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Experimental studies with two novel silicon detectors for the development of time-of-flight spectrometry of laser-accelerated proton beams

Abstract

Laser-accelerated proton beams exhibit remarkably different beam characteristics as compared to conventionally accelerated ion beams. About 10^5 to 10^7 particles per MeV and nsr are accelerated quasi-instantaneously within about 1 ps. The resulting energy spectrum typically shows an exponentially decaying distribution. Our planned approach to determine the energy spectrum of the particles generated in each pulse is to exploit the time-of-flight (TOF) difference of protons with different kinetic energies at 1 m distance from the laser-target interaction. This requires fast and sensitive detectors. We therefore tested two prototype silicon detectors, developed at the Centre for Medical Radiation Physics at the University of Wollongong with a current amplifier, regarding their suitability for TOF-spectrometry in terms of sensitivity and timing properties. For the latter, we illuminated the detectors with short laser pulses, measured the signal current and compared it to the signal of a fast photodiode. The comparison revealed that the timing properties of both prototypes are not yet sufficient for our purpose. In contrast, our results regarding the detectors' sensitivity are promising. The lowest detectable proton flux at 10 MeV was found to be 25 protons per ns on the detector. With this sensitivity and with a smaller pixelation of the detectors, the timing properties can be improved for new prototypes, making them potential candidates for TOF-spectrometry of laser-accelerated particle beams.

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Experimental studies with two novel silicon detectors for the development of time-of-flight spectrometry of laser-accelerated proton beams

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Abstract. Laser-accelerated proton beams exhibit remarkably different beam characteristics as compared to conventionally accelerated ion beams. About 10^5 to 10^7 particles per MeV and msr are accelerated quasi-instantaneously within about 1 ps. The resulting energy spectrum typically shows an exponentially decaying distribution. Our planned approach to determine the energy spectrum of the particles generated in each pulse is to exploit the time-of-flight (TOF) difference of protons with different kinetic energies at 1 m distance from the laser-target interaction. This requires fast and sensitive detectors. We therefore tested two prototype silicon detectors, developed at the Centre for Medical Radiation Physics at the University of Wollongong with a current amplifier, regarding their suitability for TOF-spectrometry in terms of sensitivity and timing properties. For the latter, we illuminated the detectors with short laser pulses, measured the signal current and compared it to the signal of a fast photodiode. The comparison revealed that the timing properties of both prototypes are not yet sufficient for our purpose. In contrast, our results regarding the detectors' sensitivity are promising. The lowest detectable proton flux at 10 MeV was found to be 25 protons per ns on the detector. With this sensitivity and with a smaller pixelation of the detectors, the timing properties can be improved for new prototypes, making them potential candidates for TOF-spectrometry of laser-accelerated particle beams.

1. Introduction

With the advent of petawatt laser systems, laser-driven ion acceleration may become an alternative way of producing ions with energies relevant for radiation therapy or medical imaging [1]. However, characteristics of laser-accelerated particle beams are quite unique and remarkably different compared to conventionally accelerated particle beams. They typically exhibit high divergence, a small source size and a wide spectral bandwidth [2]. About 10^5 to 10^7 particles per MeV and msr, depending on the resulting kinetic energy are accelerated quasi-instantaneously within about 1 ps [3]. Due to relatively

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large shot-to-shot fluctuations in the energy spectrum and other physical properties of the ion bunch, a precise characterization of each particle pulse is required for practical applications. This information is often obtained using spectrometers based on electric or magnetic deflection. A convenient alternative would be to exploit the time-of-flight (TOF) difference of ions with different kinetic energies in order to measure the energy spectrum of the beam and its spatial distribution. A crucial requirement for this approach is fast and sensitive detectors, as well as broadband amplifiers and readout. The rise time of the detector determines the accuracy of the energy spectrum measurement, while the signal fall time of the system needs to be short ensuring that the low-energetic part of the proton spectrum can still be resolved and is not hidden in a saturated signal.

We tested two prototype silicon detectors, developed at the Centre for Medical Radiation Physics at the University of Wollongong regarding their suitability for TOF-spectrometry of laser-accelerated proton pulses. Our interest was to examine the timing properties and to estimate the lowest detectable proton number, since this puts a lower boundary for the size of pixelation.

2. Experimental setup

2.1. Detector prototypes

Two prototype silicon detectors were tested regarding their suitability for TOF measurements of laser-accelerated proton spectra. The first detector (“bridge detector”) is a pseudo-pixelated detector with a sensitive thickness of 10 μm . The total chip size is 3.6×4.1 mm and it consists of three segments, each with two arrays of small pixels connected in parallel in each array. The pixel size is $30 \times 30 \mu\text{m}^2$.

The sensitive thickness of the second detector (“thin detector”) is also 10 μm , but it was manufactured without supporting wafer. This makes it a potential candidate to be used in transmission mode to obtain the proton spectrum prior to an interaction with the final target for a specific application. Although the prototype we tested is not pixelated, segmentation of this detector in order to gain also spatial information about the proton spectrum, is foreseen.

2.2. Setup for the determination of the rise and fall times of the detectors

The timing properties of the prototype detectors were evaluated using short light pulses from the ATLAS Ti:Sapphire laser system at the Laboratory for Extreme Photonics (LEX Photonics) in Garching near Munich, Germany. The pulse duration at the detector position was well below 100 fs FWHM and it was centered at 795 nm wavelength. Several absorptive neutral density filters were placed prior to the detector, thus the pulse energy at the detector was in the order of tens of μJ .

Both detectors were reverse biased, assuring full depletion, and were coupled to a high-speed broadband current amplifier (*HSA-X-2-20, FEMTO, Germany*). The amplified signal was visualized in a fast oscilloscope with a bandwidth of 4 GHz (*WaveRunner 640Zi, Teledyne LeCroy, USA*), using the 50 Ω DC input. A commercial photodetector (*DET10A/M, Thorlabs, USA*) with a rise time of about 1 ns was used as a reference and for triggering the oscilloscope. It was placed adjacent to the detectors in order to measure the scattered laser pulses.

2.3. Setup for estimating the lowest detectable proton flux

The aim of this estimation is to judge whether the expected proton fluence from laser-acceleration at our facility will be sufficient to generate a signal in the detector which is well above noise level. We mimicked the energy deposition of a proton beam in the thin detector by illuminating it with short light pulses from a frequency-doubled Nd:YAG laser ($\lambda = 532$ nm). The pulse width was about 15 ns FWHM and the repetition rate was 10 Hz. We used the same setup as described in section 2.2. The laser intensity was then gradually reduced by adding absorptive neutral density filters until the measured photocurrent only scarcely exceeded the noise level. The current amplifier was then replaced by a charge sensitive pre-amplifier (*model PCP 5, FAST ComTec, Germany*), followed by a spectroscopy amplifier (*model 2021, Canberra Industries, USA*) and a multichannel analyzer (*MCA8000A, Amptek, USA*) which was connected to a PC. To avoid saturation when measuring the produced integral signal charge, we used an

additional neutral density filter which reduces the laser intensity by a factor of 100, as compared to the experiments using the current amplifier. Prior to the experiments at the Nd:YAG laser, we performed an energy calibration of the detector using a mixed alpha source, consisting of Am-241, Cm-244 and Pu-239.

2.4. Experimental setup at the Munich Tandem van-de-Graaf accelerator

First experiments with the thin detector have been performed at the Tandem van-de-Graaff accelerator of the Maier-Leibnitz-Laboratorium (MLL) in Garching. Protons were accelerated to an energy of 20 MeV. A chopper was used at the low energy side of the accelerator to obtain short pulses of about 120 ns. From the beam current which was measured using a Faraday Cup, we could estimate the proton flux on the detector. Within each pulse, the proton flux at the detector was about 6×10^3 protons/cm²/ns and could be reduced by a factor of 30 by using an additional attenuator. The proton energy could be lowered to around 14 MeV by placing a 1 mm thin aluminum plate between vacuum window and detector. We used the same amplifier and read-out as described in section 2.2.

3. Results and Discussion

3.1. Timing properties of the detector prototypes

The photocurrent measured with the photodiode is compared to the current measured by the bridge detector and the thin detector (figure 1). The high-frequency noise, which was induced by the electronics of the laser system, could only partially be suppressed. For the bridge detector, the signal rise time from 10% to 90% was found to be 0.42 ± 0.02 ns, which is comparable to the measured rise time of the fast photodiode. The time it took for the signal to recover from the 90% to the 10%-level was 2.88 ± 0.36 ns, which is slightly longer than for the photodiode. The relatively long tail of the signal decay can be attributed to electron-hole pairs created in the non-depleted silicon under the bridge connecting two adjacent pixels. Timing properties of the thin detector were found to be poorer. We measured a rise time of 2.76 ± 0.34 ns and a fall time around 20 ns.

For a reasonable accuracy of the TOF spectrometry of laser-accelerated proton pulses, sub-ns time resolution is required. This was achieved only by the bridge detector. However, its fall time is rather long which will result in a loss of sensitivity due to saturation, when it comes to the TOF spectrometry of the low-energetic part of proton energy spectra. Since we assume that the insufficient timing properties of the thin detector is mostly attributed to its capacitance, we are aiming to reduce it for the next prototype of the thin detector by pixelating it.

3.2. Estimation of the lowest detectable proton flux

Protons with a kinetic energy of 10 MeV will deposit on average 81 keV in the 10 μ m sensitive thickness of the detector [4]. According to the energy calibration using the mixed alpha source, the deposited energy in the thin detector was 0.3 MeV per laser pulse, i.e., the total deposited energy of a laser pulse which scarcely exceeds the noise level in current mode is 30 MeV. Since the laser pulse duration was 15 ns FWHM, the lowest detectable flux for 10 MeV protons is 25 protons per ns and sensitive detector area. For higher proton energies, the required proton flux slightly increases due to their lower energy deposition in the detector.

Realistic proton yields from laser acceleration experiments at 10 MeV are around 10^5 to 10^6 per MeV, msr and pulse [3]. In a distance of 1 m, which is a convenient drift space for TOF spectrometry at our facility, the resulting proton flux would thus range between 10^2 and 10^3 mm⁻² ns⁻¹. The expected proton flux is therefore sufficient to be detected when operating the thin detector in current mode. For the next prototype of this detector, segmentation is foreseen. Based on our investigations, a sensitive area of each segment of around 1 mm² is planned.

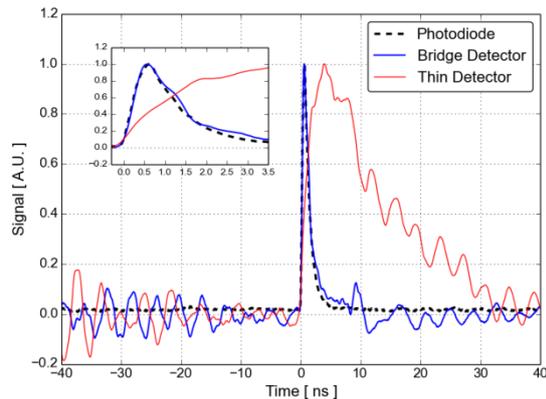


Figure 1. Photodiode signal compared to signal from bridge detector and thin detector. The inset shows a zoom in the time axis.

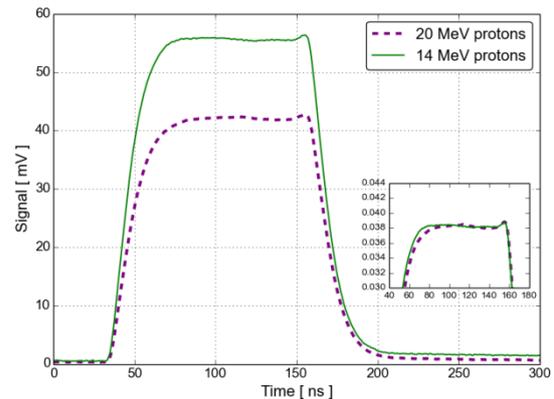


Figure 2. Current signal (converted to voltage) of mono-energetic proton pulses. In the inset, the signal is normalized by the proton number and the average energy deposition in 10 μm silicon for the respective proton energy.

3.3. Experiments at the Munich Tandem van-de-Graaf accelerator

In the experiments at the local Tandem accelerator we obtained a clear current signal for the attenuated proton pulses (figure 2), where according to beam current measurements, the fluence on the detector was around 200 protons per ns. The ratio of the signal height of proton pulses with 20 MeV and 14 MeV perfectly fits the ratio of the corresponding energy deposition in 10 μm silicon (inset in figure 2). In case of the non-attenuated proton beam with a fluence of around 6000 proton per ns, saturation of the detector could already be observed. However, no detailed study on the saturation limit has been performed so far. Yet, this problem can be solved by pixelation of the detector in the next prototypes.

4. Conclusion

We tested two prototype silicon detectors regarding their suitability for TOF-spectrometry of laser-accelerated proton beams in terms of timing properties and sensitivity. By using a broadband current amplifier and a fast oscilloscope the generated signal current in each detector was visualized.

According to our experiments, the timing properties of both detector prototypes are not yet sufficient for quantitative TOF-spectrometry. While the relatively long fall time of the bridge detector is attributed to its specific design, the long rise and fall times of the thin detector can most likely be improved by a lower capacitance. This can be achieved by pixelation, which will also increase the detector's saturation limit. On the other hand, from the signal height we could estimate that at 10 MeV at least 25 protons per ns on the detector are required to generate a signal that clearly exceeds the noise level. This hence gives a lower boundary for the pixel size.

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