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NOVEL FAST RADIATION-HARD SCINTILLATION DETECTOR FOR ION BEAM DIAGNOSTICS*

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Abstract

Novel radiation-hard scintillators were developed in the last years based on indium-doped zinc oxide ceramic with an extremely short decay time below a nanosecond. Fast counting detectors and fast screens were considered as potential beam diagnostic applications of this material. At the GSI/FAIR facility, scintillation detectors are commonly used for measuring the intensity and detailed time structure of relativistic heavy ion beams. The scintillating material is inserted directly into the beam path. Signals from individual ions are counted, providing systematic-error-free beam intensity information. Standard scintillators require frequent maintenance due to radiation damage. To address this limitation, a large area ZnO radiation-hard detector prototype was developed. The prototype detector operates at orders of magnitude higher irradiation levels, at higher counting rates and has better time resolution compared to a plastic scintillator. In addition, the novel detector material opens the possibilities for applications in other beam diagnostic systems, for example, scintillation screens for transverse profile measurements. Therefore, ZnO scintillation ceramics are of general interest for beam diagnostics.

INTRODUCTION

Scintillation detectors are used at the GSI/FAIR facility for intensity and micro-spill structure measurements. Ion beams from protons up to uranium with energies in the range of hundreds of MeV/u up to tens of GeV/u have to be characterized. The detectors utilize the interaction of the ion beam with a scintillator which generates photons. A photomultiplier tube (PMT) converts the light into an electrical signal.

The detector produces one pulse for each detected ion. Typical signal width measured from a BC400 or EJ212 plastic scintillator near the PMT location is of an order of 5 ns. The complex slow extraction process from the particle accelerators and the sub Poisson ion particle distribution [1] of the extracted particles lead to a non-negligible percentage of signal pile-ups at counting rates above a few times 10^6 particles per second. Higher counting rates are requested, hence scintillator materials with decay times of the order of nanosecond or shorter are desirable.

The typical dose at which a plastic scintillator has to be exchanged due to radiation damage is of the order of 50-100 kGy. This dose is regularly reached during micro-spill optimization. Therefore we investigated zinc oxide, an inorganic material which can substitute the plastic scintillator.

ZnO(In) RESPONSE TO HEAVY IONS

Fast luminescence from ZnO with indium or gallium doping was discovered in the sixties. A structureless band with a decay constant below a nanosecond located near the optical absorption edge was reported by W. Lehmann in Ref. [2]. The latter property limited the detector applications to cases where a few micrometers of scintillator material provide sufficient light output. In 2012, a breakthrough in ZnO scintillator production was reported by P. A. Rodnyi et al. [3]. Transparent ceramics from ZnO micro- and nano-powders were produced with a diameter of the order of 2 cm and thickness of 0.4 mm. The response of this material was tested at GSI with heavy ions. The results of these tests were reported in Ref. [4]. A photograph of the tested sample and an image with ion beam induced luminescence from 300 MeV/u ^{124}Xe ions is shown in Fig. 1.

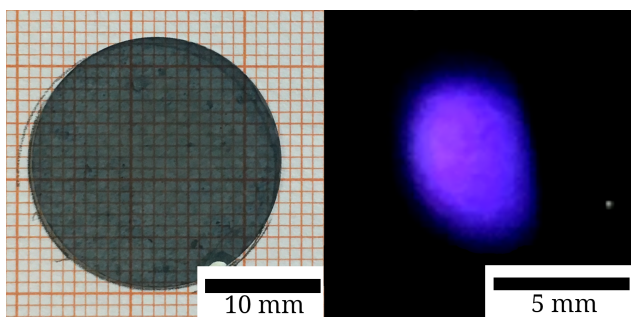

Figure 1: To the left, a ZnO(In) ceramic sample photograph. To the right, a color image of an ion beam induced luminescence by 300 MeV/u ^{124}Xe ions.

An international collaboration was formed under the ERA.Net RUS Plus Project RUS_ST2017-051 with the aim to develop ultra-fast ceramic detectors of ionizing radiation based on zinc oxide. Samples were produced and characterized at the Research Technological Institute of Optical Materials "Vavilov State Optical Institute" and Peter the Great St. Petersburg Polytechnic University. The ceramic microstructure was investigated at the Institute of Solid State Physics of the University of Latvia, while ionoluminescence

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characterization and detector developments were performed at GSI.

Ionoluminescence properties of ZnO(In) and ZnO(Ga) samples were investigated at GSI with a variety of relativistic heavy ions, Ref. [4–7]. We discovered that:

Radiation Hardness of ZnO

The radiation hardness of ZnO is at least two orders of magnitude higher compared to plastic scintillators. Figure 2 shows the evolution of the ZnO(In) scintillation spectrum as a function of fluence. The ionoluminescence was induced from ^{197}Au ions with an energy of 4.8 MeV/u. In this experiment, the energy deposition per unit length by a gold ion is larger than that of ^{238}U ions at 250 MeV/u. The latter will deposit the highest energy density under the planned operation of ZnO-based detectors at GSI/FAIR. The data shows a single structureless band with a maximum intensity at ~390 nm. This is the fast near-band-edge (NBE) emission of ZnO(In). This study was presented at IBIC2022 by M. Saifulin et al. [5].

The response to radiation damage with 0.3 GeV/u Xe and U ions is reported in Ref. [4] and other heavy relativistic ions in Ref. [7]. In our investigation, apart from NBE, we did not observe new emission bands forming due to radiation damage.

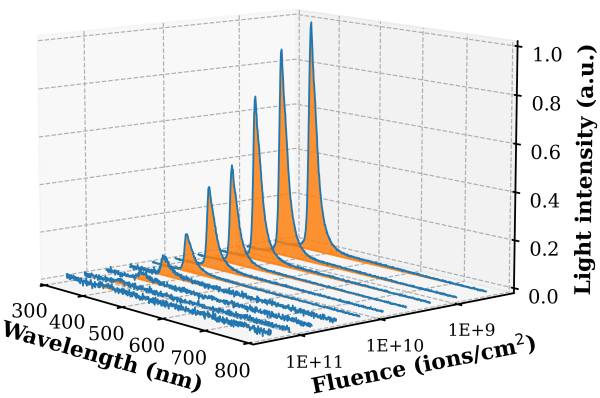

Figure 2: Ionoluminescence spectrum of ZnO doped with In, excited with ^{197}Au ions with energy of 4.8 MeV/u.

One of the samples irradiated with 0.3 GeV/u U ions was annealed in air at 500°C. Its radioluminescence properties before and after annealing were reported in Ref. [8]. The measurement shows that after annealing in air, the luminescent properties of the radiation-damaged material were improved relative to not damaged material. Further investigations performed at GSI with heavy ions confirmed that the luminescence properties of the bulk material are restored [7].

ZnO Light Output

The ZnO light output follows nearly the same trend versus deposited energy as BC400/Ej212 plastic scintillators. The light output of various ZnO samples as a function of deposited energy is discussed in Ref. [6, 7]. Figure 3 shows one of this data sets. The light output of all investigated samples as a function of deposited energy followed the same trend as the one of BC400/EJ212 plastic scintillators.

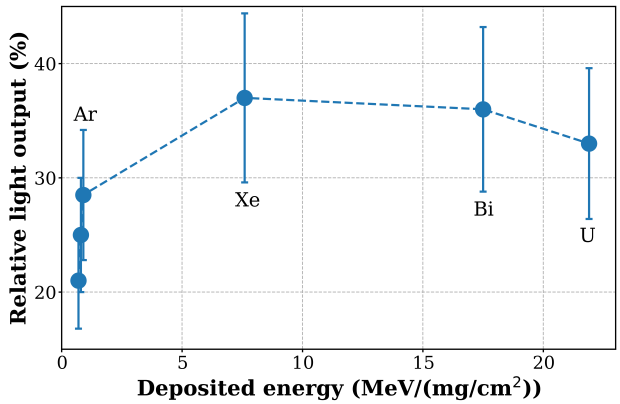

Figure 3: The light output of ZnO(In) as a function of deposited energy normalized to the light output of BC400/EJ212 plastic scintillators.

The research and development within the ERA.Net RUS Plus Project led to improvements in the production of the ZnO scintillating ceramics. A large number of samples with a variation of the light output of less than 5% were manufactured. These samples were used to build the multi-tile detector described below. In general, the light output of ZnO(In) ceramics obtained by using an optimized manufacturing process is of the order of 0.5 of the corresponding light output of the BC400 plastic scintillator.

ZnO Signal

The ZnO signal induced via ionoluminescence has a full-width at half-maximum below one nanosecond. Figure 4 shows a comparison of the signals from the ZnO(In) and the BC400 plastic scintillators acquired under the same conditions. The signals are convoluted with the PMT and the oscilloscope response. The PMT used for the measurement was Hamamatsu H13661, with a rise time of the order of 230 ps and full-width at half-maximum of the order of 430 ps. The 2 GHz oscilloscope which captured the signals was Tektronix MSO58. The signal width of bellow 1 ns resolves any pile-up limitations for the micro-spill structure measurements performed at GSI.

ZnO Radiation Damage

The reduction of the ZnO light output due to radiation damage follows the trend predicted by the Birks-black model. A fit with the Birks-Black model [9] of the experimental data from irradiation of a ZnO(In) sample with 4.8 MeV/u Au ions is shown in Fig. 5. The model has two parameters, the light output before irradiation and the critical fluence, this is the fluence at which the light output is reduced by a factor of two.

Figure 6 shows the data on the critical fluence, $\Phi_{1/2}$, versus deposited energy for ZnO(In) and BC400. The critical

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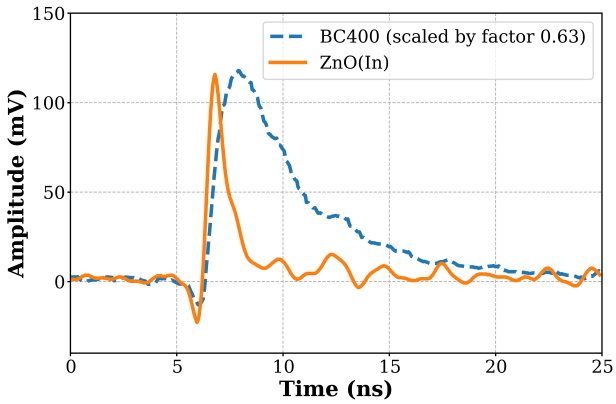

Figure 4: Comparison of the signals from ZnO(In) and BC400 plastic scintillator. The scintillators were bombarded with 300 MeV/u ^{238}U ions. The plastic scintillator data is scaled in order to match the ZnO(In) signal amplitude. The continuous orange line: ZnO(In) signal. Dashed blue line: BC400 signal.

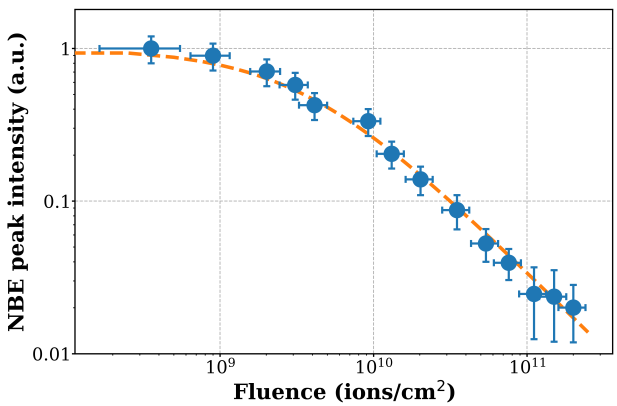

Figure 5: ZnO(In) light output as a function of fluence of ^{197}Au ions. The beam energy was 4.8 MeV/u. Blue dots represent experimental data. Dashed orange line represents a fit of the experimental data by the Birks-Black model.

fluence is determined from the damage mechanisms of the heavy ions interacting with the ZnO ceramics. The correlation between experimentally determined $\Phi_{1/2}$ and the calculated energy loss allows to predict the material longevity under operation conditions that were not investigated before.

Further data and details on this investigations are given in Ref. [10].

MULTI-TILE LARGE AREA DETECTOR

The production of the ceramic samples described in these studies is optimized for round samples with a diameter of the order of 2 cm. Square tiles with the size of 15×15 mm^2 were cut from the round samples. A detector prototype with an active area of 45×45 mm^2 was constructed by placing the scintillating ceramic tiles on a radiation-hard glass light guide. Photographs of part of the detector active area and the light guide are shown in Fig. 7. The detector was constructed

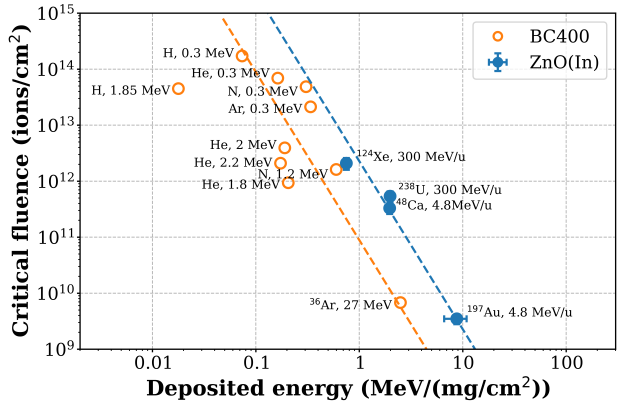

Figure 6: Critical fluence versus deposited energy for ZnO(In) and BC400. The dashed lines indicate the correlation between the material damage and the deposited energy.

from 18 tiles. Two layers of 3×3 tiles each were placed on each side of the radiation-hard light guide. The interfaces between the front and back tiles were shifted. Thus, if a particle passed between two front tiles, it was guaranteed to interact with a tile on the back of the detector.

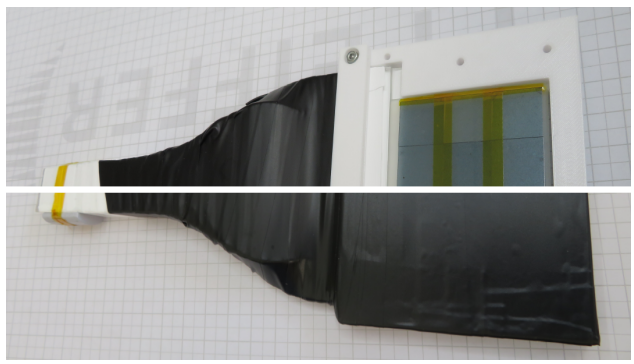

Figure 7: Photographs of the ZnO-based multi-tile scintillator detector. The upper photograph shows a part of the multi-tile assembly, while the bottom half is a photograph of the detector wrapped with PTFE and black tape.

The detector counting efficiency was validated relative to a 75×80 mm^2 BC400 plastic scintillator detector. All particles that passed the 45×45 mm^2 active area of the ZnO(In) multi-tile detector generated a clean easy-to-discriminate signal. Figure 8 illustrates the tile-detector concept and the experiment layout for this measurement. Further details on the detector construction, optimization and performance are given in M. Saifulin thesis [7].

It should be noted that there are no fundamental constraints for the production of larger samples. The tools and production technology can be scaled following a demand for larger ceramic pieces.

OUTLOOK

Zinc-oxide-based counting detector will be used at GSI/FAIR for micro-spill structure measurements.

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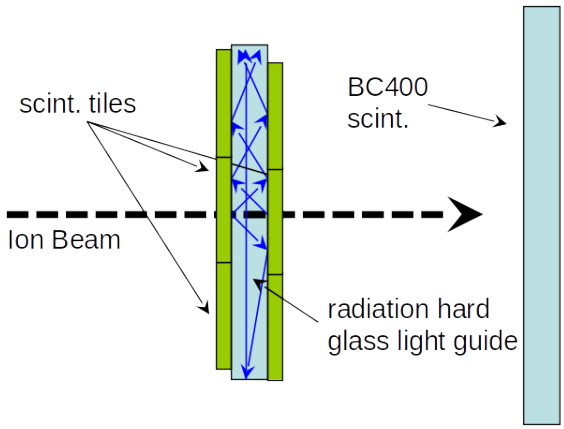

Figure 8: A conceptual drawing of the experiment in which the counting efficiency of the multi-tile detector was measured.

Currently, we are investigating ZnO as a scintillation screen material for transverse profile measurements at the future FAIR facility. Based on the measurements performed at XFEL [11] we expect that the CROMOX screens used at GSI will saturate when bombarded with 10^{10} fast-extracted U ions, focused to a 10 mm beam spot. ZnO has orders of magnitude shorter decay constant relative to CROMOX. The extraction time from SIS18/SIS100 is much longer than the decay time of ZnO, which makes it an excellent candidate for transverse profile measurements of the intense heavy ions beams at FAIR.

CONCLUSIONS

ZnO-based scintillating ceramics are promising materials to be used for heavy-ion particle detection applications. They are fast and radiation hard.

The response to relativistic heavy ions of ZnO scintillating ceramics with In and Ga doping was determined. It was discovered that the decrease of ionoluminescence as a function of ion fluence follows the Birks-Black model. The trend of the critical fluence as a function of deposited energy was established. Based on this data, the reduction of ionoluminescence due to radiation damage can be predicted for various operating conditions.

A multi-tile detector with a counting efficiency of 100% for relativistic heavy ions was constructed. With this achievement, it was demonstrated that there is no fundamental limit for the detector active area which can be reached with the current ZnO scintillating ceramic production technology.

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