Simple X-ray cameras for beam-line instrumentation

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Abstract. The design and performance characterization of simple X-ray cameras are shortly presented. These cameras are installed on each high-energy beam-lines of SOLEIL. Main topics, such as the choice of the scintillator, the effect of the thickness of the scintillator on the resolution, the relation between the X-ray flux and the signal, are addressed in this article.

1. Introduction

One goal of this paper is to show that available off-the-shelf industrial optics and scintillators can cover most of the usual needs of the instrumentation for beam-lines.

2. Common X-ray cameras

Some CCTV objectives are specified, in reverse position, for magnification up to five. An adapter ring is used to add a hollow ring bearing the scintillator disk. It is convenient to mount the paper window in a separate ring, since the focus is made, without the window, on the defects of the surface of the scintillator, and also because the window is exposed to damages. Thus a dust and light-tight assembly as the one shown in Figure 1 can be built in minutes.

Figure 1 Set-up with a Basler SCA-640gm camera. The scintillator is a 2mm thick YAG:Ce disk. The objective lens has a 12mm focus length, with a 0.5 magnification. The total length is about 155mm.

To keep a compact design, short focus lengths (12mm or 25mm) are suitable. The camera length can also be reduced with a 90° housing with respect to the beam. The visible light is emitted along the optical axis, in a few absorption lengths. An example of two common scintillator’s (YAG and CWO) absorption length is shown in Figure 5. At first glance, the heavier material is the best choice, but the refraction index of the CWO is high, and the CWO cannot be currently polished down less than 200µm because it cleaves. At high energies, more seldom at SOLEIL, a thin ruby 1 scintillator is quite transparent. Such a device is planned for the PSICHE beam-line.

The length along which the light is emitted should not exceed the depth of field of the optics. Also, the reflection coefficient on both plane surfaces of the scintillator will cause a ghost image. A solution is to add an anti-reflexive layer on the rear face of the scintillator, or to get a thicker...
scintillator, in order to set the ghost image largely out-of-focus, under the noise floor of the camera signal. Thus, a relatively thick scintillator is a simple solution for a low energy and low magnification design. The objective lens of the camera shown in Figure 1 has a Depth Of Field (DOF) of about 250µm in the air, and about 460µm inside a plate of a refraction index of 1.85 such as the YAG. This represents a few absorption lengths under 20keV as shown in Figure 5. Details separated by less than 3 object pixels i.e. 44µm can be resolved. The DOF in the YAG of the camera of Figure 3 is 30µm.

At higher transverse magnification, let us say over two, another adverse effect becomes noticeable, i.e. the aberration of the plane parallel refractive plate of the scintillator. As this effect depends on the numerical aperture, it is simple to describe such a plate preceding a perfect lens on a free optical program, and to plot the effective spot diameter vs. the numerical aperture as in Figure 6.

The diffraction limit is plotted as the radius of the Airy disk \(1.22\lambda F/S\) with \(\lambda=550\text{nm}\), \(F/S\) is the program computed F-Stop. This optimization of \(F/S\) is necessary at high magnification. The corollary of using a thin scintillator, usually in YAG:Ce, mounted by the supplier on an adequate washer, is the necessity of a mirror, to protect the optics and the camera from the X-rays. The spatial resolution can be estimated with the projection of an edge. The spatial derivative gives the Line Spread Function (LSF). It is interesting to compute the Modulation Transfer Function (MTF) which is the Fourier transform of the LSF, and to compare it with a classical model of the MTF for a circular
aperture and incoherent light as defined in (2). The model on Figure 7 is the product of (2) by the camera spatial sampling \( [\text{sinc}(\pi F \text{Pix})]^2 \) where \( \text{Pix}=7.4\mu\text{m} \) and \( F \) is the spatial frequency. The example of Figure 7 is for a double achromatic lens, with a focus length of 300mm, a magnification of one, and a free aperture of 43mm, limited by the holding ring. The F-Stop number fits the MTF for \( FS=F/42 \). The spatial frequency cut-off \( F_0=4.3 \times 10^4 \text{m}^{-1} \) is defined in (1).

\[
F_0 = \frac{1}{\lambda \cdot FS} \quad (1)
\]

\[
\text{MTF} \left( F \right) = \frac{2}{\pi} \left[ \arccos \left( \frac{F}{F_0} \right) - \left( \frac{F}{F_0} \right) \left[ 1 - \left( \frac{F}{F_0} \right)^2 \right]^{\frac{1}{2}} \right] \quad (2)
\]

A goal of Figure 7 is to illustrate the necessity to suit the lens resolution to the size of the pixels of the camera. In principle, the spatial cut-off frequency should be near the Nyquist frequency, half of the camera sampling frequency. Not to do so leads to a loss of details, or high-frequency aliasing. When the cut-off and Nyquist frequency are equal, the FWHM LSF is about two pixels.

![Figure 7 MTF vs. spatial frequency (m⁻¹). The red squares are the data. The blue solid line is the model (2)](image)

![Figure 8 Signal of the camera (ADCUs⁻¹) vs. the product of the measured flux by the energy. The straight blue line is the model (4)](image)

3. Estimating a monochromatic flux from a camera signal

The total signal of the camera, for a given time exposure, can be compared to the power of the impinging beam, \textit{i.e.} in practical units the product of the flux by the energy. A set of such data, taken at four energies on the METROLOGY beam-line of SOLEIL, is presented in Figure 8. The photon flux has been measured by substituting the camera with a Si photodiode (IRD AXUV-100) calibrated by the PTB. The horizontal axis of Figure 8 is the power measured by the calibrated photodiode, and the vertical axis is the power measured by the camera. The camera was a Basler 1390-17gm with a reversed Pentax C2514-M objective lens, and the scintillator was a 200µm thick CWO. The total camera signal stands for the sum of all the pixels, after subtraction of the level of the dark level.

It is interesting to compare in Figure 8 this calibration of the camera with a simple model, since the optical collection and the sensitivity of the camera are known. \( SY=28 \) photons per keV is the scintillator yield, the only adjusted parameter in (3) to fit the data of Figure 8. \( RI=2.2 \) is the refraction index of the scintillator at 550nm. \( M=3.2 \) is the transverse magnification. \( FN=2 \) is the F-number. \( QE=42\% \) is the Quantum Efficiency at 550nm of the camera. The manufacturer of the CCD camera gives \( K1=7.4 \) as the number of 550nm photons per ADC unit. In this example the result of (3) is \( K2=350 \) keV.ADCU⁻¹, which shows that an X-ray camera is not a sensitive device, the standard deviation of the read-out noise being 3ADCU. However, with a magnification up to one and an exposure time of about 1s, this sensitivity suits for checking the focus point of a rotating anode X-ray
generator. Also, despite of that modest sensitivity, cameras can monitor vibrations. In (3) the term with the refraction index describes the relative optical loss of collection due to Snell’s law, and the following term is a classical approximation of the optical collection by the entrance pupil of a lens. The result \( Flux_1 \) (4) is in \( s^{-1} \). The signal \( \text{SumPixels} \) is in ADCU, the \( \text{Energy} \) is in keV, and the exposure time \( T_{\text{exp}} \) is in s.

\[
K_2 = \frac{RI^2}{SY} \left[ 4 \cdot FN \frac{M+1}{M} \right] \frac{K_1}{QE}
\]  

(3) 

\[
Flux_1 = K_2 \frac{\text{SumPixels}}{\text{Energy} \cdot T_{\text{exp}}}
\]  

(4)

4. In-vacuum designs

Sometimes, the scintillator is in the vacuum, at some distance of the viewport. It is often possible to use a pair of inexpensive achromatic doublets. An example, with a 5µm thick YAG:Ce disk on a 200µm quartz substrate, is shown in Figure 10. The distance between the lens and the sample is 250mm. For a higher magnification, combining two long-focal doublets would lead to an excessively long assembly. A solution is to combine a pair of identical doublets with a reversed objective lens. Another use of the doublets is to distance the lens from the camera. If the optical axis is not perpendicular to the scintillator, the camera must have an angle with respect to the optical axis, in order to keep the whole object plane in focus, according to Scheimpflug’s principle.

![Figure 9](image1.png) Picture taken with the optical set-up of Figure 10. The front lens is a pair of doublets with a focus length of 250mm. The FWHM focus spot is 40µm(V) x 90µm(H).

![Figure 10](image2.png) An assembly for the HAXPES branch of the GALAXIES beam-line. The magnification is one.

It is worth mentioning the materials used for monitoring the monochromatic and white beams at SOLEIL. The monochromatic beams are observed with 200µm YAG disks for the undulator beam-lines, and with large vitreous ceramic YAG for the magnet beam-lines. The white beams are observed with 200µm CVD-Diamond disks for the undulator beam-lines, and with large brazed ceramics doped with chromium oxide for the magnet beam-lines. On the low-energy beam-lines, the alignment of the undulator beam with the diaphragm is done with an energy-resolved device named DiagOn.

References

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