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MULTI-TILE ZINC-OXIDE-BASED RADIATION-HARD FAST SCINTILLATION COUNTER FOR RELATIVISTIC HEAVY-ION BEAM DIAGNOSTICS: PROTOTYPE DESIGN AND TEST*†

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Abstract

This contribution summarizes the design and performance test of a prototype radiation-hard fast scintillation detector based on the indium-doped zinc oxide ceramic scintillator, ZnO(In). The prototype detector has been developed for use as a beam diagnostics tool for high-energy beam lines of the SIS18 synchrotron at the GSI Helmholtz Center for Heavy Ion Research GmbH. The new detector consists of multiple ZnO(In) scintillating ceramics tiles stacked on the front and back sides of a borosilicate light guide. The performance of the detector was tested in comparison to a standard plastic scintillation detector with 300 MeV/u energy ^{40}Ar, ^{197}Au, ^{208}Pb, and ^{238}U ion beams.

The investigated prototype exhibits 100% counting efficiency and radiation hardness of a few orders of magnitude higher than the standard plastic scintillation counter. Therefore, it provides an improved beam diagnostics tool for relativistic heavy-ion beam measurements.

INTRODUCTION

The heavy-ion accelerator facility at the GSI Helmholtz Center for Heavy Ion Research (Darmstadt, Germany) and other similar ion-beam facilities worldwide provide energetic heavy-ion beams for a wide range of research purposes, including fundamental nuclear and particle physics, atomic and plasma physics, material sciences, radiation biology, and cancer therapy research.

Various diagnostics systems are used to measure heavy-ion beam parameters to ensure the safety and reliability of the accelerator facility operation, as well as to optimize the beam delivery to the experimental locations. For example, this includes beam position, profile, intensity, energy, and emittance measurements.

The information provided by the beam diagnostics tools is used by the operating team for the online feedback controls of the accelerator and beam transfer lines. This helps to maintain the desired quality and stability of the beam. The beam diagnostics systems are also used by experimental users directly for the characterization and calibration of the experimental setups, which require precise knowledge of the incoming beam parameters.

In particular, at the high-energy beam transfer lines (HEST) of the GSI facility, the intensity of heavy-ion beams slowly extracted from the SIS18 synchrotron is measured using three different detector types (particle detector combination, PDC): scintillation counter (SC), ionization chamber (IC) and secondary electron monitor (SEM). Each detector type is used to cover a specific range of beam intensity [1].

Plastic scintillation counters based on BC-400 (Saint Gobain), or EJ-212 (Eljen Technology) scintillators are currently used as a part of the HEST ion beam intensity diagnostics, covering counting rates in the range up to 1×10^6 ions/s. The heavy-ion beams induce a large amount of radiation damage when passing through the plastic scintillator. This leads to frequent detector services where plastic scintillators are exchanged, which is highly undesirable from an operational point of view.

In this work, we investigated an alternative to the plastic scintillation counter, that could provide less frequent detector maintenance through the use of a more radiation-hard scintillator. We developed a new detector prototype based on indium-doped zinc oxide (ZnO(In)) ceramic scintillator. We report on the new prototype design and performance, which was evaluated experimentally through in-beam tests and simulations using the OpenGATE [2].

ZINC OXIDE CERAMIC SCINTILLATOR

Zinc oxide (ZnO) is a well-known inorganic compound used in various applications [3–5]. In particular, it has been used for the detection of X-rays and α-particles [6–9].

ZnO exhibits two luminescence bands when excited by light or ionizing radiation: (1) emission in the ultraviolet (UV) spectral range (~390 nm) with a short scintillation decay time (<1 ns), and (2) emission in a broad-band with a maximum around 550 nm wavelength (green luminescence) with a longer decay time (>1 µs). The green luminescence is unsuitable for fast-counting applications. Therefore, it is avoided either by annealing in a reducing environment or doping with a group 3A element impurities, such as Al, Ga, or In [3, 10, 11].

In-doped and Ga-doped ZnO ceramics prepared by uniaxial hot pressing in vacuum have been investigated as promising scintillators for fast heavy ion counting appli-

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cations [12–15]. They exhibit orders of magnitude higher radiation hardness than plastic scintillators, and thus can provide longer exploitation time before scintillator replacement is required. Furthermore, narrow signals with the pulse width below 1 ns can be obtained, when ZnO(In) scintillation is registered with a fast photomultiplier tube. This resolves pile-up limitations for the micro-spill structure measurements [13].

The fast scintillation component in ZnO is located close to its self-absorption edge. Thus, the detection of fast scintillation photons through a few millimeters thick ZnO is not efficient. This peculiarity and difference compared to standard plastic scintillators have been considered in the new ZnO-based prototype detector design.

PROTOTYPE DETECTOR DETAILS

Prototype Detector's Parts

The detector consists of three main components: the active volume, the light guide, and the photosensor, as shown in Fig. 1.

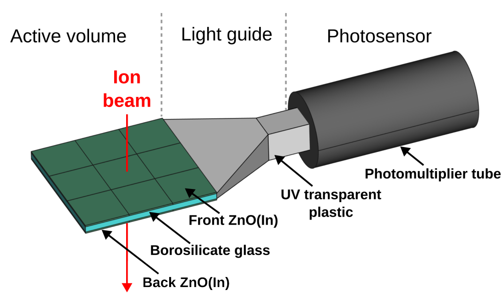

Figure 1: Schematic view of the multi-tile ZnO-based scintillation counter prototype.

The active volume is the central part of the detector that directly interacts with the incident ion beam. It consists of square-shaped scintillator tiles made of ZnO(In), stacked on both the front and back sides of a borosilicate glass plate. When the ion beam passes through the active volume, it deposits part of its energy in the scintillator and borosilicate glass layers, leading to the emission of scintillation light.

The scintillation mainly comes from ZnO(In) layers, as they efficiently convert the deposited energy into light photons. Due to self-absorption, the scintillation photons mainly go out from the material through the surfaces where ions enter and exit the scintillating tile. The borosilicate glass, which is transparent to scintillation photons from ZnO(In), acts as a light guide, assisting in collecting scintillation light from the ZnO(In) surfaces. This arrangement enables the extraction of scintillation photons from the active volume.

An additional light guide made of UV-transparent plastic is used to match the shapes of the borosilicate glass and photosensor. Optical silicon (Momentive, RTV-615) improves light coupling between the plastic light guide and both borosilicate glass output and photosensor input.

The photosensor, responsible for converting scintillation light into an electrical output signal, consists of a photomultiplier tube (PMT, Hamamatsu R6427).

The active volume and the light guide are fixed on a 3D-printed holding structure and wrapped with Teflon to improve light collection and black tape to avoid penetration of any external light.

In the design of the new ZnO-based scintillation counter, only the active volume component is replaced, while the plastic light guide and photomultiplier tube remain unchanged compared to the standard plastic scintillation counter for GSI beam diagnostics. This design approach ensures the proven performance and compatibility with existing plastic scintillation counter components, while introducing the enhanced scintillation properties of ZnO(In) in the active volume.

Materials of the Active Volume

The 0.046 at.% In^{3+} doped ZnO ceramic scintillators have been produced at the Joint Stock Company "Research and Production Corporation S.I. Vavilova" (St. Petersburg, Russia) using the uni-axial hot pressing in vacuum. The obtained ZnO(In) ceramics were polished and cut into $15 \times 15 \times 0.5\,\mathrm{mm}^3$ square tiles.

The borosilicate radiation-hard glass (material catalog name BK7G18) was purchased from SCHOTT (Germany) and cut into the $50 \times 50 \times 2\,\mathrm{mm}^3$ rectangular shape. The material surfaces had a root-mean-square roughness of 2–4 µm.

The ZnO(In) ceramic tiles and BK7G18 plate are fixed together using a Kapton tape as shown in Fig. 2.

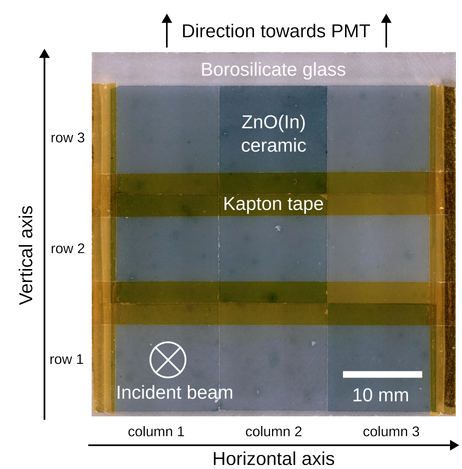

Figure 2: Photograph of the prototype detector's active area. The white crossed circle shows the incident beam direction and the beam spot size in scale with the active area.

EXPERIMENTAL PERFORMANCE TEST

To evaluate the performance of the prototype detector, a series of tests were conducted at GSI using ion beams extracted from the SIS18 accelerator. The experimental parameters are summarized in Table 1.

The ^{40}Ar, ^{197}Au, ^{208}Pb, and ^{238}U ions had an initial energy of 300 MeV/u. Before reaching the entrance of the proto-

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Table 1: Experimental Beam Parameters and Photomultiplier Gains Used for the Tests of the Prototype Detector

Ion	Energy, MeV/u	Energy loss, MeV	PMT gain
^{40}Ar	300 [a] 297.14 [b]	231.85 [c] 516.89 [d] 240.39 [e]	2.20×10^6 (1300 V)
^{197}Au	300 [a] 288.62 [b]	4654.27 [c] 10900 [d] 5499.17 [e]	1.15×10^5 (850 V)
^{208}Pb	300 [a] 288.41 [b]	5006.94 [c] 11800 [d] 5932.97 [e]	1.15×10^5 (850 V)
^{238}U	300 [a] 287.32 [b]	6272.86 [c] 14900 [d] 7586.86 [e]	1.15×10^5 (850 V)

[a] SIS18 extraction energy, [b] Energy at the prototype detector entrance, [c] front ZnO(In), [d] borosilicate glass, [e] back ZnO(In)

type detector, the ion beams underwent energy loss. This loss occurs as the beam exits the vacuum chamber through a 100 µm thick stainless-steel window and travels a 40 cm distance through air. To accurately determine the incident beam energies and quantify the energy losses within the detector's active volume layers, the ATIMA code was employed [16]. For the energy loss calculations, we used 5.5 g/cm^3 ZnO(In) and 2.58 g/cm^3 BK7G18 material density.

The ion beam was collimated to a circular spot with a diameter of 5 mm before interacting with the prototype detector. The prototype detector was mounted on a stage capable of horizontal and vertical movement, enabling exposure of different regions of the active volume to the ion beam.

A standard plastic scintillation counter was placed behind the prototype and used as the reference detector.

Output signals from both the prototype and reference detectors were digitized and read out with a high-speed oscilloscope (Tektronix MSO58) with a bandwidth of 2 GHz. The reference detector provided a trigger for the oscilloscope read-out. The counting efficiency of the prototype detector relative to the reference detector was estimated by counting the number of prototype detector signals higher than 50 mV.

The PMT gain of the prototype detector was adjusted so that the maximum amplitude of the signal is of the order of 1 V.

RESULTS AND DISCUSSION

Contribution of Borosilicate Glass Signal

By scanning the incident ion beam near the edge of the prototype's active volume, we collected signals corresponding to ions passing through: (1) only borosilicate glass plate, (2) borosilicate glass with one layer of ZnO(In), and (3) borosilicate glass with two layers of ZnO(In).

As shown in Fig. 3, the scintillation light yield of the borosilicate glass (BSG) is lower compared to the ZnO(In)

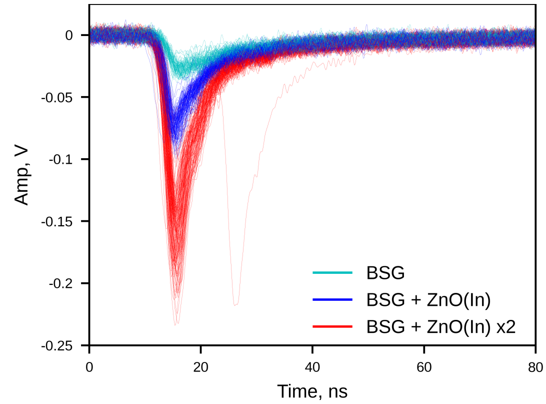

Figure 3: Signals of the prototype detector exposed to 300 MeV/u Au ion beam at the edge of the active volume.

scintillator. In the case of Au ion irradiation, the signal amplitude from the borosilicate glass layer is around 30 mV, while the signal amplitude from borosilicate glass with one layer of ZnO(In) is almost 3 times larger. The signal from the borosilicate glass with two layers of ZnO(In) scintillator is roughly 5 times larger than the signal from the borosilicate glass.

Despite the lower energy loss in ZnO(In) compared to borosilicate glass (see Table 1), ZnO(In) scintillation light represents the main part of the output signal amplitude, indicating that it is a brighter scintillator than the BK7G18.

For all three investigated regions, the registered output signals have a rise time of 2.5 ns. This rise time is related to the response of the PMT and has nothing to do with the scintillation material and beam position in the active area.

The use of borosilicate glass provides a solution to overcome the challenge related to the self-absorption of ZnO(In). It provides efficient extraction of scintillation light out from the active volume and, at the same time, it has a negligible contribution to the prototype's output signal.

Prototype Detector Signals Across Active Volume

Figure 4 shows the prototype output signals registered when different ion beams hit the active volume at different locations. We collected 10000 output signals corresponding to individual ions passing through the center of each ZnO(In) scintillating tile located at various horizontal and vertical positions (various columns and rows), as is shown in Fig. 2.

Depending on the beam position, there is no difference in the signals registered along the horizontal axis (fixed row, various columns). In contrary to that, there is a significant change in the output signal amplitude along the vertical axis (fixed column, different rows). The signal amplitude dependency along the vertical axis has a similar trend for all the investigated ion species.

It should be noted that the plastic light guide and PMT are placed along the vertical axis. The higher amplitude signals are registered when the beam hits the active volume closer to the PMT (row 3 in Fig. 4).

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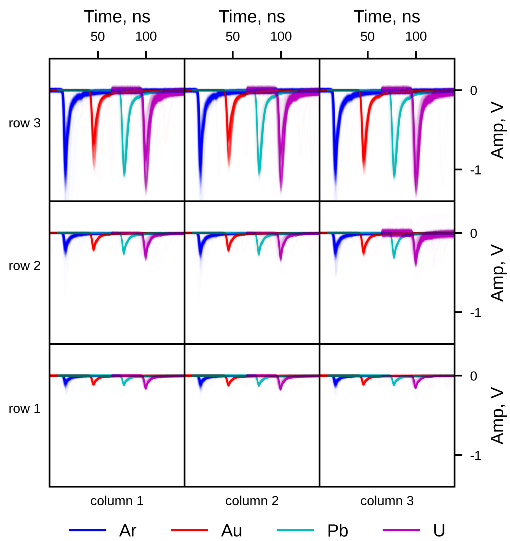

Figure 4: Output signals obtained for various ion beams hitting the prototype detector at different horizontal and vertical positions. Signals of different ion species are shifted on the x-axis for better visibility and comparison. Each subplot corresponds to the center of the scintillating tile in the corresponding column and row, as shown in Fig. 2.

Light Propagation Simulation

The propagation of the scintillation light from ZnO(In) through BK7G18 glass was simulated using the OpenGATE [2]. As a result of the simulation, it was found that the ZnO(In) scintillation photons transmission through the BK7G18 glass varies from 2 to 9% depending on the vertical axis coordinate. Figure 5 shows a comparison of the experimentally measured signal amplitude and the simulation result, confirming that the prototype signal amplitude variation is consistent with the ZnO(In) scintillation light transmission through the BK7G18 glass.

Further borosilicate glass plate optimizations (geometry and surface quality) together with OpenGATE simulations are required to find the optimal shape and surface quality of the borosilicate glass to suppress the changes in the output signal amplitude along the vertical axis of the active volume.

Prototype Detector Counting Efficiency

The counting efficiency has been estimated as a ratio of the number of ions counted by the prototype divided by the number of ions counted by the reference detector. Despite the signal amplitude variation in the vertical axis, the prototype detector exhibits 100% counting efficiency relative to the plastic scintillator for all the investigated ion species.

SUMMARY

We developed a new radiation-hard fast scintillation detector prototype based on ZnO(In) transparent scintillation ceramics to be used for relativistic heavy-ion beam intensity diagnostics.

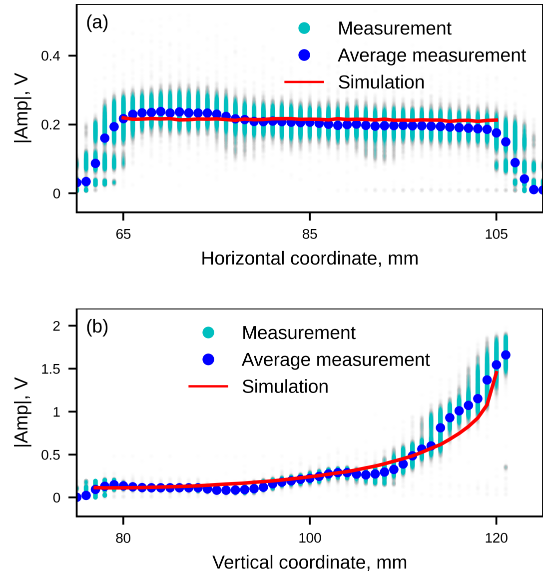

Figure 5: The signal amplitude changes for the 300 MeV/u Au beam incident at various positions on the active volume. Figures (a) and (b) correspond to beam scans along the horizontal and vertical axis, respectively.

The developed prototype showed 100% counting efficiency relative to the standard plastic scintillation counter when tested with Ar, Au, Pb, and U heavy-ion beams at 300 MeV/u energy. By considering the few orders of magnitude higher radiation hardness of ZnO(In) than plastic scintillator, the new prototype provides an improved beam diagnostics tool.

We observed a spatial dependency of the prototype output signal amplitudes registered when the ion beam hits different positions on the active volume. We showed that this dependency is related to the ZnO(In) scintillation light transmission through the borosilicate glass. The experimentally observed signal amplitude change is in agreement with the light transmission through the borosilicate glass simulated by OpenGATE.

The borosilicate glass, used as a part of the active volume, exhibited scintillation light yield much lower than ZnO(In). Thus, it makes a negligible contribution to the prototype detector output signal and serves mainly as the light guide.

In the current prototype version, we used a rectangular-shaped borosilicate light guide. Further investigations of more complex shapes of the light guide are needed to eliminate the spatial dependency of the output signal.

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