LOW GAIN AVALANCHE DETECTOR APPLICATION FOR BEAM MONITORING

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Abstract

The Superconducting DArmstadt LINear ACcelerator (S-DALINAC) was constructed as a twice-recirculating electron accelerator. During the upgrade in 2015/2016 a third recirculation line as well as the option to operate the S-DALINAC in Energy recovery LINAC (ERL) mode were added. In order to optimize the beam during operation in ERL mode, it is important to provide a dedicated non-destructive beam monitoring system. A promising detector technology for this task is the low gain avalanche diode (LGAD), which is a novel silicon detector optimized for 4D-tracking, i.e. the simulataneous measurement of the particle's position and time with high spatial (< 100 µm) and timing (> = 30 ps) precision. In this contribution we present the results of a first proof-of-principle measurement utilizing LGAD technology for beam time structure monitoring at the S-DALINAC at the Technical University of Darmstadt, Germany, in the normal (non ERL) operation mode.

INTRODUCTION

Energy recovery LINAC (ERL) is a novel technique in electron beam acceleration [1]. In contrast to the normal operation mode, where the major part of the beam energy remains unused, the beam in ERL mode can be sent back to the accelerator with a phase shift of 180° resulting in a negative energy gain. Consequently, energy is put back into a radio frequency (RF) field of the accelerating cavity, which can be used for the acceleration of the next beam. Thus, ERL reduces the required RF power for the acceleration and allows to accelerate high current beams with higher energy in comparison to traditional LINACs.

The S-DALINAC [2] (Fig. 1) is a superconductive linear electron accelerator at TU Darmstadt, Germany. It was constructed as a twice-recirculating accelerator in continuous wave (cw) operation at 3 GHz. Since an upgrade with a third recirculating beam line in 2015/2016, it is possible to operate S-DALINAC as an ERL [1]. A one circulation ERL mode was successfully demonstrated in 2017 with efficiency $92.1^{+3.7}_{-13.9}\,\%$ [1]. In August 2021 S-DALINAC was successfully operated in twice recirculated ERL mode [3]. In this mode both once decelerated and once accelerated beams share the same beam line but have a different orbit, leading to a repetitive bunch rate of 6 GHz. In order to measure both beams simultaneously and to optimize the acceleration and deceleration process, a non-destructive beam monitoring system able to resolve this 6 GHz time structure, corresponding to 166 ps between the bunches, is required [4]. A promising detector technology that could potentially fulfil this task is the low gain avalanche diode (LGAD), which is a novel silicon detector optimized for 4D-tracking applications [5]. The high spatial granularity (< 100 µm) and excellent time resolution (< 50 ps [6]) of LGADs make an LGAD-based detector a promising candidate for beam time monitoring tool at the S-DALINAC.

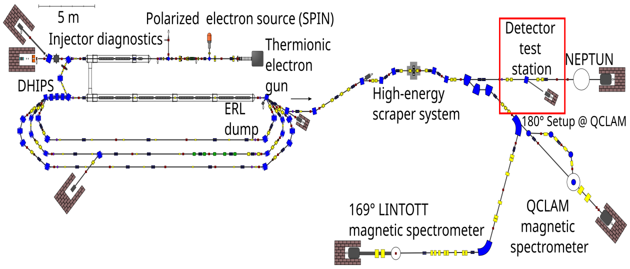

Figure 1: Layout of the S-DALINAC including experimental areas. The red rectangle represent the position of the experimental setup.

In October 2021, the first proof of principle measurement of an LGAD-based beam monitoring system was performed at the S-DALINAC. The main goal of this experiment was to resolve the beam time structure of an 85 MeV electron beam using an LGAD strip sensor. For this purpose, a simplified setup was prepared and placed in a dedicated test beam area (marked by the red square in Fig. 1) outside the recirculating beam lines. Since placing the detector outside the accelerator made it impossible to simultaneously monitor the accelerated and decelerated beams, the measurement was done in the S-DALINAC normal operation mode, which, in contrast to its ERL mode, features a beam time structure of 3 GHz. Although the overall goal is to eventually use an LGAD-based setup as a monitoring tool during the ERL operation of the S-DALINAC, measuring the S-DALINAC in its normal operation mode still allowed to show the proof-

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of-concept of the proposed beam monitoring system. The preliminary results of this experiment were presented at the Vienna Conference of Instrumentation in February 2022 as a part of the LGAD application overview talk [7]. In this contribution, however, we present a more detailed analysis and discussion.

SETUP

For the first measurement, a prototype setup based on an LGAD multi-strip sensor was prepared. The sensor was produced at Fondazione Bruno Kassler (FBK) with a size of 0.5 × 1 cm^2, a thickness of 200 µm and a sensor pitch of 50 µm. As shown in Fig. 2, the readout pads of the LGAD were bonded to a Printed Circuit Board (PCB). The signals from the LGAD were processed by a PaDiWa [8] leading edge discrimination board connected to Field Programmable Gate Array (FPGA) based Time-to-Digital (TDC) converter [9]. The full experimental setup is shown in Fig. 3.

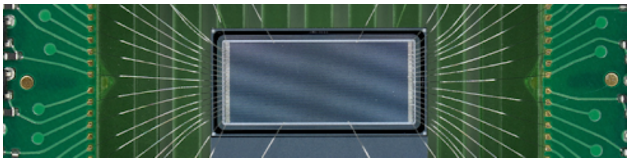

Figure 2: Photograph of the LGAD sensor mounted on the PCB.

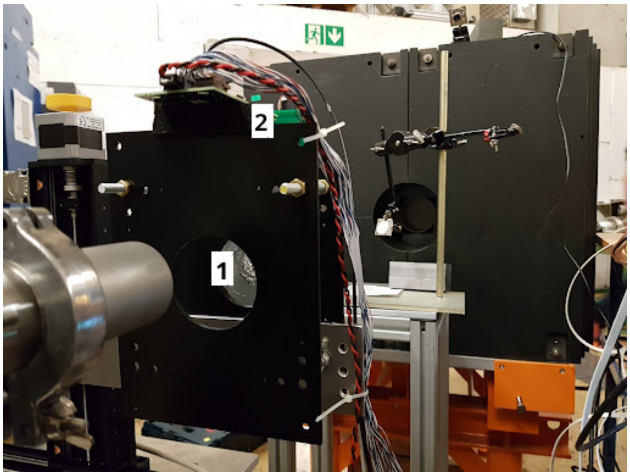

Figure 3: Photograph of the setup at S-DALINAC. LGAD sensor marked as (1), PaDiWa board - as (2).

RESULTS

The Time of Arrival (ToA) and Time over Threshold (ToT) of electrons passing through the sensor were measured and the difference between the ToAs of two hits registered inside the same strip was calculated. Figure 4 demonstrates a dependence of the difference of ToA between two registered hits as a function of ToT. The absence of data in the time difference region below 50 ps represents the dead time of the system. Because of the leading edge discriminator board used in the system, an additional calibration was performed to remove the dependence of the ToA of the signal based on its corresponding ToT (i.e. time walk effect). First, a narrow cut of 100 ps on partner signal ToT was introduced to focus on a signal that comes from a real particle passing through the LGAD sensor. Figure 5 demonstrates raw data for small time difference and ToT ranges without (top) and with (bottom) the narrow ToT cut. Also, the bottom plot of Fig. 5 exhibits so-called time walk effect. To compensate for this time walk and, therefore, remove any systematic dependence of the ToA difference based on the ToT, a time walk calibration was performed. To calculate the calibration parameters, one of the peaks in Fig. 5 was fitted with a linear function. The calibration parameters were then applied on an event-by-event basis by correcting the individual ToAs based on their corresponding ToTs. The results of this calibration are shown in Fig. 6. Additionally, a cut on ToT lower that 4 ns was applied to remove signals that originates from

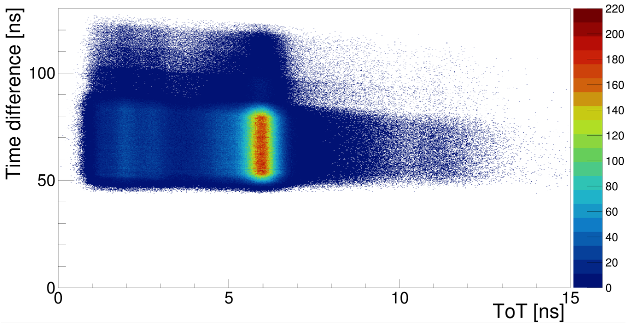

Figure 4: ToA time difference as a function of reference hit ToT for two hits inside the same strip.

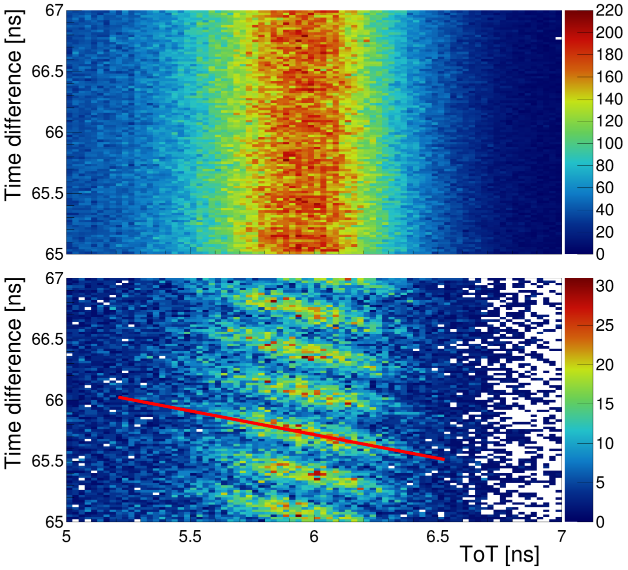

Figure 5: Raw data without (upper) and with (bottom) narrow ToT cut. Red line on the bottom plot represent time walk calibration parameters.

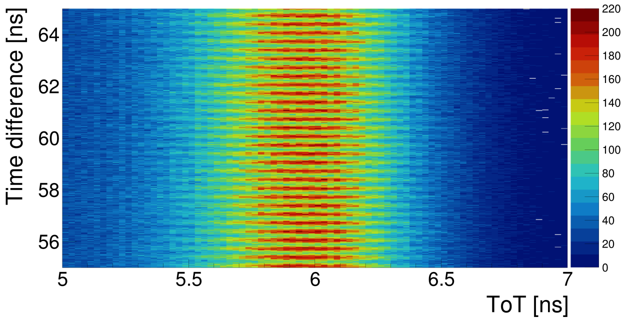

Figure 6: Time walk calibrated data.

capacitive coupling. Detailed discussion on this topic was given in [6]. After applying the calibration, the next step was to identify all peaks in the time spectrum and fit them with a sum of Gaussian and constant to estimate the background. The fits were done by making a projection onto the Y axis of the histogram shown in Fig. 4. The outcome of this procedure is depicted in Fig. 7. In the last step, the time difference between each of the consecutive peaks was calculated and the one-dimensional histogram was fitted with the Gaussian function. The result is shown in Fig. 8. The mean time difference between two consecutive peaks, obtained from the fit, is 333.4 ps which corresponds to the 3 GHz operating frequency of the S-DALINAC. This indicates that the beam time structure was successfully resolved during normal operation mode.

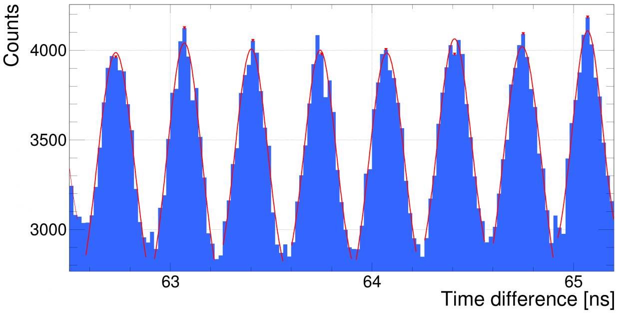

Figure 7: Projection on time difference axis of the histogram shown in Fig. 4 in small range. Red triangles represent position of each identified peak, red lines - fit function.

FUTURE UPGRADE

A new telescope setup, based on 2 LGADs, is being prepared for the upcoming beam time. Each sensor has a form factor of 1 cm × 1 cm with 100 μm pitch and 200 μm thickness (thinned sensor to minimize multiple scattering inside the sensor) with 86 channels per sensor. The telescope setup will allow the measurement of the same electron twice, which increases the time resolution. In addition, it will be possible to remove the signal propagation time inside the strip and remove the signals that come from capacitive coupling. Also, the front end electronics will be upgraded with 8 DiRICH5s1 [8] boards, which is an amplification and leading edge discriminator board that features 32 read-out channels with an FPGA based TDC on board.

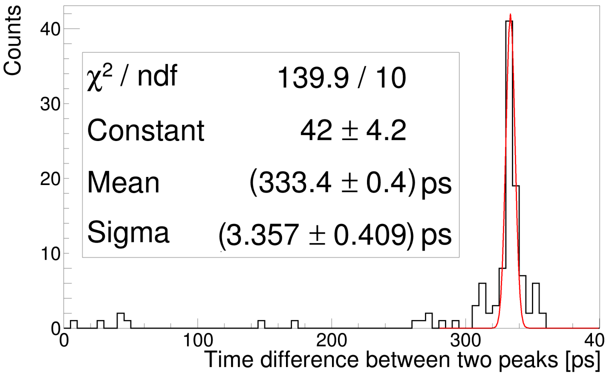

Figure 8: Gaussian fit of the time difference between two consecutive peaks from the data presented in Fig. 7.

SUMMARY

For the twice recirculating ERL mode of the S-DALINAC, a monitoring system capable of measuring of two beams passing the same beam line with the bunch rate of 6 GHz is needed. An LGAD-based detector is a promising candidate for such kind of monitoring because of its excellent timing resolution. The setup for beam timing monitoring based on LGAD was prepared and installed at the dedicated experimental hall at the S-DALINAC. Due to the placement of the setup simultaneous measurement of two beams in the same beam line was not possible. Nevertheless, the first proof-of-principle measurements was successful, showing that the 3 GHz beam time structure of the S-DALINAC operated in its normal mode could be resolved with the LGAD strip sensor.

ACKNOWLEDGEMENTS

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