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PRAGUE (PROTON RANGE MEASUREMENT USING SILICON CARBIDE): A DETECTOR TO MEASURE ONLINE THE PROTON BEAM RANGE WITH LASER-DRIVEN PROTON BEAMS

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Abstract

Laser-driven proton beams are characterized by very high intensities per pulse with a very short duration, extremely high dose rates, and broad energy spectra. These specific features do not allow the use of the conventional dosimeters typically suggested by the international dosimetry protocols for conventional proton beams. Precise dosimetry for laser-accelerated protons is an ambitious task as well as a crucial prerequisite for successful radiobiological experiments. We will present the work done within the PRAGUE project funded by the H2020 in the framework of the MSCA-IF IV program and by the INFN. The main goal of PRAGUE was the design, simulation, realization, and characterization of a real-time depth-dose distribution detector system based on thin Silicon Carbide multilayers for conventional and laser-accelerated proton beams in the energy range between 30 MeV to 150 MeV. The detector developed was designed to work at the regime of extremely high dose rate beams and it allows the retrieval of real-time and shot-to-shot depth dose distributions with a high spatial resolution thanks to the development and use of a 10 μm, fully depleted 15x15 mm^2 square SiC detector. Potentially this newly developed detector could enable new detector technology capable of providing online information of dose delivered at a biological sample with a laser-driven proton beam.

INTRODUCTION

In the last decades, ion acceleration from laser-plasma interaction has become a popular topic for multidisciplinary applications and opened new scenarios in the protontherapy framework, representing a possible future alternative to classic acceleration schema. The high-intensity dose rate regime that can be obtained with this approach is also strongly attracting the radiation oncologist community thanks to the evident reduction of the normal tissue complication probability [1].

The new field of laser-plasma accelerators is rapidly evolving thanks to the continuing development of high-power laser systems, thus allowing to investigate the interaction of ultrahigh laser intensities (>10^{19} W/cm^2) with matter. As a result of such interaction, extremely high electric and magnetic fields are generated (>100 GeV/cm) that are allow particle acceleration at relativistic energies [2]. Many laser facilities carried out experiments on ion acceleration, exploring different regimes of laser interaction with a variety of targets, which gave rise to the proton beam with the energy of about 100 MeV from nm-scale foils of solid density.

One of the many challenges to bring laser acceleration to a clinical setting consists in the development techniques and technologies that allow for accurate dosimetry of a short and intense ion bunch length. In comparison with conventional accelerators, dosimetry of laser-accelerated beams is an ambitious task. Conventional accelerators typically operate at quasi-continuous milliampere currents rather than proton bunches with a temporal structure of the order of nanoseconds.

Laser-driven ion beams are typically characterized by very high intensities per pulse with a very short duration (10^{10} protons in 1ns), extremely high dose rates (10 MGy/min) and broad energy spectra (40%). These specific features do not allow the use of the conventional dosimeters typically suggested by the international dosimetry protocols for conventional proton beams. Precise dosimetry for laser-accelerated protons is an ambitious task as well as a crucial prerequisite for successful radiobiological experiments. At today the percentage depth-dose (PDD) distribution, is only measured by using passive detectors (e.g. CR39 or radiochromic films) and scintillator detectors in stack configuration [3]. If multiple films are stacked, each of them records the deposited energy and thus an energy-resolved measurement is possible. However, radiochromic films exhibit a dependence on LET and don't allow an online measurement. A temptative has been done in using scintillator-based detectors [4]. Scintillator foils can spatially resolve the transverse profile of a laser-driven proton beam but are affected by radiation damage contemporary showing a dependence on incident particle energy.

The aim of PRAGUE (Proton RAnGe measure Using silicon carbidE) project is to design and construct a detector, based on a new generation of Silicon Carbide (or SiC) devices, to measure proton depth-dose distributions in real-time and with high spatial resolution (10 μm). The extreme radiation hardness of such devices and the independence of their response with the proton beam energy [5], makes them capable to operate with conventional clinical hadrontherapy beams as well as laser-driven ion beams, where extremely high dose rates are delivered. The PRAGUE project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 871161 and in the framework of the Marie Sklodowska-Curie Individual Fellowship 2019 program. The project was also funded by INFN in the young researchers grant in 2020.

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PRAGUE PROJECT

The main goal of the PRAGUE project is the design, realization and characterization of a real-time depth-dose distribution detector system based on thin SiC multilayers for conventional and laser-accelerated proton beams in the energy range between 30 MeV to 150 MeV. PRAGUE targets mainly to high dose rate protons beams and will profit from a properly designed detector with one of the hardest materials present in nature: the Silicon Carbide [6]. Table 1 lists the main physical properties of Silicon Carbide, Silicon and Diamond at room temperature. Among the tabulated properties, some make SiC a very singular material with respect to Si, such as its three times wider bandgap, the three times higher thermal conductivity, and ten times higher breakdown electric field strength. As respect to the Diamond, the SiC exhibit a higher amount of produced charge and a fast response time.

Table 1: Summary of the Silicon Carbide, Silicon and Diamond material properties

Properties	Diamond	Silicon	4H-Silicon Carbide
Energy Gap [eV]	5.45	1.12	3.26
Hole lifetime	10^{-9}	$2.5*10^{-3}$	$6*10^{-7}$
Relative dielectric costant	5.7	11.9	9.7
e-h pair energy [eV]	13	3.62	7.78
Density [gr/cm^3]	3.52	2.33	3.21
Thermal condicivity [W/cm °C]	20	1.5	3-5
Electron mobility [cm^2/Vs]	1800-2200	1400-1500	800-1000
Hole mobility [cm^2/Vs]	1200-1600	450-600	100-115
Breakdown electric field [MV/cm]	10	0.2-0.3	2.2-4.0
Max working temperature [°C]	1100	300	1240
Displacement [eV]	43	13-20	25

Currently a real-time detector based on solid-state technology to measure the PDD distribution and the particle energy spectra of laser-driven ion beams doesn't exist.

The device working principle is simple: a charged particle crossing the PRAGUE detectors will release energy and the collected charge in each layer will increase with depth up to the Bragg peak position; the depth-dose-distribution, the incident particle spectra, and the particle range will be reconstructed based on the measured charge.

An appropriate calibration procedure will allow obtaining the relative dose distribution and consequently, with the proper correction factor, the released absolute dose.

A preliminary sketch of the assembled detector is reported in Fig. 1.

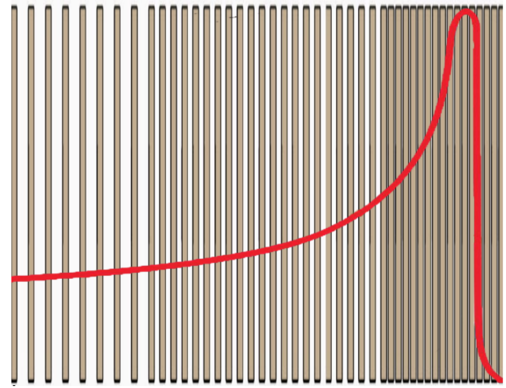

Figure 1: Preliminary sketch of the assembled detector.

The dedicated electronic read-out, based on charge integrator amplifier will allow a proper operation with both conventional and laser-accelerated beams. Charged collected in each detector will be connected to a read-out system based on 60 current-voltage converters directly connected to the cathode.

ADOPTED SIC DETECTORS

The SiC wafers needed for the device's production will be obtained starting from a growth of 10 µm 4H-epitaxial layers on a commercial four inches (400 µm thick) wafers by means of the Chemical Vapor Deposition process. During such phase dopants are provided for p and n-type doping to realize p-n junction devices. Such processes will be performed in a low-pressure regime at high temperatures (1630 °C). Wafers will be subsequently treated with several photolithographic steps to implement the prototypes. The first lithography for the definition of the detector area by Inductive Coupled Plasma etching will be performed. Then, the second lithography will be performed to define the edge structures. The process continues with the deposition of an isolation oxide and the opening of the contacts with a further lithographic process and consequently annealed to contact the p+ region. Only on the periphery of the detector a thicker layer of Ti and Al will be deposited for the bonding. Finally, the ohmic contact will be formed by Titanium/Nickel/Gold deposition.

A sketch of the detector that will be adopted for the reconstruction of the Bragg peak curve is shown in Fig. 2. It has a 0.3 µm thick p-layer with a doping concentration $N_A=1\cdot10^{19}cm^{-3}$ and a 10 µm thick n-layer with a doping concentration $N_D = 0.5 - 1 \cdot 10^{14}$ cm^{-3}. The detector has an active area of about 15 x 15 mm^2 and was mounted on PCB board designed to be housed in an aluminum box. A substrate of 100 µm thick with a doping concentration $N_D > 10^{18}$ cm^{-3} is placed close to the active layer. The depletion voltage of the device is about 10 V.

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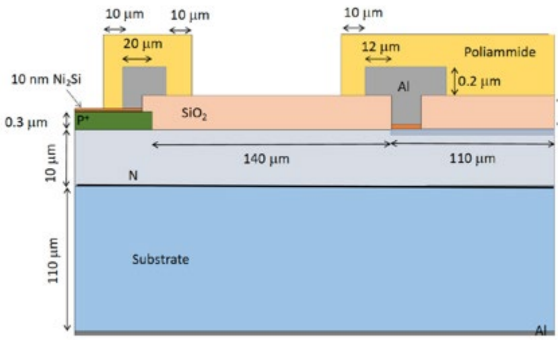

Figure 2: Layout of 10 µm SiC devices.

ELECTRONIC READ OUT

The electronic chain of the entire detector will be based on the charge integrator chip TERA commercialized by the DET.EC.TOR. company [7]. The TERA08 chip hosts 64 identical channels integrated in a 4.5mm x 4.5mm die and is designed in the CMOS AMS 0.35 um technology. In each channel, a conversion from the instantaneous current to a digital pulse frequency is performed, where each digital pulse corresponds to a fixed input charge quantum. To have a wide dynamic range, the ASIC architecture is based on a current frequency converter, followed by a 32-bit synchronous up/down digital counter. Using these elements, the charge can be measured by counting the number of pulses from the converter. Therefore, the circuit output is digital counts/channel. In Fig. 3 the entire chip is shown.

Figure 3: Front side of the TERA08 chip mounted on the electronic board.

PROJECT IMPACT

PRAGUE has the potential to radically change the panorama of the current research in relative dosimetry with extreme intense dose rate proposing new detector technology capable of providing online information of dose delivered at a biological sample. At today the so-called FLASH radiotherapy (or radiotherapy at the high-dose rate) is attracting great attention in the radiation oncology community and it's considered the future of clinical radiotherapy. The reduction of the normal tissue complication probability associated with FLASH radiotherapy is very significant, and the potential clinical benefit very large. Nevertheless, the scientific community investigates the biological effects and the potentiality of this new strategy of treatment, the technology on the development of dosimetric devices is still not sufficiently precise to perform biological experiments. PRAGUE will provide the experimental information needed to drive the technical research and development of dosimetry for proton treatments in the future of FLASH radiotherapy. The proof of principle of SiC detector in the dosimetric application would expand the possibilities of developing devices based on this technology for space application and conventional clinical dosimetry. The proposed detector could also change the panorama of QA in conventional ion therapy providing a device with a limited time-consuming and high spatial resolution.

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