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DEVELOPMENT OF A TRANSPARENT PROFILER BASED ON SECONDARY ELECTRONS EMISSION FOR CHARGED PARTICLE BEAMS

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Abstract

The PEPITES[1] project aims at realizing an operational prototype of an ultra-thin, radiation-resistant profiler able to permanently operate on mid-energy (O (100 MeV)) charged particle accelerators. Initially motivated by the needs of protontherapy, the proposed development may have a range of applications that is well beyond the foreseen framework.

INTRODUCTION

Beam profiling during patient treatment in hadrontherapy requires ultra-thin monitors to preserve the high beam quality. For detectors upstream in the line, a material budget as low as ~15 µm water-equivalent is needed. Besides, the current trend of dose escalation to treat highly resistant tumors implies challenging requirements to the monitor in terms of radiation hardness and dynamic range.

To fulfil these requirements, PEPITES, a new type of transparent beam profiler (< 10 µm water-equivalent thickness (WET)) is under development. It will equip the beam line of the ARRONAX cyclotron [1] and will be used daily to monitor the beam during radiobiological and preclinical experiments [2]. 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 [3, 4] 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. Aromatic polyimides (PI), such as Kapton® or CP1™, are chosen as polymer substrate due to their insulating properties and resistance to radiation [5]. 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.

Prototype Layout

The layout of the prototype is shown in Fig. 1. It will consist of four electrodes: two segmented cathodes each facing an anode (with a 15 mm gap) biased at 100V 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 developed by the NeXolve company [6]. Initially developed for solar sails, its availability in very small thickness and the presence of aromatic cycles in its structure, thus making it extremely resistant to radiation, make it an element of choice for the construction of the detector.

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 the strips. A dedicated low-noise Application Specific Integrated Circuit (ASIC) chip being developed at CEA

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will read independently each strip present on each of the two blocks. The whole system will operate in the vacuum of the beam line and will be put online and offline by a translation movement device.

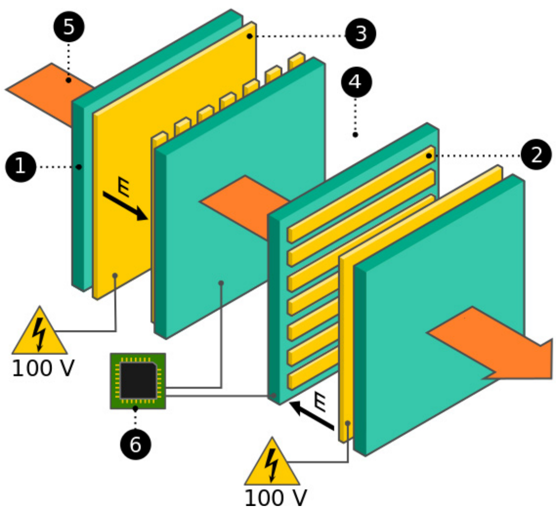

Figure 1: Schematic layout of PEPITES prototype. CP1™ membranes (1) sustain 50 nm thick gold strips (2) or are fully metallized (3). They stand in vacuum (4) where the beam (5) crosses the strips and produce secondary electrons. The signals coming from each strip are read by a dedicated readout chip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

BEAM TESTS AND RESULTS

The technique was validated at ARRONAX with 68 MeV proton beams for intensities from 100 fA to 10 nA [7]. SEE is being characterized up to 100 nA at ARRONAX and medical energies (70-230 MeV) at Orsay Protontherapy Center (CPO – Institut Curie).

Several irradiation campaigns were conducted to assess the radiation resistance of the various materials and components of the detector. We undertook to irradiate several samples with gold strips on CP1™. The irradiations were done with the samples in vacuum, to mimic the real conditions of the final monitor.

Doses of 10^8 Gy and 10^9 Gy were delivered at LSI (“Laboratoire des Solides Irradiés”, Ecole polytechnique) with 2 MeV electrons beams with current up to 25 µA, irradiating a surface of 1 cm of diameter on the sample. For the highest dose, the irradiation duration was 25 hours. Only the sample receiving the highest dose showed a light brown coloration of the CP1™ side without geometrical distortion of the sample. That observed effect is far to impact the integrity of the system, meaning that even higher doses could be tolerated.

We irradiated two samples at the CSNSM (“Centre de Sciences Nucléaires et de Sciences de la Matière”, Orsay, France): one received a 10^8 Gy dose with 2 MeV protons, with a beam current of 100 nA during 90 minutes on a surface of about 1 cm^2, and a second was irradiated with 200 keV protons entering from the CP1™ side, so that protons stopped at the CP1™-gold interface in order to stress this interface to eventually favor gold delamination. In this context, where protons can stop into the material, nuclear recoil effects become important. Such effect should be rather aggressive on the material structure, displacing atoms, and would then mimic nuclear interaction effects that would also break the structure by destroying atoms. As a result, no significant effect was seen on the two irradiated samples.

Potential radiation induced permanent damages on polymeric substrates were specifically studied at ARRONAX [8]. Kapton® was considered on a first step and irradiated with 68 MeV proton beams. Both dynamics and permanent damages were observed and characterized using UV-Vis spectroscopy and scanning electron microscope. The permanent damages have occurred due to the irradiation with a high level of fluency (~7×10^{15} H^+/cm^2). Nevertheless, it should be noted that this high fluency level corresponds to several years of detector radiations exposure in a proton therapy center and opens the possibility to operate the PEPITES detector on a long-term basis. The next step is to characterize the damage of an irradiated CP1™ membrane with and without a deposited nanometric gold layer. The conductivity measurements will also be performed during and after irradiation. It will provide crucial information concerning the impact of the electrical properties evolution of CP1™ on the PEPITES detector performance.

FUTURE AND PLANS

Additional studies will be conducted on potential radiation induced damages on CP1™ at very high doses.

A demonstrator with dedicated electronics will be installed at ARRONAX and used routinely. It will be placed at the end of the beam line and will require an adaptation of this line in order to accommodate the detector. The performances of the system and its behavior over time will thus be characterized.

CONCLUSIONS

We propose a new type of beam profiler, PEPITES, using secondary electron emission. Build with thin film techniques and using very thin materials, the detector has WET of less than 10 µm. Studies of radiation induced damages have shown than the detector integrity will remain up to dose far beyond the medical yearly needs.

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