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PEPITES: AN ULTRA-THIN BEAM PROFILER WITH WIDE DYNAMIC RANGE FOR CHARGED PARTICLE BEAMS *

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Abstract

PEPITES is an ultra-thin profiler with wide dynamics range for charged particle beams. Secondary Electron Emission (SEE) is used for its signal, which provides these assets. A first, 10 µm Water Equivalent Thickness (WET), monitor has been permanently installed at ARRONAX, Saint-Herblain, France, in May 2022. It is used in routine operations with continuous and "FLASH" beams, the latter referring to a promising radiotherapy modality based on short and intense pulses. A second profiler is developed with CNAO, Pavia, Italy, in view of being integrated in the beam control protocol for conventional patient irradiation. The monitor is foreseen 6.5 m upstream the patient, contraining its material budget to a few µm WET, to maintain the beam dispersion at a tolerable level.

Researches on the FLASH modality explore irradiation durations from O(100 ms) down to O(10 fs), for a same delivered dose. The intense beams used challenge the beam instrumentation, calling for innovation in the domain.

This contribution presents results on PEPITES at ARRONAX, the development for the CNAO version, and a series of measurements to assess the viability of the SEE signal for µs down to 10 fs long beams.

PEPITES DETECTOR PRINCIPLE

SEE occurs near the surface of materials when a charged particle generates ionisation electrons that escape from the volume. If emitted in vacuum, these low energy electrons can travel away, which, in a metal, generates an electrical signal. Only the O(10 nm) closest to the surface contribute to SEE, which, augmented to at least 30 nm for a metal to make it conductive, allows for ultra-thin electrode design. SEE is in addition a very linear phenomenon.

Figure 1 a) illustrates the PEPITES detection principle. Gold is chosen for the strips as it is a good electron emitter and is easy to handle. Thin films techniques are used to construct the sensitive area electrodes. Their versatility allows for many monitor variants, beyond the simple strip pattern used here. As the monitor operates in vacuum, the membranes are free from mechanical stress, which is favorable to the detector lifetime. In addition, the membranes are made of CP1™, which, as a polyimide, has a good resistance to radiation [1]. These plans have shown to withstand up to 10^9 Gy with electron irradiation [2].

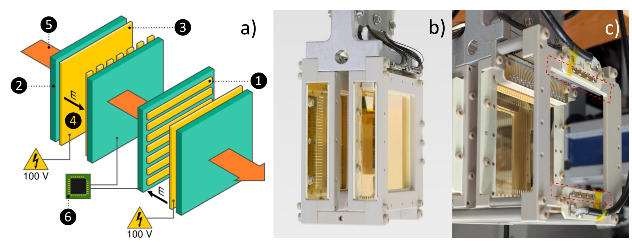

Figure 1: a) Schematic representation of the sensitive area: ❶ 50 nm thick gold strips are deposited on a ❷ 1.5 µm polyimide membrane; the beam profile along X and Y axes by plans with vertical and horizontal strips, respectively; ❸ an anode is made of a fully golden membrane facing the trip plane, ❹ a positive bias voltage is applied to collect the emitted electrons. When the ❺ beam crosses the monitor, secondary electrons leave the crossed strips, the related generated currents are read individually by ❻ a dedicated low noise electronic. Picture b) shows the sensitive area as built for ARRONAX. There are 32 strips, 1.9 mm wide, with a 0.35 mm inter-strip gap. The sensitive area is about 7×7 cm^2 large and has a 10 µm WET. Picture c) shows one anode of the modified sensitive area as tested at CNAO to reduce to 5 µm WET the amount of material crossed by the beam: the "in-axis" anodes of a) are replaced by metallic bars (indicated by the dashed red lines) that are put "off-axis". The collection electric field is hence not parallel and not uniform anymore, the effect of which is discussed in the text.

PEPITES AT ARRONAX

The sensitive area built for the monitor installed at ARRONAX is shown on Fig. 1 b). The beam is sampled along the X(Y) direction by one plan with vertical(horizontal)

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strips. A dedicated low-noise electronic[1] ASIC was developed for reading the strip currents. Figure 2 a) shows the PEPITES monitor installed on the AX3 ARRONAX beam line. Beam profiles from 1 pA to 20 nA with 68 proton continuous beams are shown in [2].

In the recent years, ARRONAX has developed a FLASH beam production capacity to respond to the high research demand on the topic. The PEPITES readout is fast enough to perform current measurements of pulses longer than O(1 ms). Figure 3 shows a measurement of a 10 ms FLASH pulse. Shorter FLASH beam measurements are planned.

The O(pA) to O(10 µA) beams were measured with the same PEPITES setup, demonstrating its high dynamic range.

PEPITES DEVELOPMENT FOR CNAO

The CNAO is treating patients with proton (62 – 227 MeV) and carbon (115 – 399 MeV/u) ion beams and, in the continuous process of improving the protocol of the beam control, is interested in a distant monitor, 6.5 m upstream the patient. High energy carbons ion beams would suffer little dispersion with a same monitor than the ARRONAX one, but it would be too thick for the low energy carbons and most of the protons. The current approach is to reduce the sensitive area WET by a factor 2, by removing the anode plans from the beam axis, replacing them by simple metallic bars off the beam axis, as shown on Fig. 1 c). The lower WET is hence obtained at the cost of moving to a non-parallel and non-uniform collection electric field.

A “PEPITES NOMAD” system, Fig. 2 b), is used to take data at CNAO. It is originally a copy of the ARRONAX one, including the readout electronic.

Figure 4 shows a comparison of profiles obtained with the original sensitive area and with the modified one, for various applied anode voltages. For the lowest ones, we see that the central peak is lower than with the highest tensions, and that some “undershoots” on both side of the peak are formed. These correspond to currents with an opposite polarity than the signal one, hence, electrons moving towards the strips instead of leaving them. We can interpret this as signal electrons from the central part not finding a field strong enough to reach the anode and going back on neighbour strips. This effect almost disappears for higher voltages. Numerically, the measured profile positions are found nearly identical between the two setups, while the RMS are wider by 0.5–1.0 mm with the off axis anodes system. More details can be found in [3].

GOING TO ULTRA-HIGH DOSE RATE

The “FLASH modality” is a novel approach in radiotherapy and has become a subject of intense research. It is observed that delivering in a fraction of second the same dose than conventional minutes-long irradiation spares better healthy tissues while remaining as active on tumor ones. The irradiation times studied range in the very wide O(100 ms) to O(10 fs) domain, while the charges involved remain grossly the same. The short and intense pulses are challenging the usual beam instrumentation, preventing the usage of online systems in many cases, calling for new solutions.

In the previous section and Fig. 3 we showed that PEPITES can withstand O(ms) FLASH beams. We present here a preliminary assessment of using SEE as a signal for moderately short (O(µs)) and intense (O(mA)) beams up to ultra-short (O(10 fs)) and ultra-intense ones (O(10 kA)).

We produced a simple system composed of a vacuum chamber hosting two parallel plans, each made, as before, of a 50 nm thick gold layer deposited on a 1.5 µm CP1™ membrane, itself mounted on a 7×7 cm^2 plastic frame. The golden faces of the plans face each other; one plan is the emitter and is grounded (through the readout apparatus, a commercial electrometer), the other is applied a positive voltage to create a parallel electric field and to collect the emitted electrons. The gap between the two plans can be

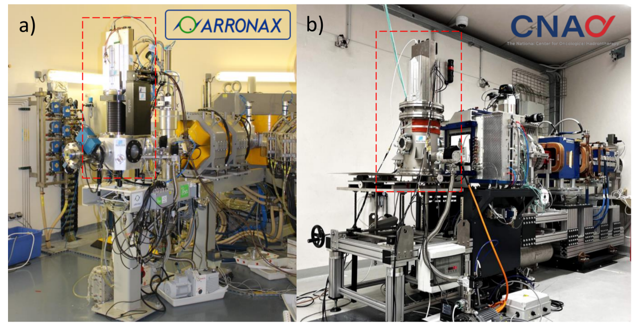

Figure 2: Picture a) shows the PEPITES monitor installed permanently on the AX3 beam line at ARRONAX. A translation stage, driven by a linear actuator (black part), allows the monitor to be positioned in or out of the beam. In the working position, the monitor is inside the vacuum chamber, at the bottom. The readout electronic is hosted inside the metallic box, at the top of the system. Picture b) shows the “PEPITES NOMAD” system: an standalone vacuum chamber hosts in a fixed position a copy of the PEPITES monitor used at ARRONAX. The beam enters the chamber through a 250 µm polyimide window and exits it through a second one. This system is for now used at CNAO for developments presented in the text.

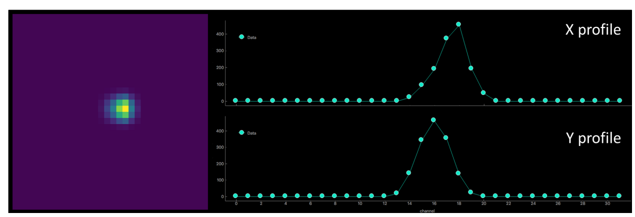

Figure 3: FLASH beam profile obtained with the PEPITES monitor installed at ARRONAX with 68 MeV protons. The beam is 10 ms long with a 10 µA current. The two 32 channels profiles are measured (right), they peak at about 400 nA; the 2D profile (left) is reconstructed as geometrical mean of the two 1D profiles.

[1] For a O(1 cm^2) beam of 1 pA spread over several strips, and with a typical SEE rate of 10 % for protons, strip currents can be as low as O(10 fA).

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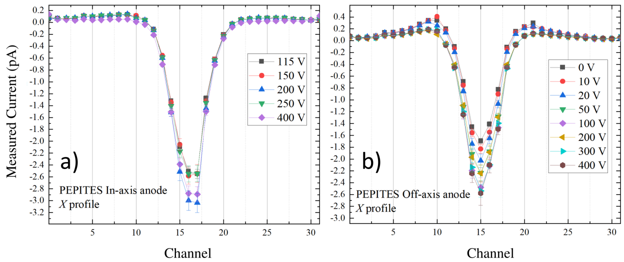

Figure 4: Comparison of beam profiles obtained with 115 MeV/u carbon ions at CNAO: a) reference profile obtained with a sensitive area as in Fig. 1 b), with a parallel and uniform collection electric field for several applied tensions, and b) profiles obtained with the modified, off-axis anode (Fig. 1, c)) with lower WET but non-parallel and non-uniform electric field, for several applied voltages. (The slight shift between the maxima of the two profiles is due to a small displacement of the vacuum chamber which happened during the manual operations to change the anodes; this same shift is consistently seen on all X profiles we measured.). The shape variations are discussed in the text.

changed in order to modify the electric field and/or give some handle on possible geometrical effects that could lead, for example, to space charge problems.

A 1 kV/cm electric field was applied (either with a 1 cm or 5 mm gap) in the measurements presented here. The field strength changes only slightly the signal, provided this field is strong enough. We took electron beam data at three sites: 1) Institut Curie, in Orsay, on the same site than the Centre de Protonthérapie d'Orsay (CPO), using the commercial ElectronFlash™ machine with 1 µs and O(440) pC pulses, 2) ELYSE, in Orsay too, at the "Institut de Chimie Physique" in "Université Paris-Saclay", with 10 ps pulses, and charge varying from 100 pC to 1000 pC, and 3) LOA, in Palaiseau, in the "Yellow Room" with the "ZITA" chamber producing O(30 fs) pulses by laser-plasma acceleration, with a charge of a fraction of nC. The energy are respectively 7 MeV, 8.3 MeV and a broad spectrum from O(20) MeV to O(200) MeV that varies somewhat shot per shot.

Figure 5 shows the SEE rate as function of the beam charge density. A strong SEE suppression is observed with increasing charge densities, the physical reason of which being to be understood. Space charge in the gap is not a convincing hypothesis as even a large change of applied collection electric field has marginal effect. This suppression looks hence happening in the emission region itself.

More data points are desirable to cover the large gaps in this figure. These would be important in particular to see if several regimes may exist. For example, we may expect a regime in which the SEE rate remains constant for beam charge density low enough, followed by an other one with a decay of the rate: in the first regime, the monitor response would be linear, while in the second one, tailored calibrations and corrections per beam charge density ranges, would be needed to partly overcome the non-linear response.

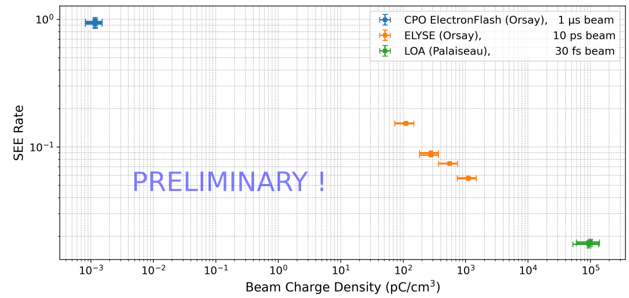

Figure 5: Measured SEE rate, Q_{SEE}/Q_{beam}, as function of beam charge density, Q_{beam}/V_{beam}, with $V_{beam} = S_{beam} \times (c \cdot T_{beam})$, and where Q_{SEE} is the measured SEE charge, Q_{beam} the incident beam charge, V_{beam}, the beam volume, S_{beam} its transverse section, and T_{beam} its duration, indicated in the legend. Each of these experimental quantities is attributed an uncertainty, and the overall errors are further scaled by a 1.5 factor to account for beam inhomegeneity. Several measurements were performed at each density: they largely overlap, showing a good repeatability of the technique. These results are preliminary.

We can nevertheless point that SEE provides a response in a very wide range of beam density, making it a process to consider for the signal of beam monitors to be operated online in very challenging beam conditions.

CONCLUSION

The PEPITES monitor and subsequent versions benefit for the SEE properties allowing both ultra-thin and high dynamic range monitors. Reducing the WET is still possible by modifying the geometry; further options, not presented here, like changing the support membranes can be considered too. FLASH beams can already be measured with the existing PEPITES monitors in the O(ms) range. Beyond this, SEE enters in a non-linear regime, the exact point where this is happening being to be determined. But exploiting an SEE signal in these challenging domains may still be possible for designing online ultra-thin beam profilers.

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