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RADIATION HARDNESS INVESTIGATION OF ZINC OXIDE FAST SCINTILLATORS WITH RELATIVISTIC HEAVY ION BEAMS

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Abstract

At GSI ion beams of many elements, from H up to U, are produced with energy as high as 4.5 GeV/u with the SIS-18 synchrotron. For absolute beam intensity and micro-spill structure measurements a BC400 organic scintillator is used. Due to the low radiation hardness of this material, alternative inorganic scintillators like ZnO:Ga and ZnO:In were investigated. The properties and possible application of these novel radiation hard fast scintillators will be discussed. Their response to Sn, Xe and U ion beams will be reported.

USE OF FAST SCINTILLATORS AT GSI/FAIR

The complete range of possible beam intensities at GSI/FAIR cannot be covered by one detector type. The task is accomplished by a combination of three detectors, a plastic SCintillator (SC), an Ionization Chamber (IC) and a Secondary Electron Monitor (SEM). The SC detector utilizes 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. In contrast the IC and SEM detectors generate a current proportional to the beam intensity. The systematic errors in the calculation of the beam current are removed by calibration of the IC versus a SC detector. Next, at higher beam intensities, the current determined by SEM is compared to the reading of the calibrated IC detector.

The plastic scintillator has to be exchanged regularly, due to radiation damage. The typical dose at which an exchange has to be performed is 40 kGy. This dose is regularly reached, therefore we started an investigation of an inorganic material which can substitute the plastic scintillator.

ZINC OXIDE RESPONSE TO HEAVY IONS

Zinc oxide (ZnO) is known as an efficient phosphor. It exhibits two emission bands, a fast decaying narrow band located near the absorption edge of the crystal and a broad band, with maximum usually in the green-yellow spectral range. The typical decay time of the broad band is of order of ms while the narrow one decay in less than a ns. Producing large area ZnO based scintillator is challenging. In the recent year there have been breakthroughs in manufacturing ZnO optical ceramics. The combination of nano-materials with improved manufacturing technology led to fast ZnO based scintillators with area of order of 5 cm^2, disks with diameter of 25 mm. A key part of the production is the introduction of doping which suppresses the long lived green-yellow spectral component and enhances the fast narrow band luminescence, see Ref. [1, 2] and the references within for more details.

In this paper we present an investigation of the new ceramic scintillators with heavy ions. A schematics of the experimental setup is shown in Fig. 1. The heavy ion beam from SIS-18 comes from the right, it passes into air through a 100 µm steel window. It is collimated to a spot with a diameter of 5 mm by the Aluminum collimator. An ionization chamber is used to determine the dose deposited by the beam into the studied samples. The samples are inserted into the beam with a remotely controlled manipulator, indicated as target ladder in the figure. A photomultiplier detects the scintillation light.

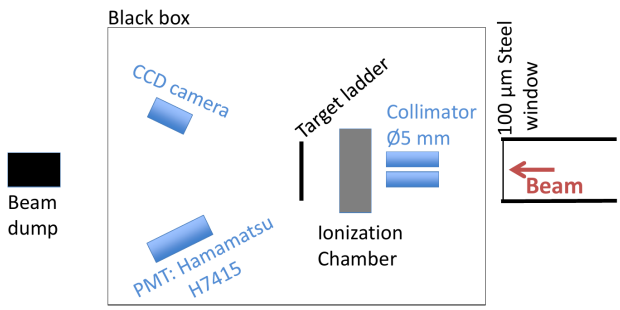

Figure 1: A schematics of the experimental setup. See the text for details.

A CCD camera and a Cromox screen installed on the target ladder were used for beam tuning. The charge collected from the IC was measured with a charge to frequency converter [3] which was calibrated versus a plastic scintillator installed on the target leader.

ZnO ceramic scintillators doped with In and Ga were investigated with relativistic Xe and U ions. The response to 300 MeV/u ^{124}Xe ions of 1 mm thick BC400 plastic scintillator and 0.4 mm thick ZnO:Ga and ZnO:In ceramics is shown in Fig. 2. The observed rise and decay times are faster than the one of BC400 plastic scintillators. The PMT signals are transmuted over 75 m long cable to the oscilloscope used to record them. This is reflected in their shape.

In Fig. 3 the light yield of the ZnO ceramics is compared to the one of BC400 scintillator. We have to investigate the light yield from heavy ions as function of ZnO thickness and energy loss in the material. Nevertheless, the 300 MeV/u ^{124}Xe data shows that the light yield from 0.4 mm ZnO:In is 10% higher than the one from 0.4 mm BC400 scintillator.

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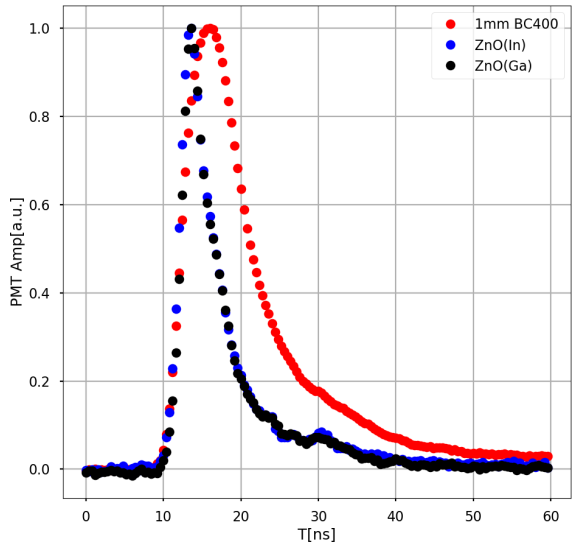

Figure 2: Comparison of the rise and fall times of the studied materials. The scintillators are bombarded with from 300 MeV/u ^{124}Xe. The signals are scaled to 1 V. Red points: BC400 signal. Blue points: ZnO:In signal. Black-circles: ZnO:Ga signal.

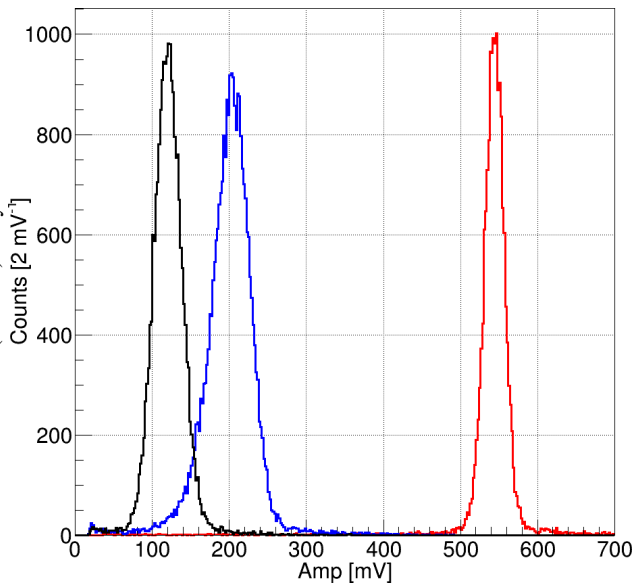

Figure 3: Comparison of the amplitude distribution of the investigated materials. The scintillators are bombarded with 300 MeV/u ^{124}Xe. In red: 1 mm thick BC400, in blue: 0.4 mm thick ZnO:In and in black 0.4 mm thick ZnO:Ga.

The energy loss of 300 MeV/u ^{124}Xe in 0.4 mm ZnO is about 4 times higher compare to the one in 0.4 mm BC400 plastic. Therefore, under the above conditions the light yield per MeV of the ZnO:In ceramics is 4 times less than a BC400 scintillator.

The radiation hardness of ZnO is orders of magnitudes higher compared to a plastic scintillator. Figure 4 compares the amplitude distribution before and after irradiation with 9x10^9 ions/cm^2. This corresponds to a dose higher than 2.2 MGy, more than 50 times than the one at which a BC400 scintillator will have to be exchanged. The exact dose at which the light output of the ZnO ceramics is reduced bellow a reasonable detection threshold still needs to be determined, as the evolution of the light output as a function of dose did not exhibit a sharp drop. This is illustrated with the data in Fig. 5.

The data shown in Fig. 5 points that the number of photons leaving the material does not scale scale linearly with the energy loss, i.e. there are quenching processes in the material.

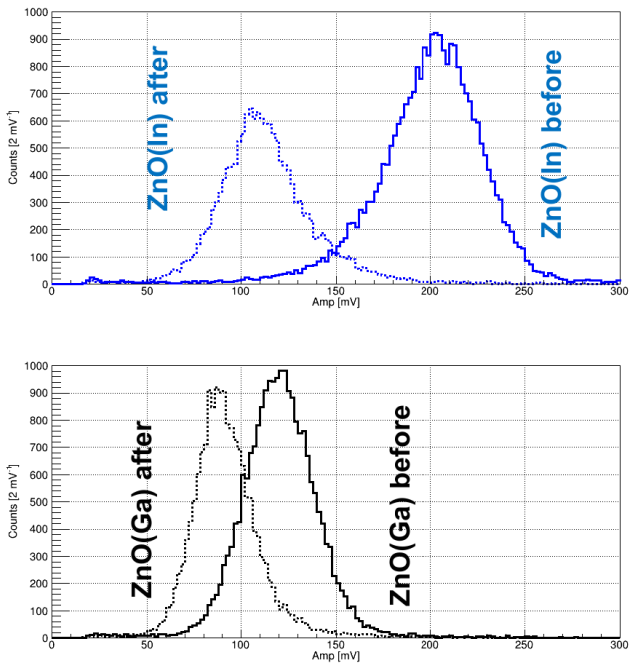

Figure 4: Comparison of the average signal amplitude of ZnO:In and ZnO:Ga before and after irradiation with 9x10^9 ions/cm^2, 300 MeV/u, ^{124}Xe ions.

Nevertheless even at this stage of our investigations we can claim that the ZnO is a superior detector material for counting of heavy ions because the material can be annealed. Figure 6 compares the luminescence spectrum of ZnO:In before and after ^{238}U irradiation to a dose of 4 MGy. In this measurement the luminescence was induced by x-rays, see Ref. [4] for further details. The measurement shows that after annealing in air the luminescent properties of the radiation damaged material were improved. The ZnO:In had a higher light yield compared to the one before irradiation.

Another application of the ZnO scintillators is bunch profile measurements, and investigations of non-homogenious particle distribution as function of time for fast extracted beam. Hence it is interesting to study the light yield at even higher energy densities than the one discussed until now. As a first step we measured the optical spectrum of ZnO:In under irradiation with 4.8 MeV/u ^{120}Sn ions. The beam stopped in the material and deposited its full energy, the calculated average energy loss of the ^{120}Sn ions is 26 MeV/µm. In comparison the energy loss of 300 MeV/u ^{238}U is 12 MeV/µm. In Fig. 7 the spectra acquired over 5 and 10 s are shown. The optical spectrum of the ZnO:In from excitation with

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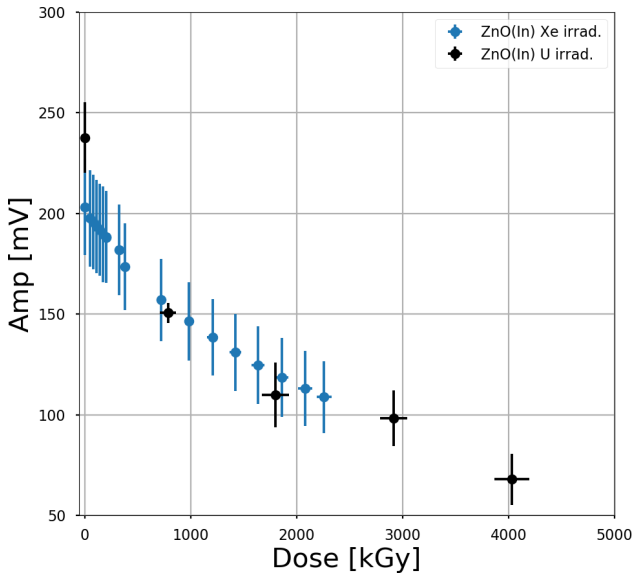

Figure 5: Comparison of radiation damage from ^{124}Xe and ^{238}U ions. The signal amplitudes form U data is scaled by 0.58. Note: $Z(Xe)^2/Z(U)^2$ is 0.34.

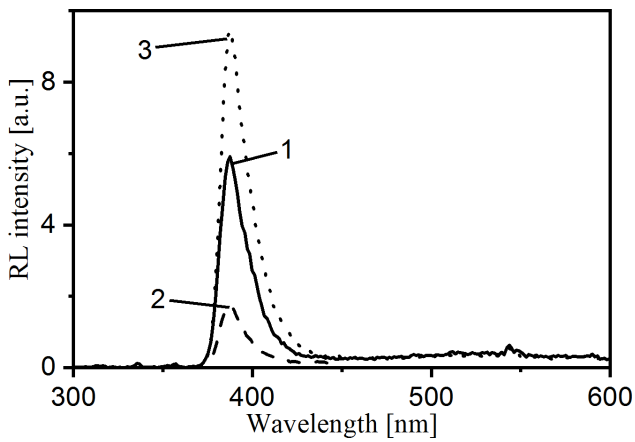

Figure 6: Optical characteristics of ZnO:In ceramics. Radioluminecence spectra under continuous excitation by an x-rays: 1 –- initial sample; 2 –- after irradiation with ^{238}U; 3 –- after annealing, figure from Ref. [4].

heavy ions has shape similar to the one obtained with x-ray excitation. The depth of the layer in ZnO in which the Sn ions and x-rays penetrate is similar but the deposited energy density per ion/x-ray differs dramatically.

SUMMARY AND FUTURE PLANS

In summary, ZnO:In and ZnO:Ga are promising substitutes of the plastic scintillators used in heavy ion detection applications. The first investigation with relativistic heavy ions showed that:

- the observed rise and decay times are faster than those of BC400 plastic scintillators.
- the radiation hardness of ZnO is at least two orders of magnitude higher compared to plastic scintillators.

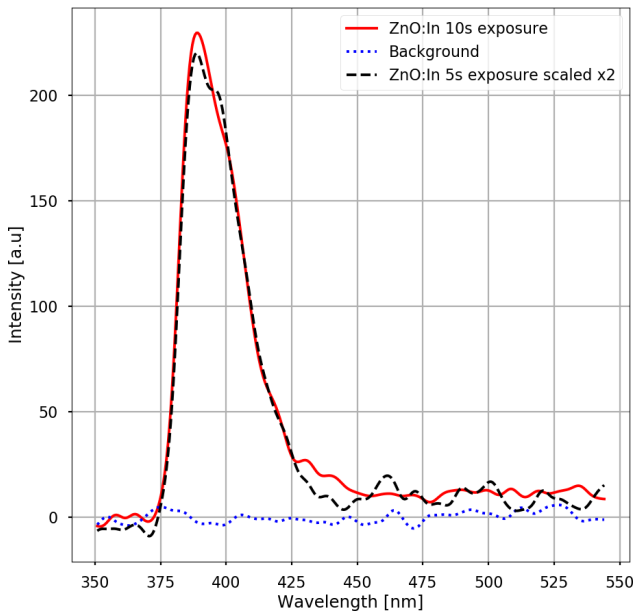

Figure 7: Optical characteristics of ZnO:In ceramics under irradiation with 4.8 MeV/u ^{120}Sn ions. The two spectra are taken with 5 and 10 s exposure time.

Further development of higher light output ZnO materials and large area detectors for particle counting and time of flight measurements is ongoing in collaboration between: Peter the Great Saint Petersburg Polytechnic University, GSI, Institute of Solid State Physics of University of Latvia with the framework of the ERA.Net RUS Plus, Project RUS_ST2017-051.

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