Abstract
Scintillation screens are widely used for qualitative beam profile monitoring. However, precise measurements might yield ambivalent results especially for high beam currents. We have investigated the optical properties of various scintillating materials with different beams in the energy range 5.5 to 11.4 MeV/u delivered by the heavy ion LINAC at GSI. Investigations were not only focused on well-known sensitive scintillators but also on ceramic materials with lower light yield. Their properties (yield, beam width, higher statistical moments) were compared to different Quartz-glasses. The image of each macro-pulse was recorded by a digital CCD camera and individually evaluated. For some materials, a decrease of the light yield occurs. For a focused beam, the imaged width depends on the material. Moreover, the light yield and width depends significantly on the screen temperature, which is increased by beam impact.

DEMANDS AND SETUP
Since decades, scintillation screens are widely used for beam profile measurement in nearly all accelerator facilities. Moreover, these screens are an essential part of a pepper-pot emittance system used for the determination of the width of ‘beamlets’ created by a plate with ≈100 small holes, The realization at GSI as used for the high current operation of UNILAC is described in [1]. The angular distribution within the phase space is calculated from the intensity distribution of the ‘beamlets’. This requires an accurate measurement of the spot’s light distribution. However, there had been doubts concerning the accuracy of the pepper-pot method [2], which might be related to possible image deformation by the scintillating screen.

We investigated the optical properties of 16 fluorescence materials with beams of C²⁺, Ar¹⁰⁺, Ni³⁺ and U⁸⁺ ions at energies between 5.5 and 11.4 MeV/u and different beam currents as delivered by UNILAC at GSI. Typical sizes for the focused beam were σ≈2mm. Sensitive scintillation screens, like YAG:Ce or ZnS:Ag were irradiated in addition with lower currents. Ceramic materials with less light yield, like BN, ZrO₂, ZrO₂ doped with Mg, pure Al₂O₃ and Al₂O₃ doped with Cr (Chromox) were investigated and compared to Quartz-glass (Herasil 102) and Quartz-glass doped with Ce (M382), see Table 1.

A movable target ladder, as shown in Fig.1, was equipped with 6 different screens of Ø30mm and installed in a vacuum chamber. The irradiations were performed with pressure of ≈5·10⁻⁷ mbar. The target ladder allows beam observations without longer interruption, which ensures the same beam properties for all materials. The scintillation was observed by a digital CCD camera (AVT-Marlin) equipped with a monochrom chip of VGA resolution. A Pentax B2514ER lens system of 25 mm focal length equipped with a remote controlled iris was used for compensation of material dependent light yield. Moreover, the camera’s inherent amplifier was changed by the gain setting. The calculation of the light yield corrects both settings. The reproduction scale for the beam image was 10 pixel/mm. Data transmission was performed by the camera’s Firewire interface to a high performance data acquisition system [3] which enables the storage of an image from each macro-pulse for individual offline analysis.

Table 1: Compilation of investigated materials

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal Scintillator</td>
<td>YAG:Ce, BGO, CdWO₄, CaF₂:Eu</td>
<td>Saint Gobain Crystals</td>
</tr>
<tr>
<td>Powder</td>
<td>ZnS:Ag</td>
<td>HLW</td>
</tr>
<tr>
<td>Ceramics</td>
<td>ZrO₂(Z700 20 A), ZrO₂:Mg (Z507), BN, Al₂O₃ and Al₂O₃:Cr (Chromox)</td>
<td>BCE Special Ceramics</td>
</tr>
<tr>
<td>Quartzglass</td>
<td>Pure: Herasil 102, Ce doped: M382</td>
<td>Heraeus Quartzglass</td>
</tr>
</tbody>
</table>

Figure 1: The target ladder equipped with Ø30mm screens is shown. The screen materials prior to irradiation are from left: pure Al₂O₃, Al₂O₃:Cr, Herasil, Quartz:Ce, ZrO₂ and YAG:Ce.

TYPICAL RESULTS AND ANALYSIS
The original beam image (an example is shown in Fig.2 top) was projected to the beam’s horizontal and vertical plane. A quantitative analysis was performed with the projection. In this work we show the horizontal projection but comparable results were obtained for the vertical direction. Two examples of such projections are shown in Fig. 2 bottom. For both displayed materials the total light yield decreases during irradiation. The shape of the peak is preserved for ZrO₂:Mg (shown left). On the contrary, for Al₂O₃ (shown right) the shape is modified mainly around the maximum; this behavior is reflected by a
broader width $\sigma$ of about 11%. A typical increase of $\approx 10\%$ corresponds to 0.2 mm, which is too small to be detected by a SEM-Grid, and is of minor importance in case of regular beam alignment. However, for the pepper-pot method it results in an overestimation of the emittance value. For the characterization of the distribution $p(x_i)$ not only the centre $\mu$ ($1^{st}$ moment) and standard deviation $\sigma$ ($2^{nd}$ moment) were used, but also the skewness $\gamma$ ($3^{rd}$ moment), describing the asymmetry and the kurtosis $\kappa$ ($4^{th}$ moment), describing the peakedness of the distribution as given by:

Skewness: $\gamma = \frac{1}{\sum p_i} \sum p_i \left( \frac{x_i - \mu}{\sigma} \right)^3$

Kurtosis: $\kappa = -3 + \frac{1}{\sum p_i} \sum p_i \left( \frac{x_i - \mu}{\sigma} \right)^4$

Figure 2: Examples of an original beam image (top) and the projection for ZrO$_2$:Mg (left) and Al$_2$O$_3$ (right) targets irradiated by 40 $\mu$A U$^{238+}$ at 11.4 MeV/u. The variation form 1$^{st}$ to 60$^{th}$ pulse are for ZrO$_2$:Mg concerning the width form $\sigma = 1.78$mm $\rightarrow$ 1.83mm, for the kurtosis from $\kappa = -0.50$ $\rightarrow$ -0.61. For Al$_2$O$_3$ it varies significantly from $\sigma = 1.30$mm $\rightarrow$ 1.45mm and $\kappa = -0.66$ $\rightarrow$ -0.88.

MEDIUM CURRENT INVESTIGATIONS

For a medium current of 30 $\mu$A and 100 $\mu$s delivery of Ar$^{10+}$ beam at 11.4 MeV/u, the light yield and the beam width for different materials are compared in Fig. 4. As expected, the investigated materials have up to two orders of magnitude different light yield (integrated over 100 $\mu$s beam delivery) with Al$_2$O$_3$:Cr being the most and ZrO$_2$ the least sensitive material. This is consistent to a measurement reported by CERN [5]. The light yield was nearly constant during the irradiation for all materials. However, the determined beam width differed in a reproducible manner between the materials: For the given beam parameters Herasil showed 22 $\%$ smaller width compared to ZrO$_2$:Mg. For three materials (BN, Al$_2$O$_3$:Cr and ZrO$_2$) the same width was recorded. As depicted in Fig. 5, the shape of the distribution differed for the materials, as represented by the relative peakedness. While the centre and the skewness were the same for all materials within the statistical fluctuations. The described behaviour was reproduced with other ion beams of comparable parameters.

The average beam power for the parameters of Fig. 4 was 150 mW resulting in an average temperature of 47$^\circ$C on the backside of the ZrO$_2$:Mg screen as determined by a PT100 thermo-element. The peak power was 1.5 kW. Temperature effects will be discussed later on.

Figure 3: Left: Light yield and beam width $\sigma$ for BN target irradiated by 1800 macro-pulses of $\approx 4 \times 10^{10}$ ppp Ar$^{10+}$ at 11.4 MeV/u. Right: The $\Phi 30$mm BN screen after irradiation.

Figure 4: Light yield and beam width for different materials irradiated by 1000 macro-pulses of 1 Hz repetition rate with $\approx 2 \times 10^9$ ppp Ar$^{10+}$ at 11.4 MeV/u.

SURFACE MODIFICATION

In Fig. 3 an example is shown for the irradiation with a high current 11.4 MeV/u Ar-beam of about $4 \times 10^{10}$ particles per pulse (ppp) which corresponds to 0.7 mA and a 100 $\mu$s long pulse. The light yield of the BN screen decreased within the 1800 macro-pulses where as the beam width increased significantly caused by an irreversible damage of the screen. As expected from investigations of BN at CERN [4], the initially white surface became grey. Comparable surface modifications were observed for most ceramic materials with the least changes for ZrO$_2$:Mg. However, these modifications do not necessarily imply a lower light yield. In particular, ZrO$_2$ showed a very fast surface modification without significant decrease of the yield; this result confirms the finding in [4]. By baking ZrO$_2$ to 250$^\circ$C over 4 hours, this modification was reversible. The investigated Quartz-glass Herasil showed no visible, permanent surface modification.

Figure 5: Left: Light yield and beam width $\sigma$ for BN target irradiated by 1800 macro-pulses of $\approx 4 \times 10^{10}$ ppp Ar$^{10+}$ at 11.4 MeV/u. Right: The $\Phi 30$mm BN screen after irradiation.
Presently, the reason for the different width reading is not well understood; it might be attributed to saturation effects or self-absorption. The different values of the kurtosis could help to clarify this topic. A more positive value is expected if absorption dominates, while a more negative value should occur for saturation. Moreover, a diffuse refraction at the surface and within the bulk material could contribute to a broadening. For ceramics it could be more pronounced due to the finite grain size. A laser-based method described in [5] let to estimate a spatial resolution for Al₂O₃:Cr ceramics to be \(\approx 100\mu m\) (compared to 50 \(\mu m\) for YAG:Ce and 35 \(\mu m\) for CsI, respectively). Since in all cases previously untreated materials were used, the broadening cannot be attributed to any surface degradation caused by the beam, as discussed above for Fig. 3.

**HIGH CURRENT INVESTIGATIONS**

The interest of pepper-pot emittance measurements arises from the UNILAC high current operation with several mA. An example for high current measurement is shown in Fig. 6 where the screens were irradiated by Ar¹⁰⁺ with a current of 310 \(\mu A\) within 100 \(\mu s\) delivery time corresponding to \(2\times10^{10}\) ppp. The peak power was \(\approx 14\) kW while the average power was 3.8 W. As expected the light yield of the various materials differed of several orders of magnitude. In contrary to the medium current measurement of Fig. 4, the yield of ZrO₂:Mg relative to the other materials is lower.

For the four materials Quartz:Ce, ZrO₂:Mg, BN and Heraasil the yields dropped significantly during the irradiation. The determined image widths vary within a factor of 2. The variation is larger as compared to the medium current measurement. A light yield decrease coincides with a smaller image width reading, but with a slightly different time constant. Since it was expected that the yield reduction is correlated with the screen temperature, a break in the beam delivery of 3 min was scheduled to let the screens relax to the original room temperature. For Heraasil and ZrO₂:Mg the behaviour of the image width for Heraasil and ZrO₂:Mg can be qualitatively described by the fact that the material is significantly stronger heated at the beam centre as compared to the beam edges. This results in a dominant decrease of the light yield at the peak area. After a certain (material dependent) irradiation time, a steady-state temperature distribution is reached leading in a constant yield and width reading.

For the Al₂O₃:Cr the yield increases with temperature. It might be related to an increased excitation probability from trapped states of the lattice (as it is the basis of thermo-luminescence). Whereas BN and Quartz:Ce the discussed irreversible decrease of the light yield seems to dominate. Due to the different temperature dependent physical processes for the various materials, it does not astonish that the equilibrium width reading differs. For a quantitative interpretation, a detailed model is required.
taking thermal diffusion, emissivity and temperature dependent light yield into account.

To investigate the temperature dependences, variable breaks between the irradiation were introduced to allow cooling to room temperature. As depicted in Fig. 7 for Herasil and ZrO₂:Mg, the length of the break did neither influence the time constant for the yield reduction, equilibrium value nor the width reading. It also proved the reproducibility for those materials.

![Figure 7](image7.png)

Figure 7: Light yield and beam width for ZrO₂:Mg and Herasil irradiated by 5500 macro-pulses of 2.4 Hz repetition rate with \( \approx 2.4 \times 10^{10} \) ppp Ar\textsuperscript{10}\textsuperscript{+} at 11.4 MeV/u; break durations are indicated. (The irradiation time varies.)

LOW CURRENT INVESTIGATIONS

For comparison the properties of ‘well known’ scintillators under low current irradiation were investigated. In Fig. 8 the results are shown for the 17 nA C\textsuperscript{2+} beam of 100 µs length and 12.6 Hz repetition rate. The average power was 0.6 mW and the peak power 1.1 W. The yield of the materials differs by one order of magnitude with YAG:Ce being a very efficient scintillator. However, even for these materials, quite different image widths were recorded. BGO showed the smallest value, while irradiation of YAG:Ce, CdWO₄ and CaF₂:Eu results in a \( \approx 25\% \) larger reading. This is remarkable, because YAG:Ce is frequently used for low current beams profile measurements. The powder ZnS:Ag shows a significant decrease of the yield and width reading even for this low current irradiation with light ions i.e. low energy deposition.

CONCLUSION

Several scintillation materials were investigated under various beam conditions. Different readings of the image width for various materials were determined even for ‘well known’ crystalline scintillators. The described behavior was reproducible under different beam conditions. Further data analysis is in progress to distinguish between saturation, diffuse refraction and self-absorbing of scintillation light. Statistical moments are considered for this purpose, but an interpretation might be difficult due to the presence of several effects. Additional beam-based tests are required to distinguish between these effects. For high current applications, the properties seem to be strongly dependent on the surface temperature, which is significantly increased during beam delivery. This knowledge is essential for choosing a well-suited material for the peeper-pot emittance device. Following the high current investigations at least BN and Quartz:Ce can’t be used due to the permanent degradation. It seems that Herasil is a good candidate, because it shows a narrow image width and no significant surface modification even by high current irradiation. Being a transparent material, the diffuse reflections at the grain boundaries are avoided. However, its suitability has to be confirmed by ongoing beam-based investigations.

ACKNOWLEDGEMENT

We acknowledge the valuable discussion and practical support by T. Sieber and M. Frauenfeld from MPI-Kernphysik, Heidelberg. Moreover, we thank Z. Soares Macedo and G. C. Santana from University of Sergipe, Brazil for the supplier of several BGO ceramics [8].

REFERENCES