A quasi-non-invasive ultra-thin luminophore foil detector system for secondary beam monitoring

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Abstract

High-intensity secondary beams play a vital role in today's particle physics and materials science research and require suitable detection techniques to adjust beam characteristics to optimally match experimental conditions. To this end we have developed a quasi-non-invasive, ultra-thin, CsI(Tl) luminophore foil detector system, based on CCD-imaging. We have used this to quantify the beam characteristics of an intensity-frontier surface muon beam used for next-generation charged lepton-flavour violation (cLFV) search experiments at the Paul Scherrer Institut (PSI) and to assess the possible use for a future High-intensity Muon Beam (HiMB-project), currently under study at PSI. An overview of the production and intrinsic characteristics of such foils is given and their application in a high-intensity beam environment.

Keywords: Luminophore, Beam diagnostics, High intensity, CsI(Tl), Thin scintillator films

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1. Introduction

Inorganic luminophore based screens made of ZnS have been known since the turn of the 20th Century when first used as single particle detectors [1] or for the pioneering work on atomic structure [2]. Since then the luminescent properties of luminophores have been developed from both organic and inorganic compounds and tailored to a multitude of applications and subjects from high-energy particle physics experiments through x-ray tomography and medical diagnostics to accelerator beam diagnostics as well as industrial applications such as new display technologies.

High-intensity secondary beams of muons and pions are in ever increasing demand to match the required intensity needs of a spectrum of fundamental experiments both in the low-energy precision sector: cLFV, muonic-atom/muonium spectroscopy, muon anomalous magnetic moment/electric dipole moment (g-2/EDM [3] and at the high-energy scale, such as the front-end sources for a neutrino factory or muon collider or the high-energy version muon g-2 [4].

In order to achieve the sensitivity goal of such experiments, it is essential to be able to reliably check the beam optics and have the ability to tune the beams to maximize intensity, while minimizing beam-correlated background and maintaining a good achromaticity at the final focus for stopped beams. This ideally requires quasi-non-invasive, in vacuum, detectors capable of working at high intensities and being sufficiently radiation hard.

The most intense continuous surface muon beams in the world exist at PSI, with muon yields in excess of 10^8 muons/s [5]. The PiE5 channel coupled to either the MEG or Compact Muon Beam Line (CMBL) feeds the two cLFV search experiments MEG II [6] and phase I of Mu3e [7], which both require running at the maximum intensity and hence require beam diagnostics during tuning and ideally quasi-non-invasive diagnostics during data-taking. The former was generally achieved using an automated remote 2-D beam scanning pill scintillation detector system. Although a very reliable and stable technique, able to handle rates $\mathcal{O}(10^9)$, it is however an invasive and somewhat time-consuming method.

31 In order to improve on this, a quasi-non-invasive, in-situ vacuum measurement
 32 was sought capable of handling a high-rate environment and without correc-
 33 tions required for multiple scattering in beam windows or air, as with the beam
 34 scanner system. For low-energy surface muon beams of 28 MeV/c with a kinetic
 35 energy of ~ 3.6 MeV, close to the kinematic edge of stopped pion decay, very
 36 thin foils at the sub-10-micron level are required, if not used as a degrader. This
 37 is necessary in order to minimize multiple scattering while maintaining sufficient
 38 light-yield for image capture, since the mean range is of the order of 480 μm in
 39 CsI. To this purpose we have developed a luminophore foil of CsI(Tl) of a few
 40 microns in thickness on a polyester (PET) substrate of 3 microns, produced by
 41 thermal vapour deposition.

42 Although the use of CCD imaging of CsI(Tl) plates/screens/foils has been
 43 known for a while, its usage has been mainly in the areas of X-ray imag-
 44 ing/radiography [8, 9] or with primary ion beams of higher current density in-
 45 volving beam profiling with either thicker layers of CsI or thicker substrates [10–
 46 12]. Hence, primarily beam destructive measurements. Secondary beams such
 47 as pions and muons, even at the intensity frontier, distinguish themselves from
 48 their primary production counterparts by their larger emittances and smaller
 49 current densities. Secondary beam monitoring techniques employed at some of
 50 the dedicated pion and muon beam facilities around the world such as RIKEN-
 51 RAL in the UK, J-PARC MUSE facility in Japan or PSI in Switzerland, use
 52 extractable, destructive imaging techniques of scintillation plates [13–15] placed
 53 in the beam. Other less invasive techniques such as scintillating fibre arrays
 54 are also used [16–18]. In this paper we concentrate on the use of ultra-thin
 55 luminophore detection foils capable of detecting a low-energy continuous par-
 56 ticle beam with beam-spot current densities ranging from $\sim (0.3\text{--}30)$ fA/mm²,
 57 corresponding to $(10^7\text{--}10^9)$ particles/s for a 1σ beam-spot size of $\sigma_x \sim 15$ mm
 58 and $\sigma_y \sim 12$ mm. In Section 2 we give a brief overview of the foil production,
 59 the CCD imaging systems used and general image analysis procedure, as well
 60 as the intrinsic characteristics of such foils, while in Section 3 we demonstrate
 61 their usefulness in characterizing the beam properties of a high-intensity surface

muon beam and compare the results to our standard 2-D remote scanning pill
scintillator system. In Section 4 we briefly look to the future.

2. Luminophore foil production, CCD imaging and foil intrinsic characteristics

CsI(Tl) is a well-known scintillation medium, with a high light yield of $\sim$
54 thousand photons per MeV energy deposition [19]. It also has an optimal
emission spectrum, well matched to the sensitivity of most common CCD visible
light sensors (see below) and hence is a favourable candidate as a luminophore
foil beam monitor.

2.1. Foil production

The thermal vapour deposition technique we used is described elsewhere [20]
in the context of later developed luminophores specifically for X-ray imaging, so
here we provide only a brief overview together with the differences. A mixture
of CsI and Tl (doping concentration ~ 0.08 mole%) was maintained at a tem-
perature of 680 °C in a tantalum boat placed some 65 cm below the rotating,
frame-mounted ultra-thin PET substrate. The 3 μm thick and 130 mm diame-
ter substrate was maintained at 25 °C and subjected to a pressure of $5\text{-}10^{-3}$ Pa
during the process. The deposition rate was kept low (17 ± 2 Å/s) in order to
achieve an even coverage. The CsI(Tl) layer structure, when analyzed by a
scanning electron microscope (SEM), was found to consist of grains between
2-5 μm in size [20].

Of the four foils employed in these measurements one (foil 4) had a 100 nm
layer of Al deposited on the PET substrate prior to vapour deposition. This was
intended to act as a mirror, however, the CsI layer here was only 3 μm thick,
whereas the foils 1-3 had layers of between 5.0-5.2 μm thickness. None of the
foils had a special surface coating added as mentioned in [20].

88 2.2. CCD Imaging and image analysis overview

89 In total three different types of Camera system [21–23] were used during
90 the development of the beam monitor described here. The initial camera used
91 was an IDS UI-2220SE non-cooled, low resolution (0.44 Mpixels) CCD camera
92 with an 8-bit depth, this was followed by the superior 16-bit high resolution
93 (4 Mpixels) Hamamatsu ORCA Flash 4.0 thermoelectric/liquid cooled CMOS
94 camera with a much higher dynamic range than the IDS. Both of these cameras
95 were used extensively for the muon beam measurements. The 16-bit QSI RS-
96 9.2S camera with its high resolution (9.2 Mpixels) was procured for the final
97 beam line installation and specifically used for the luminophore characterization,
98 as this thermoelectric/liquid cooled CCD with its particularly high dynamic
99 range shows, when cooled, a superior dark current to the other cameras. The
100 main lens used for the majority of measurements was a Canon Telephoto lens
101 EF-S 18-200 mm f/3.5-5.6 IS, which served to meet the varying setup conditions
102 required during the testing, in and out of the beam.

103 Analysis of the CCD images was common to all cameras and involved taking
104 a series of typically five beam images, as well as an equivalent set of background
105 images. In the case of beam imaging the background was taken with the chan-
106 nel beam-blocker closed and for the same exposure time as the beam image, so
107 enabling the subtraction of any stray light from other sources, as well as the
108 inherent thermal noise of the sensor. Furthermore, calibration images of the
109 foil with its calibration-grid (see Figure 18) illuminated using a UV-LED were
110 also taken and served two-fold: firstly, as means of calibrating the image pixel-
111 to-mm ratio and secondly to perform any image perspective transformations
112 required when viewing the foil off-axis. After each image has undergone its per-
113 spective transformation [24] using the transformation matrix derived from the
114 calibration image, the individual pixels of each image of the set are summed and
115 normalized to a nominal 2 mA proton beam intensity (the secondary particle
116 rate measured during the exposure is proportional to the proton beam inten-
117 sity), the exposure time being the same for all images. The same procedure is
118 adopted for the background images, each set, beam and background are then

119 averaged, and the background average subtracted from the beam average image
 120 yielding a background subtracted, normalized fully calibrated beam image with
 121 its associated pixel variances. From this image a region-of-interest (ROI) is se-
 122 lected, excluding the foil frame and a 2-D correlated Gaussian function is fitted
 123 to the image. This then yields the beam centroid position and the transverse
 124 widths and correlation, while the secondary beam intensity is obtained from
 125 an initial one-off independently measured secondary particle to proton intensity
 126 ratio.

127 *2.3. Luminophore intrinsic properties*

128 The characterization of the luminophore foil involved measuring the relevant
 129 intrinsic properties, such as one of the main spectral attributes, the emission
 130 spectrum, as well as assessing the homogeneity of the CsI(Tl) layer. Finally,
 131 a study of the radiation hardness of such a foil was made using the Budker
 132 Institute's (BINP) ILU-10 electron accelerator at Novosibirsk [25].

133 Both the spectral and homogeneity measurements used a monochromatic
 134 UV-source centred at 285 nm. The measurements were performed in a light-
 135 tight box with diffuse black, non-reflecting surfaces. The UV-LED was shone
 136 at the CsI(Tl) side of the foil, allowing a partial reflection. For the emission
 137 spectrum measurements, the emitted light was analyzed by an Ocean Flame-
 138 S-XR1-ES spectrometer, sensitive between 200-1025 nm. In the case of the
 139 homogeneity measurement the light yield (LY) was analyzed using the CCD-
 140 camera with and without a UV-filter to cut-out the UV-LED emission below
 141 approximately 390 nm.

142 The emission spectrum of all three components, the UV excitation source,
 143 a Thorlabs LED-285W, the PET substrate (Mylar[®]) and the CsI(Tl) layer
 144 were measured and are shown in Figure 1. The total luminophore spectrum,
 145 including all three components, is shown by the blue points, while the PET
 146 emission spectrum obtained by exciting and measuring the substrate side of
 147 the foil is shown by the green points. This was cross-checked by comparing it
 148 to a separately measured pure Mylar[®] foil spectrum, which showed the same

characteristics. Also shown, in red, is the emission spectrum of the UV-LED,
normalized to the reflection in the total spectrum.

Figure 1: Measured total emission spectrum of the luminophore CsI(Tl) foil and its components: PET, CsI(Tl) and the UV-LED itself. See text for details.

The characteristic visible and UV emission bands from the Tl-activator [26, 27] can clearly be seen at 530-570 nm, while only a shoulder can just be discerned from the other visible band at ~ 500 nm. The UV-band around 390-440 nm can also be seen, though also as a shoulder, due to both the narrow absorption band width [26] and the almost monochromatic excitation source centred around 285 nm. An excitation peak around 609 nm can also be seen in the figure, which has also been addressed in the literature [26].

The Light-yield (LY) homogeneity of the foils was sampled by means of measurements using the UV-LED with its monochromatic excitation wavelength centred at 285 nm. The LY of foil 3 was measured using the QSI camera with a UV-filter placed on the lens to cut wavelengths below 390 nm, hence only being sensitive to the emission spectrum of CsI(Tl), whereas foil 1 was measured in situ in the beam line vacuum system with a remote UV-LED placed upstream in

164 vacuum. The LY for foil 1 was measured using the IDS camera system without
 165 a UV-filter. Again, the standard background subtraction analysis procedure de-
 166 scribed in Section 2.2 was adopted yielding an averaged, background subtracted
 167 excitation image. The LY-distribution for foil 1 was analyzed by segmenting the
 168 ROI, which excludes the foil frame and edge, into $5 \times 5 \text{ mm}^2$ squares which are
 169 fully contained. Each region's summed pixel value is then placed in a 2D his-
 170 togram. The variation in LY homogeneity is taken from the maximum difference
 171 of LY between squares, which corresponds to 13% for foil 1. An independent
 172 set of measurements using the QSI-camera with UV-filter were undertaken with
 173 foil 3 in the light-tight box. Here the UV-light source was placed such as to in-
 174 directly illuminate the foil allowing a more homogeneous illumination. The ROI
 175 was then segmented into 16 equal azimuthal sectors each of 22.5° . The average
 176 and rms deviation for each sector were then compared. A plot of the average
 177 sector LYs and the corresponding rms-values are shown in Figure 2. The max-
 178 imum variation of the LYs corresponds to $15.3 \pm 2.3\%$ giving a variation of less
 179 than 8% from the average LY, consistent with foil 1. However, this is considered
 180 an upper limit on the LY homogeneity as the evident left-right asymmetry seen
 181 in Figure 2 could still have a partial source reflection dependence.

182 The final intrinsic property studied was the effect of ionizing radiation, in
 183 the form of fractionated doses from a low-energy, 5 MeV electron beam, on the
 184 LY of such foils. This was carried out with an ILU-10 industrial accelerator
 185 at BINP using a small foil of 38 mm diameter. This underwent a fractionated
 186 irradiation programme in 15 kGy steps, up to a total dose of 75 kGy. This dose
 187 is approximately 30% higher than the estimated total central 1σ muon spot
 188 dose expected from a 1-year running period of the MEG II experiment at PSI.
 189 The estimated energy deposition per 28 MeV/c muon in the CsI(Tl) layer is
 190 $\sim 21 \text{ keV}$ leading to a 1σ -beam spot dose rate of $\sim 0.46 \text{ kGy/day}$. The effect
 191 of the fractionated dose on the LY was studied after every 15 kGy increase by
 192 measuring the LY of the foil exposed to a ^{226}Ra source. The total LY is obtained
 193 from the integral of the pixels after background subtraction. The systematic
 194 uncertainties associated with the integrated dose measurements are two-fold:

Figure 2: Plot of mean azimuthal sector LYs for the total ROI corresponding to $16 \times 22.5^\circ$ sectors. The insert shows the corresponding rms values per sector. The variation of the LY from the average is less than 8%.

195 the first is the uncertainty on the absolute dose, which is estimated to be $\sim 30\%$,
 196 though the relative variation between fractionations is much smaller; the second
 197 and significant contribution comes from the reproducibility of the alignment
 198 of source, foil and camera for each measurement, which was determined by
 199 comparing the LY from the same selected central pixel row and column. This is
 200 shown in Figure 3 where the pixel rows and columns for each image, taken after
 201 each fractionation measurement, are superimposed. The estimated uncertainty
 202 on each measurement is 0.7%. The non-uniform variation across the central
 203 pixel row is due to the non-uniformity of the ^{226}Ra source itself.

(a)

(b)

Figure 3: Log plot of the superimposed central column (top) and central row (bottom) LY, showing the influence of the alignment precision. The colour coding corresponds to measurements after the following fractionated doses: Black-0 kGy, Magenta-15 kGy, Green-45 kGy, Blue-60 kGy, Red-75 kGy

Figure 4 shows the final relative LY-change versus integrated dose, where $A(0)$ is the integral of the LY over the image before irradiation and $A(x)$ is the LY after the fractionated dose x . Statistically, the LY-ratio $A(x)/A(0)$ is compatible with 1.0 up to the maximum dose induced of 75 kGy.

Figure 4: Relative LY-response of the luminophore foil to fractionated 15 kGy doses from a 5 MeV electron beam. $A(0)$ is the integral of the LY over the image before irradiation and $A(x)$ is the LY after the fractionated dose x .

3. Beam characterization using the luminophore foil

The muon beam measurements described here were undertaken at the MEG and CMBL beam lines coupled to the PiE5 channel at PSI, a more detailed description of the measurement environment is given in [6, 7], as well as a brief overview of the first usage of the luminophore foil [6]. The beam line setup in its CMBL configuration is shown in Figure 5. Here we give a detailed view of the characteristics of the luminophore system comparing it to measurements

215 made with our standard pill scintillation scanning system, demonstrating that
 216 this new luminophore system can be used to characterize one of the highest
 217 intensity continuous surface muon beams in the world.

Figure 5: CMBL beam line configuration in the PiE5 area at PSI with two extra quadrupole magnets beyond the final focus, in place of the large Mu3e solenoidal magnet. Luminophore measurements were undertaken at the intermediate and final foci. The 2-D pill scanner system can be seen placed at the intermediate focus.

218 3.1. Experimental setup

219 Two basic setups were used for the measurements, one a setup in air using a
 220 light-tight box which was placed immediately downstream of the beam line vac-
 221 uum window, this had either a 20 μm Aluminium or a 50 μm Tedlar[®] (polyvinyl
 222 fluoride PVF) light-tight entrance and exit window for the muon beam. The
 223 luminophore was placed orthogonal to the incoming beam and viewed under 90°
 224 to the beam-axis by means of a 3 μm thick aluminized PET-mirror and CCD
 225 camera. The setup shown in Figure 6 allows the beam to exit with minimal

226 interaction..

Figure 6: Light-tight box setup used for beam measurements in air.

227 The second setup in vacuum is now an integral part of the beam line, in-
228 corporated into the collimator system at the intermediate focus. This setup
229 is shown in Figure 7, a view of the inside of the vacuum beam pipe with the
230 luminophore and its calibration-grid in place, covering the full 120 mm aperture
231 of the collimator which is used to stop the deflected 28 MeV/c positron beam
232 separated by the upstream Wien-filter from the undeflected surface muon beam.
233 A rotation mechanism allows the luminophore to be moved in/out of the beam.
234 The foil is viewed via a mirror support structure mounted upstream, in a side-
235 port of the vacuum-pipe with a window interface to a CCD camera outside. For
236 calibration purposes, a UV-LED is mounted far upstream in an upper port of
237 the beam-pipe which is used to excite/illuminate both the grid and the foil.

Figure 7: Vacuum measurement setup at the intermediate focus showing the collimator system with the rotatable luminophore foil holder. The foil with its calibration grid can be seen at the centre of the picture. The beam-spot is imaged via a CCD camera through a vacuum window in the side port of the beam pipe via a mirror.

Before describing the luminophore measurements in detail, we give a brief overview of the 2-D pill scintillator scanner system used as a bench-mark system for the luminophore measurements.

The system is comprised of a remotely controlled 2-axis, sub-millimetre precision, stepping-motor driven scanning arm with a fixed-mounted Hamamatsu R9880U-110 miniature photomultiplier tube (PMT) and an NE102A pill-scintillator of 2 mm diameter and 2 mm length (sufficient to totally stop

245 the surface muons). A 4-channel waveform digitizing board (DRS4 evaluation
 246 board [28]) plus fast electronics and a LabVIEW-based [29] acquisition system
 247 measures the threshold dependent particle rates (muon and positron) in the
 248 scintillator and normalizes them against the also measured proton beam in-
 249 tensity. A particle time-of-flight measurement between the production target
 250 and the scintillator is also made simultaneously, from the particle timing with
 251 respect to the measured accelerator modulo 19.75 ns RF-structure. These mea-
 252 surements are repeated for different x- and y-positions of the scintillator, either
 253 in form of a so-called “cross-scan” in which an initial rough scan automatically
 254 determines the true beam centroid and then performs a 5 mm step horizontal-
 255 and vertical-scan through the centroid. The acquisition then outputs a plot of
 256 the horizontal and vertical beam profiles together with a measure of the proton
 257 beam normalized particle intensity, obtained by fitting the profiles using three
 258 separate fitting methods. Two methods are based on fitting a Gaussian profile,
 259 one over the entered interval and one fitting a so-called infinite Gauss, since the
 260 beam profiles are predominantly Gaussian shaped. For the case that the profiles
 261 have non-Gaussian tails, the third method of fitting a cubic Hermite spline is
 262 also used. An example of such a cross-scan output is shown in Figure 8. The
 263 other form of scan performed is a so-called 2-D “raster scan”, which involves
 264 taking measurements on a grid of scan positions (raster) with 5 mm spacing in
 265 both x and y. Again, the beam centroid and corresponding sigmas are deter-
 266 mined though this time from a 2-D Gaussian fit to the beam spot. This type of
 267 scan can involve a total of ~ 1400 single measurements taking some 2.5 hours,
 268 whereas a corresponding cross-scan takes about 10 mins.

Figure 8: High-threshold cross-scan output showing the horizontally and vertically measured beam profiles with centroids and sigmas as well as the total intensity, from the various fit models.

3.2. Luminophore Measurements

The first set of measurements undertaken was a comparison of the light-yield (LY) of the four foils outlined previously. Each foil was consecutively placed in the foil holder in the light-tight box, placed at the intermediate focus of the beam line and irradiated with the muon beam for the same exposure time. The foils were then analyzed as outlined in Section 2.2 and the muon beam horizontal and vertical profile projections made (cf. Figure 9) in order to select the best foils for further study. Although the measured sigmas are all comparable and within $200 \mu\text{m}$ of that measured with the pill scintillator scanner system, the light intensities differ significantly. Foils 1 and 3 are comparable in intensity and show the highest light yield (LY). Foil 2 has $\sim 10\%$ lower LY at the centre though has the thickest CsI layer ($0.1\text{-}0.2 \mu\text{m}$ thicker compared to foils 1 and 3), while the lowest LY is from the foil with the thinnest CsI layer and the extra Al-mirror layer.

(a)

(b)

Figure 9: Shows a comparison of the four foils, when exposed to muons under the same conditions. (Top) shows the measured horizontal profile for all foils while (Bottom) shows the corresponding vertical profiles.

283 These measurements suggest that no quantitative inference can be made
 284 between LY and layer thickness due to the minimal differences in layer thickness
 285 and that the LY differences between foils 1-3 are most likely due to variations in
 286 production. The effect of the Al-mirror layer on the LY of foil 4 is not conclusive
 287 as the much lower LY is most likely due to the thickness of the CsI(Tl) layer
 288 of only $3.0\text{ }\mu\text{m}$. Based on these measurements foils 1 and 3 were selected for
 289 further study.

290 The next step was to characterize the resolution of the combined system of
 291 luminophore, mirror and CCD system. An initial qualitative approach was first
 292 tried out by making a simple muon beam radiograph of the MEG and Mu3e
 293 experiment logos, constructed of 1 mm diameter solder-wire attached to the
 294 outside of the light-tight box as shown in Figure 10.

Figure 10: (Left) Muon radiograph setup showing the experimental logos made from solder-wire mounted on the exterior of the light-tight box window. (Right) shows the raw luminophore image of the logos taken with the CCD camera inside the light-tight box.

295 The raw CCD image of the muon beam exposed logos, in which the muons
 296 stop in the solder itself, is taken with the camera inside the light-tight box
 297 and apart from showing the beam spot itself, clearly demonstrates that the
 298 luminophore acts perfectly well in producing a muon radiograph.

299 A more quantitative measure of the systems spatial resolution was made by
 300 placing a 0.75 mm thick Al-grid in front of the luminophore and exposing it to
 301 the muon beam. The grid is comprised of $4 \times 4 \text{ mm}^2$ openings separated by 1 mm
 302 wide Al walls, a radiograph of which can be seen in Figure 11. A horizontal and
 303 vertical projection centred on a $4 \times 4 \text{ mm}^2$ gap of the grid of Figure 11 was used
 304 to fit a Gaussian convoluted step function to the edges of one of the $4 \times 4 \text{ mm}^2$
 305 opening.

Figure 11: Muon radiograph of an aluminium grid structure used to measure the systems spatial resolution.

306 The fits provide an upper estimate on the spatial resolution of the combined
 307 system of luminophore, mirror and CCD camera of $544 \mu\text{m}$ as shown in Fig-
 308 ure 12. The inserts in the figures show the light intensity profile over the full
 309 image. The intrinsic resolution of the luminophore itself is much higher [20] but
 310 the spatial resolution is dominated by the divergence of the muon beam,

(a)

(b)

Figure 12: Luminophore radiograph of the Al-grid of Figure 11 used to determine the spatial resolution of the combined system: luminophore, mirror & CCD. The light intensity per pixel data points are fitted with a Gaussian convoluted step function to the edges of the openings (red curve). (Top) horizontal projection fit. (Bottom) vertical projection fit. A combined systems resolution (camera/optics, mirror & luminophore) of $544 \mu\text{m}$ is obtained.

the muon multiple scattering and the Michel positron background from stopped muon decay in the grid adding to the LY.

A direct comparison of the pill scintillator system and the luminophore system was made by comparing beam profile measurements made at the same intermediate focus location, in air, just downstream of the collimator system. The individual fit values are given in Table 1, while the corresponding combined plots are shown in Figure 13. Here the normalized measured projected vertical and horizontal luminophore intensities are shown by the black dots in the figures.

Figure 13: Comparative horizontal and vertical beam profile measurements taken with the luminophore foil (black points) and corresponding fit (green points) as compared to those of the pill scintillator scanner system (red points with fit). The luminophore fit parameters P1-P4 correspond to a fit of a Gaussian with a flat background, respectively: Gaussian normalization constant, mean, sigma and flat background normalization

A corresponding Gaussian plus flat background fit to these values is marked

by the green squares and the fit values displayed in the figure. The red squares show the corresponding pill scintillator profiles. In order to better compare the fits in the figures, the pill position data points (red squares) have been shifted slightly to coincide with the luminophore x- and y-centroids, the difference being (~ 1 mm in x and ~ 3.5 mm in y) as shown by the difference in centroids in Table 1. These differences are due to a misalignment of the two beam setups.

Table 1: Comparison of measured beam profile parameters for both the luminophore and pill scanner setups. The centroid difference is due to misalignment of the setups.

Beam parameter	Luminophore foil measurement [mm]	Pill scintillator scanner measurement [mm]
$\langle x \rangle$	-3.5 ± 0.02	-2.56 ± 0.09
σ_x	16.34 ± 0.02	16.25 ± 0.11
$\langle y \rangle$	1.41 ± 0.02	-2.14 ± 0.09
σ_y	15.13 ± 0.02	15.26 ± 0.11

The non-Gaussian tails exhibited by the luminophore data in Figure 13 are attributed to a flat Michel positron background caused by muons ranging-out in the air and material downstream of the foil. This is not present in the pill scintillator data, due to the applied pulse-height threshold for selecting muons only. The comparative results for the distribution widths in Figure 13 show excellent agreement ($\sim 100 \mu\text{m}$) and consistency within the estimated precisions. The linearity of the luminophore foil LY versus muon beam intensity is clearly demonstrated in Figure 14. Here LY-measurements with the luminophore foil were undertaken by varying the opening of the horizontal FS41L/R slits in the front-part of the channel and taking a series of beam and background images for each slit setting. The absolute beam intensity measurements versus slit setting were made with cross-scans using the pill-scintillator scanner system. A very clear linear behaviour of the LY is seen over a factor of five in rate, up to the maximum available intensity of $\sim 1.2 \cdot 10^8 \mu^+/\text{s}$. The non-zero extrapolated intercept shows a lower cut-off in muon rate at about $5.5 \cdot 10^6 \mu^+/\text{s}$, which is

342 attributed to the point where the LY approximately equals the thermal noise of
 343 the CCD.

Figure 14: Luminophore linearity check of the light-yield versus muon beam intensity up to $\sim 1.2 \cdot 10^8 \mu^+/\text{s}$. The beam intensity is varied by altering the opening of upstream slits in the channel. A lower cut-off rate at $\sim 5.5 \cdot 10^6 \mu^+/\text{s}$ can be seen and is attributed to the LY dropping to the level of the thermal noise of the CCD.

344 A further and somewhat more involved example of the measured charac-
 345 teristic beam properties using the luminophore foil is the determination of the
 346 central beam momentum of a surface muon beam, in this case, at the end of
 347 the CMBL beam line. Here one of the most precise methods, using a detector,
 348 simultaneous multiple particle types and the accelerator radiofrequency signal
 349 as a clock to measure the time-of-flight (TOF) cannot be used due to the lack
 350 of time-structure associated with the surface muons, as well as the lack of a
 351 third particle-type (pions) at this momentum. Hence, we compare an integral
 352 range-curve measurement using the pill-scintillator to a corresponding range-

353 curve measurement (Bragg-curve) with the luminophore foil to determine the
 354 beam momentum. The two methods are fundamentally different. In the case of
 355 the integral range-curve using a pill scintillator which is thicker than the range
 356 of the surface muons (2 mm), particles reaching the detector are counted versus
 357 increasing degrader thickness. By counting the sum of both the stopped muons
 358 and the through-going decay Michel positrons one ensures an accurate muon
 359 count is obtained with the changing muon pulse-height towards the end of its
 360 range. This can be considered as a digital method. The Bragg-curve, in the
 361 case of the luminophore foil is an analogue method, obtained by measuring the
 362 particle light-yield, proportional to both the energy deposition in the foil and
 363 the number of through-going particles versus degrader thickness.

364 The integral range-curve is shown in Figure 15. The black dots and associ-
 365 ated red curve show a fit to the integral range-curve data by a complimentary
 366 erf-function with mean corresponding to the mean range $\langle R \rangle$ and a sigma equal
 367 to the square-root of the quadratic sum of the range-straggling σ_R and the
 368 momentum-byte Δp of the channel. A linear background of Michel positrons
 369 is also assumed. For reasons of clarity and to compare to the corresponding
 370 Bragg-curve obtained by the luminophore, the differential range curve, based
 371 on the fit to the integral curve is shown by the green diamonds and dashed line
 372 in the plot. A mean range of 798 μm of Mylar[®] equivalent of density $\rho=1.4$
 373 g/cm^3 is obtained, this includes the full material budget of vacuum window, air
 374 and light-tight materials. The total contribution from range-straggling as well
 375 as the momentum-byte yields a 1σ value of 87 μm .

Figure 15: Integral muon range-curve measured at the final focus of CMBL beam line. The black dots correspond to the range-curve data taken with the pill scintillator. The red fitted curve represents a complimentary erf-function fit to the data points with a linear background. The green diamonds and dashed curve is a plot of the differential of the integral fit curve and serves to demonstrate that the mean range corresponds to the peak of the range-straggling distribution.

376 The equivalent Bragg-curve as measured by the luminophore foil is shown
 377 in Figure 16. Here the LY is normalized to the initial point corresponding to
 378 no degrader, only the material budget of the beam line and setup. The Bragg-
 379 curve differs from the former range-curve in so much as it being an analogue
 380 method, with the LY, based on energy deposition, being proportional to both
 381 the number of particles and their residual dE/dX after the degrader. The red
 382 curve is a fit to the data using a two-piece normal distribution with a linear
 383 background.

Figure 16: Shows the corresponding Bragg-curve for muons measured by the luminophore foil. The red curve shows a two-piece Gaussian plus linear background fit to the data.

Both the range-curve and the Bragg-curve show excellent agreement with mean ranges and range-straggling values that differ only by a few microns, with uncertainties of less than 1%.

The mean muon range associated with both measurements is obtained, in the case of the pill range-curve, from the thickness corresponding to the mid-way drop-off in muon rate. This point is equivalent to a step-function for monochromatic muons but is smeared with a Gaussian range-straggling distribution to account for energy-loss straggling of the actual muons and the finite momentum-byte of the channel. It corresponds to the peak stopping rate, as shown by the peak of the Gaussian differential range-curve in Figure 15. In the case of the Bragg-curve the mean range is given by the peak of the curve since this corresponds to the maximum energy-loss in the foil. Here, the δ -like peak for a monochromatic beam is also smeared by a Gaussian straggling distribution, with a width corresponding to the same contributions as in the case of the

range-curve.

The momentum is obtained from the range-momentum relationship of surface muons in Mylar[®], which corresponds to an expected power law relationship [30, 31] with $\langle R \rangle = a \cdot P^{3.5}$ where a is a material based constant. The range of surface muons in Mylar[®] was modeled using two simulation packages, SRIM [32] and G4beamline [33] and the combined results are shown in Figure 17 below. Both simulations are consistent with a power law fit to data over the momentum range shown, and the displayed combined fit yields a momentum exponent of (3.53 ± 0.03) and hence consistent with the expected $P^{3.5}$ -behaviour from energy-loss. The momentum for the range-curve and the Bragg-curve are then obtained by inverting this relationship.

Figure 17: SRIM and G4beamline simulation data for the range versus momentum in Mylar[®] ($\rho=1.4 \text{ g/cm}^3$). The error bars represent the calculated range-straggling. A power law fit to the data gives an exponent of 3.53 ± 0.03 .

409 The thus obtained mean central beam momentum and the individual ranges
410 and range-straggling values are presented in Table 2. The mean central momen-
411 tum of 27.30 MeV/c is obtained from the inverted range-momentum relationship
412 using the weighted means of the individual ranges in Table 2. This carries a
413 total uncertainty of 2.8%, where the dominant contribution comes from the
414 systematic uncertainty of the exponent in the range-momentum relationship.

Table 2: Comparison of the two range methods showing the individual fit values for the mean ranges and range-straggling as well as the mean central beam momentum and momentum-byte including range-straggling obtained from the range-momentum relationship.

Beam parameter	Range-curve measurement	Bragg-curve measurement
$\langle R \rangle [\mu\text{m}]$	798 ± 2	799 ± 4
$\sigma_R [\mu\text{m}]$	87 ± 4	89 ± 3
Mean Values		
$\langle P_0 \rangle [\text{MeV}/c]$	27.30 ± 0.75	
$\sigma_{\Delta P} [\text{MeV}/c]$	0.86 ± 0.03	

415 4. Future Prospects

416 A study for a new high-intensity surface muon beam is currently underway
417 at PSI (HiMB Project). This is based on a new high-power target design [34]
418 and solenoidal channel, which would allow next-generation cLFV-experiments
419 as well as μSR -experiments to access muon rates at the 10^{10} -level per second.
420 This would naturally require new beam monitoring possibilities. We are, in
421 this context, also investigating the use of luminophore foils integrated into an
422 automated beam monitoring system for high intensities. With an avalanche
423 photodiode detector (APD) placed at a fixed position in the beam spot tails,
424 just in front of the luminophore, an automatic intensity normalization for the
425 luminophore could be obtained. As a first probe of the intensity criterion we

426 subjected foil 1, placed in vacuum at the intermediate collimator position (see
427 Figure 7), to simultaneous beams of muons and an order of magnitude more
428 intense beam positron beam stemming from the production target. In order to
429 show the capabilities of the luminophore we reduced the separation power of
430 the Wien-filter to allow both beam spots to be imaged simultaneously on the
431 foil but spatially separated. Figure 18 show the CCD image of the two spots

Figure 18: Luminophore foil in vacuum, introduced into the beam at the intermediate collimator system. The foil and frame are illuminated by a UV-LED in order to show both the calibration grid and support, as well as the beam spots being shown. Upper spot is the surface muon beam and the lower, more intense spot, from the beam positrons originating from the production target. The separating power of the Wien-filter has here purposely been reduced to see both beam spots.

432 as well as the holder and calibration grid, made possible by illuminating the
 433 system with a UV-LED. The upper spot is the surface muon beam, while the
 434 lower, more intense spot, is from beam positrons. The summed beam intensity
 435 shown here is $\sim 10^9$ particles/s. Although the beam positrons can clearly be
 436 distinguished from the muons here, on account of the spatial separation, it has
 437 to be remembered that the luminophore detector does not have any particle
 438 identification capabilities as the LY is essentially proportional to the product of
 439 particle rate and the energy-loss in the foil. Further studies of the linearity of
 440 the LY with intensity are required if this method is to be successfully used for
 441 secondary beam intensities of the order of 10^{10} particles/s.

442 5. Conclusions

443 We have developed a quasi-non-invasive, ultra-thin, CsI(Tl) luminophore foil
 444 detector system, based on CCD-imaging that has successfully been implemented
 445 into an intensity-frontier surface muon beam at PSI. The system is still under
 446 development in order to achieve its automation for beam optimization and ex-
 447 periment monitoring. We have outlined the production and the image analysis
 448 and have demonstrated the usefulness of such a non-destructive method. In-
 449 trinsic optical and mechanical properties, relevant to high-intensity secondary
 450 particle beams, have also been presented. Fundamental beam characteristics
 451 have been measured and compared to our standard, ‘destructive’ beam meth-
 452 ods of measurement and show excellent agreement at the sub-millimetre level,
 453 as well as the total resolution of the luminophore system which is also at this
 454 level. Furthermore, the new system shows an excellent linear LY-response to
 455 beam intensity over a wide range in muon rate, from a lower cut-off at about
 456 $5.5 \cdot 10^6 \mu^+/\text{s}$ up to the maximum available intensity of $1.2 \cdot 10^8 \mu^+/\text{s}$, though
 457 this must be further studied if one is to go to an order-of-magnitude increase in
 458 particle rates. Finally, the radiation hardness of such a device has been tested
 459 up to a maximum induced dose of 75kGy, 30% higher than the estimated total
 460 central 1σ muon spot dose expected from a 1-year running period of the MEG II

experiment at PSI. We have also demonstrated the complementarity of such a method in determining fundamental beam properties for precision experiments, such as beam momentum and range-straggling. Even though the luminophore foil system does not have particle identification capabilities, we have shown the wide range of capabilities that such a non-destructive system can contribute to the current generation of cLFV precision experiments such as those of MEG II and Mu3e.

Acknowledgements

We gratefully acknowledge discussions with Andreas Knecht, as well as the support of the infrastructure groups of our institutes and especially those of PSI. This work was also partly supported by the Swiss SNF Grant 20021_137738.

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