Abstract—At GSI, the Helmholtz Centre for Ion Research, the properties of scintillation screens, irradiated by an ion beam, were studied. For various materials, the different ion beams H⁺, C²⁺, Ar⁴⁺, Ni⁹⁺, Ta²⁴⁺, and U²⁸⁺ in the energy range from 4.8–11.4 MeV/u were applied with currents ranging from nA to some mA, delivered by the heavy ion LINAC at GSI. Scintillation screens are widely used for qualitative ion beam profile monitoring. However, precise measurements of the beam profile yield ambivalent results, especially for high beam currents. Thus, the properties (light yield, beam width, and higher statistical moments) of well-known scintillators, ceramic materials, and different quartz glasses are compared. The image of each ion beam pulse was recorded by a digital CCD camera and individually evaluated. A change of the imaged ion beam shape was observed for some materials. The recorded beam profile shows dependence on the scintillator material. Even for low beam intensities (17 nA) a difference in the beam width of about 25% was measured. Additionally, the light yield and beam width depend significantly on the screen temperature, which is increased by the ion impact. For ZrO₂ : Al the influence of the screen temperature on the statistical moments was investigated. Furthermore the spectra of scintillation screens were studied in the region from 350 to 750 nm for the irradiation with H⁺ and Ta²⁺ ions. Empirical results are discussed and give rise to further investigations on the materials.

Index Terms—Accelerator beam line instrumentation, ion accelerators, ion radiation effects, luminescent devices, particle beam instrumentation, radiation effects, scintillator devices, spectral analysis.

I. INTRODUCTION

For DECADES, scintillation screens have been widely used for beam profile measurement in nearly all accelerator facilities as reviewed in [1]. Moreover, these screens are an essential part of a pepper-pot emittance system, a device to determine the brilliance of the ion beam. The pepper-pot setup at the Helmholtz Centre for Ion Research (GSI), as used for the high-current operation of the LINAC, is described in [2]. The angular distribution within the phase space is calculated from the intensity pattern of the “beamlets” on the scintillation screen. This requires an accurate measurement of the light distribution of the beam spots. However, there have been doubts concerning the accuracy of the pepper-pot method [3], [4], which might be related to a possible image deformation by the scintillation screen as reported, for example, in [5] and [6]. The properties of 16 luminescent materials (see Table I) were investigated for the irradiation with beams of H⁺, C²⁺, Ar⁴⁺, Ni⁹⁺, Ta²⁴⁺, and U²⁸⁺ ions at energies between 4.8 and 11.4 MeV/u and different beam currents as delivered by the LINAC.

The ceramic materials with less light yield, such as BN, ZrO₂ : Al, ZrO₂ : Mg, pure Al₂O₃ and Al₂O₃ : Cr (Chromox), were compared to Quartz-glass (Herasil 102) and Quartz-glass doped with Ce (M382). The efficient scintillation screens, such as the single crystal YAG:Ce or ZnS:Ag powder, were irradiated in addition with a lower current (some nA). A movable target ladder for subsequent irradiation of the target materials as shown in Fig. 1, was equipped with six different screens of 30 mm in diameter and installed in a vacuum chamber. The irradiations were performed at about 5 · 10⁻⁷ mbar. The target ladder allows variation of the investigated material without breaking the vacuum, which ensures the same beam properties for all materials on the ladder. The various materials are subsequently irradiated with the ion beam in the setup schematically shown in Fig. 2. Each position on the target ladder was individually inserted into the beam path, while all the other positions were not affected by the beam, due to the typical ion beam size of σ = 2 mm. Each material was irradiated for a fixed time with constant beam current and then replaced by the next position on the ladder. The scintillation process was observed by a digital charge-coupled device (CCD) camera (AVT-Marlin, 8-bit ADC) with a monochrome chip of VGA resolution. The Pentax B2514ER lens system of 25 mm focal length was used equipped with a remote-controlled iris for compensation of the material-dependent light yield. The relative light yield of

### TABLE I

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single crystal</td>
<td>YAG:Ce, BGO, CdWO₄, CaF₂:Eu</td>
<td>Saint Gobain Crystals</td>
</tr>
<tr>
<td>Ceramic</td>
<td>ZrO₂:Al (Z700-20A), ZrO₂:Mg (Z507), BN, Al₂O₃, Al₂O₃:Cr (Chromox), Si₃N₄</td>
<td>BCE Special Ceramics</td>
</tr>
<tr>
<td>Ceramic</td>
<td>GOS</td>
<td>Hitachi Metals</td>
</tr>
<tr>
<td>Ceramic</td>
<td>BGO undoped</td>
<td>G. C. Santana [13]</td>
</tr>
<tr>
<td>Quartz glass</td>
<td>Quartz (Herasil 102), Quartz:Ce (M382)</td>
<td>Heraeus Quarzglas</td>
</tr>
<tr>
<td>Powder</td>
<td>ZnS:Ag</td>
<td>HLW</td>
</tr>
</tbody>
</table>

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skewness and the kurtosis. The skewness root of second moment, beam width) were used, but also the light intensity range. showed that the deviation of beam width is below 1% for the CCD-Chip, on the results of the calculation algorithm that the chromatic abberation of the optics is negligible. Inves-
tests in the range 400 to 800 nm show (macropulse) with typically 1 Hz for individual offline analysis. which enables the storage of one image per ion beam pulse to a high-performance data acquisition system [7]

The reproduction scale for the beam image was 10 pixel/mm. Data transmission was performed via the Firewire interface of the camera to a high-performance data acquisition system [7] which enables the storage of one image per ion beam pulse (macropulse) with typically 1 Hz for individual offline analysis. Test bench measurements in the range 400 to 800 nm show that the chromatic aberration of the optics is negligible. Investigations concerning the influence of integrated light intensity on the CCD-Chip, on the results of the calculation algorithm showed that the deviation of beam width is below 1% for the used light intensity range.

II. ANALYSIS OF THE DATA

The original image of the beam spot is projected to the horizontal and vertical plane as shown in Fig. 3. In this work the quantitative analysis for the horizontal projection are presented, but comparable results are also obtained for the vertical one. For the characterization of the projected intensity distribution not only its center \( \mu \) (first moment) and standard deviation \( \sigma \) (square root of second moment, beam width) were used, but also the skewness and the kurtosis. The skewness \( \gamma \) (\( \propto \) third moment) is a measure for the asymmetry and the kurtosis \( \kappa \) (\( \propto \) fourth moment) for the peakedness of the distribution [8]. Although skewness and kurtosis are normalized to the standard deviation \( \sigma \), the performed data analyses show a correlation to the third and fourth moment respectively. An example for the analysis of the projection is shown in Fig. 4. The presented material is Quartz:Ce, which was irradiated by an \( \text{Ar}^{10+} \) beam with \( 2 \cdot 10^9 \) particles per pulse (ppp). The plot shows the light yield, the beam width, the skewness and the kurtosis as a function of the integrated number of particles. Each point in the curves represents the value for the respective moment of one projected image (one macropulse). Not only the total light yield decreases during irradiation, but also the shape of the peak is modified. This behavior is represented by a broadening of the beam width \( \sigma \) of about 8% and the changing value of the kurtosis. The value of the skewness shows that the peak is symmetric at the beginning of the irradiation (starting from almost zero) and also the kurtosis starts from zero, which represents a gaussian peakedness. It should be pointed out that the time constants for the changes in skewness and kurtosis in Fig. 4 are not the same. A change of 8% in \( \sigma \) corresponds to \( \sim \) 0.2 mm in Fig. 4, which is too small to be detected by a SEM-Grid (for SEM-Grid see [9]) 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.

III. VISIBLE TARGET MODIFICATION

In Fig. 5 an example for the irradiation with a high-current 11.4 MeV/u \( \text{Ar}^{10+} \) beam of about \( 4 \cdot 10^{10} \) ppp which corresponds to 700 \( \mu \)A and a 100 \( \mu \)s long pulse is shown. The light yield of the BN screen decreases within the 1800 macropulses. The beam width increases significantly due to an irreversible change of the luminescent properties of the screen. As expected from investigations on BN at CERN [10] the initially white surface becomes gray. Comparable modifications are observed for most ceramic materials with the least changes for \( \text{ZrO}_2 : \text{Mg} \). However, these modifications do not necessarily imply a lower light yield. In particular, \( \text{ZrO}_2 : \text{Al} \) shows a very fast change in

Fig. 1. Target ladder equipped with six screens of 30 mm diameter. The shown screen materials are unirradiated. (From left to right) Pure \( \text{Al}_2\text{O}_3 \), \( \text{Al}_2\text{O}_3 \) : Cr, Herasil, Quartz:Ce, \( \text{ZrO}_2 \) : Al, and YAG:Ce.

Fig. 2. Principle of the experimental setup. The target ladder is tilted by 45° with respect to the beam and is movable perpendicular to the plane of the paper, for the successive measurement of the target material properties. The light is necessary to determine the condition of the targets before and after the measurement series.

![Principle of the experimental setup](image)

Fig. 3. Example of an original image from the CCD camera and the projections of the beam spot on the horizontal and vertical axis.

![Example of an original image from the CCD camera and the projections of the beam spot on the horizontal and vertical axis](image)
color without significant decrease of the light yield; these results confirm the findings in [10]. By heating ZrO$_2$ : Al up to 250 °C for over 4 h in air, this modification is reversible. The temperature had to be increased to about 600 °C to remove the modifications caused by Ni$^{9+}$ and Ta$^{24+}$ beams. The modification of ZrO$_2$ : Al does not occur for a proton beam, when the screen is heated on the backside, within the vacuum chamber, to ∼300 °C. The investigated Quartz-glass (Herasil) shows no visible modification.

IV. MEDIUM CURRENT INVESTIGATION

For a medium current of 30 µA and 100 µs pulse length of Ar$^{10+}$ beam at 11.4 MeV/u, the light yield and the beam width for different materials are compared in Fig. 6. As expected from previous measurements, the investigated materials have up to two orders of magnitude different light yield (integrated over 100 µs pulse length) with Al$_2$O$_3$ : Cr having the highest and ZrO$_2$ : Al the lowest light yield. Comparable experiments were performed at CERN [10]. During the irradiation there are only slight changes in the light yield for each material compared to the high-current case (presented below). However, the determined beam width differs in a reproducible manner between the materials. For the given beam parameters Herasil shows 22% smaller width compared to ZrO$_2$ : Mg. For three materials (BN, Al$_2$O$_3$ : Cr, and ZrO$_2$ : Al) the same beam width is determined. As depicted in Fig. 6, the shape of the distribution differs for the materials (relative peakedness), while the value for the skewness (not shown) is the same for all materials within the statistical fluctuations. The described behaviors were reproduced with other ion beams of comparable parameters. The average beam power for the parameters of Fig. 6 was 146 mW (1.5 kW peak power) resulting in an average temperature of 47 °C on the backside of the ZrO$_2$ : Mg screen as obtained by a PT100 temperature sensor. Temperature effects will be discussed later on. Comparable results were also obtained by a 4.8 MeV proton beam with 3.9 · 10$^{11}$ ppp within 4 ms beam delivery and 2 Hz repetition rate, corresponding to a peak power of 75 W and an average power of 600 mW. This is not obvious, due to the different initial stopping power, which is by a factor of ∼150 higher for Ar$^{10+}$ compared to protons. Presently, the reason for the different width reading is not well understood, but 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 kurtosis is expected when absorption dominates, while a more negative value should occur for saturation. Moreover, for the ceramic materials, a diffuse refraction at the grain boundaries could also contribute to a broadening of the imaged beam width, which will be investigated in the near future. Since in all cases previously unirradiated materials were used, the broadening cannot be attributed to any visible target degradation caused by the beam, as discussed for Fig. 5.

V. HIGH-CURRENT INVESTIGATION

The interest for pepper-pot emittance measurements arises from the UNILAC high-current operation with several mA. Data obtained for high-current irradiation are shown in Fig. 7. The screens were irradiated by Ar$^{10+}$ with a current of 310 µA within 100 µs pulse length corresponding to 2 · 10$^{10}$ ppp ($P_{\text{avg}} = 3.8$ W, $P_{\text{peak}} = 14$ kW). As expected, the light yield of the various materials differs by several orders of magnitude. In contrary to the medium current measurement (Fig. 6) the relative light yield of ZrO$_2$ : Mg is lower compared to the other materials. For the four materials Quartz:Ce, ZrO$_2$ : Mg, BN, and Herasil the light yields drop significantly during the irradiation. The determined beam width varies within a factor of two, which is larger in comparison to the medium current measurements. The light yield decreases coincidently with the imaged beam width, but with a slightly
Hz repetition rate at 11.4 MeV/u screens cool down. A break in the beam delivery of 3 min was scheduled to let the screen cool down, followed by 10 min irradiation. A 3 min break was introduced to let the screen cool down, followed by 10 min irradiation.

The materials Heraasil, Al\(_2\)O\(_3\), Al\(_2\)O\(_3\) : Cr, and ZrO\(_2\) : Mg recover almost to its initial state. Moreover, the light yield and the imaged beam width show reproducible time behavior and reach a constant value. BN suffer probably from permanent modification (Fig. 5), while for Quartz:Ce the light yield decreases permanently (without visible target modification, Fig. 4). For Al\(_2\)O\(_3\) the light yield is constant, whereas for Al\(_2\)O\(_3\) : Cr it even increases. In both cases, a broadening of the beam width occurs in a reproducible manner. For all materials the center and the skewness are almost constant (not shown). The kurtosis is not shown in Fig. 7 because of the complex time behavior, which shows that not only the imaged beam width changes but also the whole shape of the distribution. Using a PT100 temperature sensor at the backside of ZrO\(_2\) : Mg, a screen the average temperature of 240 °C was determined for comparable beam parameters with an average power of 2.3 W (respectively to 3.8 W for the measurements shown in Fig. 7). However, the front-side temperature during 100 µs beam delivery was much higher due the ion range of about 20 to 70 µm (depending on the ion species, its energy, and the target density). The interpretation of the temperature behavior is challenging. As reviewed in [11] and [12] the light yield of crystal scintillators (such as NaI:Tl, BGO, and CaWO\(_4\)) decreases as a function of temperature. It is related to a higher probability of nonradiative return from the excited state to the ground state, competing with the radiative return. After a certain (material-dependent) irradiation time, a steady-state temperature distribution is reached, which is leading to a constant light yield and beam width. For Al\(_2\)O\(_3\) : Cr the yield increases with temperature. It might be related to an increased excitation probability from trapped states in the lattice (see [12]). Whereas for 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, the equilibrium width reading differs. Presently, we are lacking a detailed knowledge of these properties for the investigated materials. For a quantitative interpretation, a detailed model is required taking thermal diffusion, a temperature-dependent light yield and scintillation light transport into account.

For the investigation of the temperature dependence, a Ni layer (heating loop) was sputtered on the backside of ZrO\(_2\) : Al screen to heat the sample up to 300 °C. The Ni-layer was equipped with two connectors on each end. Thus, one can send a current through the layer and can measure the voltage via the two other connectors. By knowing the temperature dependence of the resistance for the Ni-layer, the average temperature on the backside of the screen can be determined. The light yield and the beam width for ZrO\(_2\) : Al with three different heating levels are shown in Fig. 8. The sample was irradiated by a proton beam with 3.9 \times 10^{11} ppp within a pulse length 4 ms beam delivery and a repetition rate of 2 Hz. The heating power was kept...
constant for each curve, but the sample was additionally heated by the ion beam. Thus, the temperature on the backside of the sample increases during the irradiation. Beside an initial phase, which is challenging to interpret, it is observable that the equilibrium light yield and the imaged beam width increases with the temperature. The light yield increases by a factor of 4 and the imaged beam width by a factor of 1.5 in the temperature range from 125 °C to 210 °C. During the measurement for the red curve (180 °C to 210 °C) the ion beam changed its shape a little for about 150 pulses, which is represented by an abrupt change in σ, but this is of minor importance for the results. These results clearly point out that the temperature of the scintillation screen is a critical issue, especially for high-current ion beams.

VI. LOW-CURRENT INVESTIGATION

For comparison the properties of purpose built scintillators under low-current irradiation were investigated. In Fig. 9 the results are shown for the 17 nA C^{2+} ion beam of 100 μs pulse length and 12.6 Hz repetition rate \( (P_{\text{avg}} = 138 \text{ mW}, P_{\text{peak}} = 1.1 \text{ W} \). The PT100 temperature sensor on the backside of the ZnS:Ag powder target showed no additional heating from the beam impact. The light yield of the materials differs by one order of magnitude. However, even for purpose-built scintillators, quite different beam widths are recorded, without a detectable heating from the ion beam. The BGO shows the smallest value for σ, while YAG:Ce, CdWO₄, and CaF₂: Eu depict a 25% larger beam width. This is remarkable, because YAG:Ce is frequently used for low-current beam profile measurements. The powder ZnS:Ag shows a constant decrease of the yield and beam width reading, even for the low-current irradiation with light ions, i.e., low-energy deposition. However, all the materials shown in Fig. 9 cannot be used for higher beam currents, because of the permanent radiation damage (see also Fig. 4).

VII. SPECTROSCOPIC STUDIES

The spectroscopic studies on the scintillation screens were performed with a Jobin Yvon Horiba CP140-202 spectrograph. The optical design includes a spherical mirror with 70 mm in diameter, which is holographically etched and astigmatism corrected with 140 mm focal length. A spectral dispersion of 50 nm/mm and an image field of 8 x 12 mm were achieved. With an optical resolution of 33 lp/mm the Image Intensifier CCD Camera (ICCD) limits the spectral resolution to 1.5 nm for an entrance slit ≤ 30 μm. The spectrograph was calibrated with a Mercury-Argon light source (CAL2000) from Ocean Optics. A limiting factor in the experimental setup is the low sensitivity of the tri-alkali (Na₂K₁S₅b)Cs photocathode (Fig. 10, top) for wavelengths above 600 nm.

The spectra of six different scintillation screens irradiated with a Ta^{24+} and a H⁺ ion beam are shown in Fig. 10. By comparing the luminescence spectra for Al₂O₃, Al₂O₃ : Cr, BN, Herasil, and ZrO₂: Al some significant differences due to the ion species occur. The recorded spectra of Al₂O₃ show two completely different patterns for the Ta^{24+} and the H⁺ beam. The Al₂O₃ : Cr displays a strong line around 520 nm. For Ta^{24+} an increase of the lower wavelength shoulder at ~490 nm and a line shift of about 10 nm are observed. By comparing the spectra of pure Al₂O₃ and Al₂O₃ : Cr, one can clearly see the influence of the host lattice on the band around 490 nm. For BN and Herasil the bands around 460 nm are clearly effected by the ion species. The additional sharp line around 515 nm on the recorded ZrO₂ : Al spectrum obtained with H⁺ is unexpected and has to be investigated more in detail. There is no significant change in the spectrum of ZrO₂ : Mg. The screen
temperatures are different for Ta$^{24+}$ and H$^+$ during the irradiation process, due to the different heating power of the beams ($P_{\text{avg}} - \text{Ta} = 2.91 \, \text{W}$, $P_{\text{avg}} - \text{H} = 631 \, \text{mW}$), which could cause a slight shift in the spectra.

To investigate the influence of the screen temperature on the spectrum, temperature studies were performed. The three different heating levels in Fig. 11 were applied via a heating loop on the ZrO$_2$:Al scintillation screen, as discussed for Fig. 8. Starting from room temperature with no additional heating up to a basic temperature of $\sim 245 \, ^\circ\text{C}$ for Ta$^{24+}$ and $\sim 272 \, ^\circ\text{C}$ for H$^+$. The basic temperatures are slightly different for Ta$^{24+}$ and for H$^+$ as well as average heating power of the beam. For the broad band at $\sim 480 \, \text{nm}$, a slight shift into higher wavelengths during the heating process is observed. Furthermore, the bands around 400 and 725 nm are strongly affected by the increase in temperature. An additional interesting observation is that there is no change in the position for the sharp line around 515 nm in the ZrO$_2$:Al spectra with H$^+$ ions. It turns out that the influence of the screen temperature on the spectrum is bigger for the irradiation with H$^+$ than for Ta$^{24+}$.

VIII. CONCLUSION

Several scintillation materials were investigated under various beam conditions. Different readings of the imaged beam width for various materials were determined even for purpose-built crystalline scintillators. These results were obtained with H$^+$ ions, as well as heavier elements up to U$^{28+}$. The observed behaviors are reproducible under different beam conditions. Due to the possibly high surface temperature, it is intended to introduce a filter in front of the Pentax lens system, to avoid image deformation due to infrared radiation. The influence of the surface roughness and grain size has to be investigated for the ceramics. Additionally, the linearity of the investigated scintillating materials has to be determined. Further data analysis is in progress to investigate the contribution of saturation, diffuse refraction, and self-absorption of scintillation light by evaluation of the higher statistical moments. Additional ion-beam-based experiments are required to distinguish between these effects.

For high-current applications, the properties are influenced by the temperature of the screens, which is significantly increased during irradiation. This knowledge is essential for choosing a well-suited material for the pepper-pot emittance device. Following the high-current investigations at least BN and Quartz:Ce cannot be used due to the permanent degradation. It seems that ZrO$_2$: Mg and Herasil are good candidates for a high-current application. ZrO$_2$: Mg has a high light yield, it does not show a significant visible modification, and its spectrum seems not to depend on the ion species. Herasil showed a narrow imaged beam width and being a transparent material the diffuse reflections at the grain boundaries are avoided, but its spectrum shows a significant change for Ta$^{24+}$ compared to H$^+$.

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The authors would like to thank Dr. Friedemann Völklein from the University of Applied Sciences Wiesbaden, Germany for the preparation of the nickel heating loop on one of the screens. The authors also like to thank Winfried Barth and Michael Scholz from GSI for the disposal of some valuable beamtime. Moreover, the authors thank G. C. Santana from the University of Sergipe, Brazil for the fabrication of several BGO ceramics [13].

REFERENCES

Correction to “Scintillation Screen Investigations for High-Current Ion Beams”

Eiko Gütlich, Peter Forck, Wolfgang Ensinger, and Beata Walasek-Höhne

In the original paper [1], due to an unexpected complication during the calibration of the spectrometer for Figs. 10 and 11, some corrections have been made to Figs. 10 and 11. The revised figures follow. Also, due to the changes in Figs. 10 and 11, some data and text has changed in Section VII–Spectroscopic Studies. Section VII, with updated data and text, follows.

The spectroscopic studies on the scintillation screens were performed with a Jobin Yvon Horiba CP140-202 spectrograph. The optical design includes a spherical mirror with 70 mm in diameter, which is holographically etched and astigmatism corrected with 140 mm focal length. A spectral dispersion of 50 nm/mm and an image field of $8 \times 12$ mm were achieved. With an optical resolution of 33 lp/mm the Image Intensifier CCD Camera (ICCD) limits the spectral resolution to 1.5 nm for an entrance slit $\leq 30 \mu$m. The spectrograph was calibrated with a Mercury-Argon light source (CAL2000) from Ocean Optics. A limiting factor in the experimental setup is the low sensitivity of the tri-alkali (Na,K,Sb)Cs photocathode (Fig. 10, top) for wavelengths above 600 nm.

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To investigate the influence of the screen temperature on the spectrum, temperature studies were performed. The three different heating levels in Fig. 11 were applied via a heating loop on the ZrO₂ : Al scintillation screen, as discussed for Fig. 8. Starting from room temperature with no additional heating up to a basic temperature of ~ 245 °C for Ta²⁺ and ~ 272 °C for H⁺. The basic temperatures are slightly different for Ta²⁺ and for H⁺ as well as average heating power of the beam. For the broad band at ~ 670 nm, a slight shift into higher wavelengths during the heating process is observed. Furthermore, the band around 570 nm is strongly effected by the increase in temperature. An additional interesting observation is that there is no change in the position for the sharp line around 707 nm in the ZrO₂ : Al spectra with H⁺ ions. It turns out that the influence of the screen temperature on the spectrum is bigger for the irradiation with H⁺ than for Ta²⁺.

REFERENCES