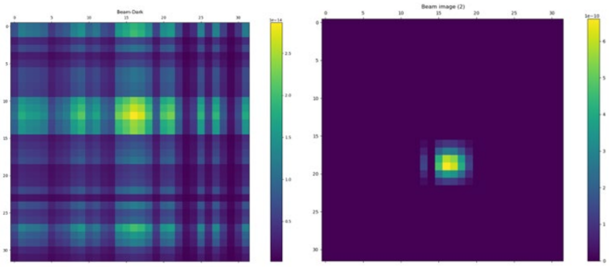

Figure 5: Profile current 1 pA (left) and 20 pA (right).

Taking advantage of the vertical translation capability we made repetitive measurements of the same beam (I_{beam} ~500 pA), shifting the detector vertically with a step equal to the width of one strip (1.95 mm) each time. All spectra were identical on vertical strips (Fig. 6, right), demonstrating the uniformity of signal emission, and identical modulo the displacement on the horizontal strips (Fig. 6, left), as it should be.

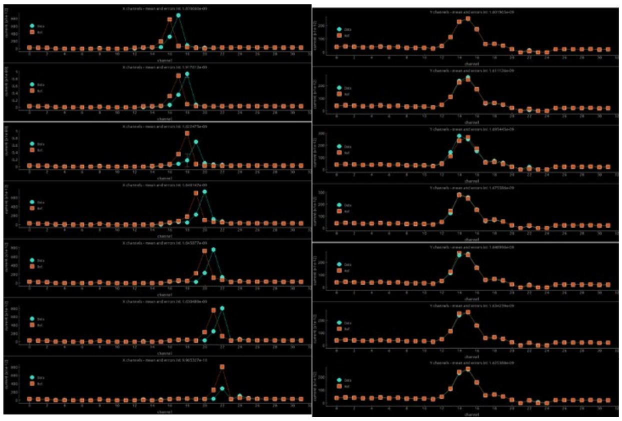

Figure 6: Horizontal strips (left) and vertical strips (right) current during vertical scan. The difference between two consecutive lines corresponds to a vertical movement of PEPITES with regard to the beam axis, with a step equal to

the strip width. On each line are also displayed the measured current (green) and the current at the position before this measurement (red).

We verified the detector WET by two means. In the first one, we measured in air the energy loss of 5.593 MeV alpha particles from a ^{238}Pu source flying through one or two metallized planes. The water equivalent loss is estimated using SRIM and is found to be 1.6 – 1.9 µm per plan (the uncertainty being related to the imprecision on the air segment lengths travelled by alphas on the setup). This is lower than then expected thickness, ~2.5 µm WET, obtained by calculation. A second, more preliminary measurement shows that the proton beam width at the beamline exit (~60 cm from PEPITES) increases by 0.13 mm when inserting PEPITES in the beam path.

CONCLUSIONS

We built and installed at ARRONAX a new type of beam profiler, PEPITES, using secondary electron emission. Built with thin film techniques and using very thin materials, the detector has a WET of less than 10 µm. The radioresistance of the materials has been investigated by several means and show that the detector should withstand several years of operation at ARRONAX as well as in medical protontherapy centers, if the monitor is adopted there. First measurements occurred with 68 MeV proton under various beam conditions. The prototype ran smoothly with 1 pA to 20 nA beams and has shown excellent behavior. The project is now entering a feedback phase which will be acquired at ARRONAX with frequent use of the system.

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