Precision linear and two-dimensional scintillation crystal arrays for x-ray and gamma ray imaging applications

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ABSTRACT

The continuing demand for greater resolution and real-time imaging and the availability of improved, position-sensitive light sensors such as a-Si arrays has pushed the development of small-pixel scintillator arrays. Both linear and two-dimensional arrays of various designs and materials are considered. A discussion of available scintillation materials for small pixel arrays is presented, along with practical decision-making selection guidelines. The trade-offs in design parameters for scintillation arrays are discussed including pixel sizes and reflector types. Examples of pitch and pixel tolerances and transmission of arrays are given. The scintillation performance of several BGO and CsI(Tl) arrays on a-Si arrays is shown. References are made to lens-coupled CCD and fiber-optic/PMT readouts. Applications of the arrays discussed include baggage scanning (line scanners), Computed Tomography imaging, Positron Emission Tomography, flash radiography and industrial X-ray inspection.

Key words: Scintillation arrays, x-ray imaging arrays, x-ray CT, line scanning, flash radiography.

1. BACKGROUND

1.1. Linear Arrays

Linear or one-dimensional arrays of scintillation crystals are commonly used in x-ray line scanners and X-ray Computed Tomography (CT) machines. Line scanner technology provides baggage/container scanning in security applications, quality control of packaged foods and imaging in other inspection applications. The primary use of X-ray CT is in medical imaging; however, there are some baggage and industrial inspection systems based on this principle. (See Ref. 1 and 2 for more information on scintillation.)

Prior to the commercial availability of integral scintillation arrays, the typical imaging array was built up from individual scintillation crystals that were mounted (optically coupled) to light detection devices. The normal light detection devices were photomultiplier tubes or silicon (Si) photodiodes. These individual crystal/light sensor assemblies were arranged side-by-side to form a linear detection array.

In the 1980's, linear or ladder-type scintillation arrays (Figure 1a) optically coupled to Si photodiode arrays were used in production quantities in X-ray baggage scanners. Common pixel sizes for these ladder-type arrays are of the order of 1-2 mm in cross-section and 2 mm in x-ray or radiation thickness. The number of pixels in each array varies from 8 to 16, 32 and higher. Primary scintillation materials were, and are, Cadmium Tungstate ($CdWO_4$) and Cesium Iodide (CsI[Tl]).

The scintillation detectors in many Medical CT scanners are linear arrays with a much larger y-dimension (Figure 1b.) Typical pixel dimensions are 1- 2 mm by 20-30 mm in cross-section and 2-3 mm in x-ray thickness. Number of pixels in each array varies by end users from 8 to 32 and higher. Primary materials for CT are $CdWO_4$ and, more recently, scintillating ceramic materials. Figure 1 shows the differences between ladder-type and CT-type linear arrays.

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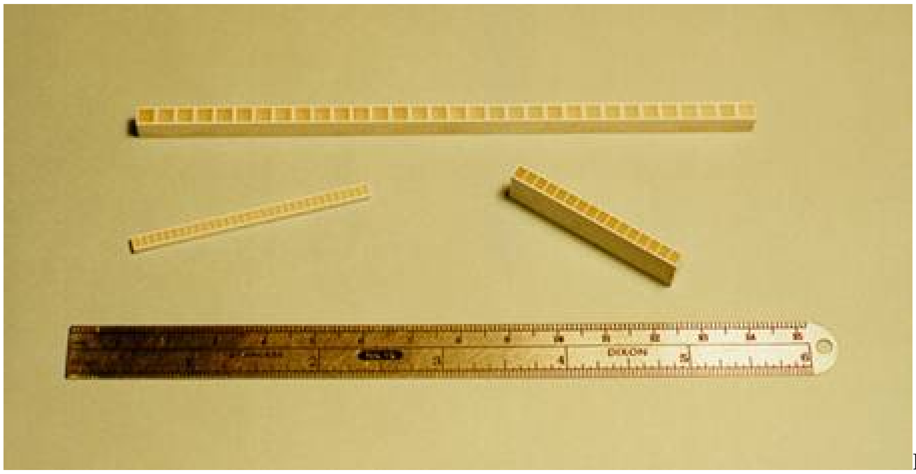


Fig.1a

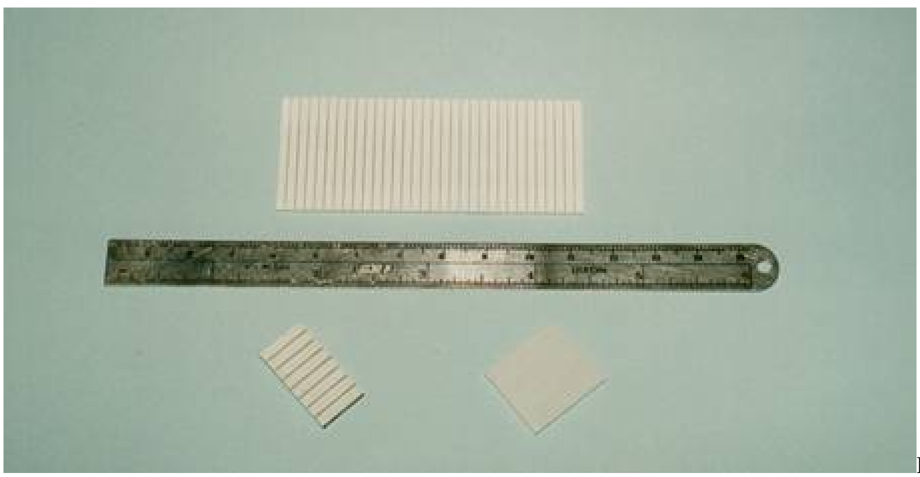


Fig. 1b

Figure 1. Examples of Linear Imaging Arrays

1.2. Two-dimensional arrays

Integral, two-dimensional (2D) arrays with larger size pixels were produced over thirty years ago for medical imaging. Sodium Iodide Thallium-doped (NaI[Tl]) crystal slabs were saw cut into 2d arrays with pixel sizes of one cm square. The separator gaps between the crystals were filled with white reflective powder. Due to the hygroscopic nature of NaI(Tl), it was necessary to do the final finishing and encapsulation in a drybox.

However, it was not until the 1990's that large area, small pixel 2D arrays of scintillator crystals were available in volume. With the advances in photo-sensors and readout electronics driven by the need for better resolution and real-time imaging, these arrays are finding application in medical, security and industrial imaging. They are commonly coupled to position sensitive PMT's, Si Photodiodes, CCD's and amorphous Si (a-Si) arrays. Today, sub-millimeter pixel arrays can be matrixed into 50 x 50 cm^2 arrays of 300,000 pixels with radiation thicknesses to 4 cm. They are available in several different scintillator materials, described later, and can be produced with white epoxy, white paint or metal reflectors in the gaps between the pixels. For clear definition, a 2D array is shown in Figure 2.

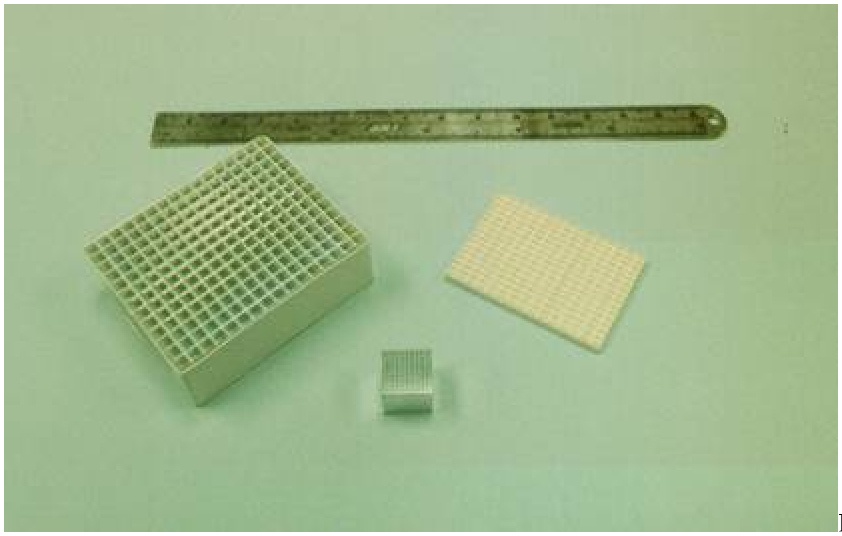


Fig.2

Figure 2. Examples of 2D Imaging Arrays

2. SCINTILLATION MATERIALS

2.1. The Ideal Scintillator

Important properties of the ideal scintillation material include:
(1) a high light output typically measured in photons/MeV;
(2) an emission spectrum that is matched to the peak efficiency wavelengths of the light detector employed;
(3) an index of refraction that provides the proper match between the interface and the light sensor;
(4) a sub-microsecond decay time with no afterglow;
(5) a stable output with long exposure to radiation (radiation damage resistance);
(6) a zero temperature coefficient [c(T)] of the light output; and,
(7) excellent mechanical properties for machining and long term stability;
(8) chemically stable (e.g. moisture insensitive).

While the search for the ideal scintillator continues, in practice we must settle for trade-offs between properties required by the application, the available scintillators and the economics involved.

2.2. Properties of Available Scintillation Materials

Many sources are available that describe the properties of the multitude of scintillators that have been discovered. [1,2,3,4,5,6,7,8.]
The scintillation materials listed in Figure 3 are examples of the property trade-offs of those frequently used.

Material	Light Output (photons/Mev)	Wavelength of Max. Emission (nm)	Decay Constant (nsec)	Density gms/cc	Index of Refraction	Moisture Sensitivity	Afterglow % of Signal After ( ) msec
NaI(Tl)	38,000	415	230	3.67	1.85	High	0.3-5 / 6msec
BGO	9,000	480	300	7.13	2.15	None	0.005 / 3msec
CsI(Tl)	59,000	560	1000	4.51	1.84	Slight	0.5-5 / 6msec
$CdWO_4$	15,000	480	1100/14500	8.00	2.20	None	0.1 / 3msec
CaF_2(Eu)	19,000	435	940	3.19	1.44	None	<0.3 / 6msec
GOS*		510	3000	7.34	2.20	None	<0.1 / 3msec
LSO**	30,000	420	40	7.40	1.82	None	
Plastics	~10,000	420	2-17	1.03	1.58	None	<0.1 / 3msec

* Gd_2O_2S with dopants; properties vary with dopant types and levels.[2]

** $Lu_2(SiO_4)O:Ce$

Figure 3. Properties of Selected Scintillators

Although not normally considered for sub-millimeter pixel arrays, NaI(Tl) is listed because it finds broad use in large single crystal applications, e.g. in nuclear medicine gamma cameras or geological exploration.. In small pixels, NaI(Tl) would produce a high light output; however, it is very hygroscopic and its wavelength of emission is not matched well with Silicon photodetectors (Si PD's). In addition to the emission mis-match, for some multipulse applications, the decay constant of NaI(Tl) is too long. In spite of these limitations, NaI(Tl) is being used in some imaging applications in pixel sizes of ~1 cm square.

Bismuth Germanate ($Bi_4Ge_3O_{12}$ or BGO) is a very dense, relatively fast scintillator that is easy to fabricate. But BGO has relatively low conversion efficiency and a large c(T) of -1.1% / ºC in the range of 20-40 ^oC.[6] With these properties, BGO finds use in applications where the incident flux is high (or where high gain light sensors are used) and the temperature is stable or is compensated.

CsI(Tl)'s conversion efficiency combined with an emission spectrum that matches well to Si PD's and a relatively low material cost are distinct positives; but its long afterglow and lower density restrict its use to line scanners at X-ray energies up to ~150 KeV. At higher incident radiation energies, because of its low stopping power, it is not the material of choice in pixelated arrays. For example, at 300 KeV, the radiation thickness required to absorb 80% of the incident X-rays is ~21mm. Unless the incident radiation is perfectly collimated, X-ray crosstalk between pixels occurs, causing loss of resolution in long pixels. In contrast to CsI(Tl), 80% of 300 KeV radiation is absorbed by 7mm of $CdWO_4$. CsI(Tl)'s slight sensitivity to moisture can be controlled with minimal protective measures such as an epoxy or spray coating or prevention of a moisture condensing environment.

The density, low afterglow and the thermal stability of $CdWO_4$ have made it a material of choice for applications where fast processing and/or higher energy X-rays are used (e.g. X-ray CT and large container line scanning). $CdWO_4$ is very stable in the environment; the crystal structure does have a cleavage plane which can limit the minimum pixel size attainable.

Gadolinium Oxysulfide (GOS) with various dopants is used as a phosphor screen material and also as a ceramic scintillator. Its conversion efficiency varies by specific composition but, in the ceramic form, is about twice that of $CdWO_4$. Because the material is not a single crystal, it is usually translucent to transparent. Even in the more optical transmitting, ceramic form, radiation thicknesses above 2 mm are not commonly used due to the self-absorption of the scintillation light.

3. STATE-OF-THE-ART ARRAYS

The mechanical and optical properties of scintillation arrays discussed below are those that we have demonstrated are achievable using discrete pixel, single crystal scintillator arrays. There are other ways in which scintillation or phosphor materials can be used for position sensing that are not covered here. For example, at low X-ray energies, it may not be necessary to pixelate the scintillator because of the thin radiation length required to absorb the radiation. The solid angle of the emitted light is large enough so that optical crosstalk is negligible for most applications. Thus, thin sheets of phosphor or scintillator can be used. Also, there are other techniques, such as columnar growth of CsI(Tl) that produces ~10 micron size random columns of deposited layers that are useful at lower energies. (For example, see References 9 and 10)

Current capabilities on discrete pixel scintillation crystal arrays differ by material, linear or 2D array design and reflector composition. These are addressed below.

3.1. Array Design Parameters

The following parameters can be used to specify a linear or a 2D array. Refer to Figure 4.

(1) Material – Type of scintillation crystal or material desired.
(2) Pixel or Element Size – The "x" and "y" dimensions of each scintillator pixel
(3) Separator Type and Thickness – The type of reflector between the crystal pixels and its overall thickness, "g". Note: this may be a composite or laminate of white reflector and metal materials.
(4) Pitch – This is the distance between the center of one element to the center of an adjacent element. Note: In 2D arrays with rectangular pixels, the pitches in the "x" and "y" directions will be different.
(5) Radiation Thickness – This is the "z" dimension and specifies the thickness of the array in the direction of the incoming radiation.
(6) Back reflector thickness – Usually a white reflector is applied to the radiation entrance side of the array to reflect the light back into the pixel so it can be directed to the light sensor.
(7) Material adjacent to the end pixels or elements – The end crystals may need a special reflector thickness or other treatment, e.g. to keep a constant pitch from array to array if they will be joined together in use.

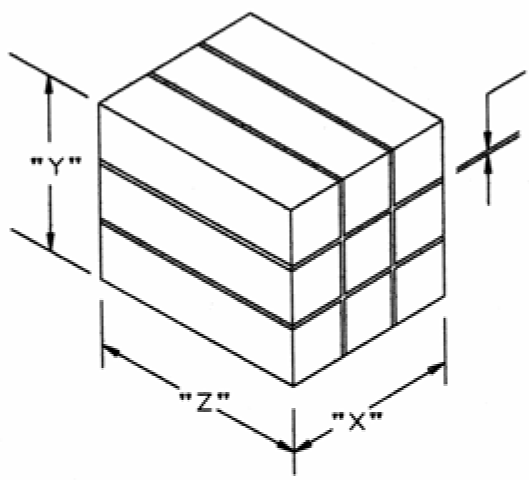


Figure 4. Array Dimensions

3.1.1. Materials and Pixel Size

Figure 5 shows the materials and the associated pixel sizes that are producible today. For 2D arrays, we have listed the sizes available in square pixels. This list is still evolving. For example, only two years ago, the table would have shown a minimum 2D pixel size for BGO at 0.6mm – twice today's value. The pixel sizes are controlled primarily by mechanical properties of the crystals, e.g. hardness, cleavage, ease of machining. For example, $CdWO_4$ has a cleavage plane in one crystallographic direction. For that reason, it is not possible, with current techniques, to achieve 0.3 mm square pixels because of fractures along the cleavage planes that occur during cutting and grinding in manufacture. However, $0.3 \times 1.0\ mm^2$ pixels can be produced.

MINIMUM DISCRETE PIXEL SIZES AVAILABLE IN CRYSTAL SCINTILLATORS

Material	**Minimum Pixel Sizes*** Linear (mm)	2D (mm)	**Comments**
Cadmium Tungstate	0.3	1.0	Cleavage Plane
Cesium Iodide (Thallium)	0.3	0.3	
Bismuth Germanate	0.3	0.3	
Lutetium Orthosilicate	0.8	0.8	Min. Untested
Calcium Fluoride(Europium)	0.5	0.7	
Sodium Iodide(Thallium)	7.0	7.0	

*Available as of this date; smaller pixel sizes may be developed.

Figure 5. Minimum Pixel Sizes Achieved

3.1.2. Separator/Reflector Type and Thickness

In Figure 6, array reflector materials are listed in the order of decreasing reflectivity. The reflectivity numbers are presented as a guide only. The geometry of the pixel, the thickness of the reflector, the scintillator material used and other factors influence the reflectivity obtained in each array design. The first two separator materials listed, White powder and Teflon sheet are not practical for the small pixel arrays discussed here – they can not provide the bonding properties required. Once mixed with epoxy, the white powder provides the diffuse reflectivity required to channel the scintillation light to the exit surface and the adhesive properties for a mechanically stable array. As noted, white paint provides better reflectivity. We believe this is because, as the vehicle (solvent or water) evaporates, the voids between the particles are filled with lower index air (versus epoxy) and more dense layers of reflective particles (e.g. Al_2O_3) are produced.

SEPARATOR TYPES AND THICKNESSES IN ORDER OF DECREASING REFLECTIVITY

Material	**Thickness Range**	**Approx. Relative Reflectivity***
White Powder (e.g. TiO2, MgO)**	1.0mm and up	100%
Teflon Sheet**	0.15mm - 0.50mm	98%
White Reflector Paint	0.04mm - 0.10mm	96%
White Epoxy	0.10mm - 0.75mm	94%
Composites***	0.10mm – up	94%
Aluminum /Epoxy	0.05mm - 0.1mm	75%
Metals (Pb, Ta)/Epoxy	0.05mm – up	65%

* These are Guidelines only and are based on optimum, not minimum, thickness. Values will vary with pixel geometry, surface finish and other specific design parameters.

** These are used as reflector materials in large scintillation crystal packaging.

*** Composite separators are clear epoxy-paint-metal-paint-clear epoxy, white epoxy-metal-white epoxy.

Figure 6. Reflector/Separator Thickness for Linear and 2D Array Construction

Metal or metallized separators prevent optical crosstalk between the pixels while maintaining minimum gap “g” thicknesses. However, the metal surfaces, even polished, do not provide the best reflection of the scintillation light to the exit surface.

This is where composites are useful. They combine the reflective properties of the white materials with the "zero" crosstalk of solid metals or films. Metal separators can serve another function: to absorb the radiation that is incident on the separator area before it strikes the light sensor and produces noise. Nuclear dense materials like Lead, Tungsten and Tantalum are used. Also available are white epoxies where the reflector particle fillers are more nuclear dense than TiO_2 or Al_2O_3. However, in practice, their effectiveness is limited to low energies, up to ~60 KeV.

3.1.3 Radiation thickness

Radiation thicknesses, "z," of up to 44 mm in both linear and 2D designs have been produced. On specific designs, minimum "z" thicknesses of 0.3 mm are achieved routinely.

3.1.4 Array Parameter Tolerances

Tolerances are very dependent on the particular scintillator material, pixel size array design and other array parameters. For example,

- in BGO, 2D **pixel** dimensional tolerances of $\pm$ 0.006 microns are common.
- in $CdWO_4$ linear arrays, **pixel and pitch** standard deviations of $\pm$ 0.006 microns have been measured.
- in a 6400 pixel, 2D CsI(Tl) detector with 1 x 1 mm^2 pixels and white epoxy separators and radiation length of 15 mm, the **average pitch** is 1.205 mm with a standard deviation of 0.021 mm or less than 2%.
- In a 2D, 30 element $CdWO_4$ array with 1.0 mm square pixels, the **pitch** is controlled to +/- 0.02mm.

Concerning the parallelism of long pixels, on sub-millimeter size BGO 2D arrays with 20-40 mm radiation length, the separation or parallelism between any two adjacent pixels, end-to-end, is $\leq$ = 2%.

3.2. Examples of Optical Properties

As noted, the performance actually achieved depends on the particular design. Here are some examples from the many designs we have produced.

3.2.1. Crosstalk versus White Epoxy Separator Thickness

As discussed above, there are property trade-offs in available scintillation materials. Likewise, in array construction, there are property trade-offs. Construction of arrays using white epoxy reflectors requires less manufacturing steps than other techniques, so it is economical. However, it does reduce the fill factor for the scintillation material and allows some crosstalk in a thickness of ~.25 mm. In some applications, such as line scanning, some crosstalk can be tolerated. In a typical line scan array using ~100 KeV X-rays, crosstalk between adjacent channels is of the order of 2-4%.

3.2.2. Transmission of Sample BGO Arrays

The sub-millimeter pixels in long radiation length arrays (i.e. "y" >10 mm) are actually like fibers in the transmission of the scintillation light. Just as with fibers, the surfaces are as important as the bulk transmission. They must have minimal surface imperfections for low reflection losses. This is especially true for scintillation light that is emitted in a spherical pattern at the point of each gamma or X-ray absorption. The light can reflect off the surfaces many times before being transmitted to the light sensor. Again, the array geometry and construction are determinants, so it is not possible to cover all of the parameters here.

In BGO 2D arrays with 0.85 x 0.85 x 20 mm^3 pixels, we measured the transmission of 480 nm light through the 20 mm path length. The separators here were epoxy/Aluminum/epoxy, 0.06 mm total. Measurements were made using a Perkin Elmer Lamda 19 UV/Vis/Near IR twin beam spectrophotometer. A thin slice of the BGO array was inserted into the reference beam to account for reflection losses. Thirty-five (35) arrays, each containing 50 x 50 pixels, were tested. We found the transmission was consistently >80%.

Also in BGO 2D arrays with 0.60 x 0.60 x 40 mm^3 pixels, the transmission at 532 nm was measured through the 40 mm path. The separators were epoxy/Al/epoxy, 0.06 mm total. These measurements were made with a Coherent 532-10 50 mW laser beam. The beam diameter was 2 mm as it entered the array surface. Results were that the average transmission at 532 nm was 91.1% with a standard deviation of 2.4%.[11] This and the above results confirm that the bulk transmission is preserved, i.e. array construction did not impact it.

In Reference 12, the light transmitting properties and the scintillation output of a 76 x 76 pixel BGO array was studied. The pixels were 0.60 x 0.60 x 40 mm^3 with the same epoxy/Al/epoxy separators. Using Cs^{137} and Co^{60} radiation, the scintillation light output was measured as generated at various positions along the 40 cm length and as a function of the viewing angle of the light exiting the array. The general conclusion is that the performance was within the range of what would be expected from material and geometric considerations. Somewhat unusual was the low value of the ratio of the efficiency (light output) of the array versus the efficiency of bulk BGO. This was probably due to the element aspect ratio and a less efficient surface reflection construction at the time this array was produced in 1995.

4. SCINTILLATION PERFORMANCE

4.1 General

It is possible that damage to the crystal material during fabrication can cause some of the properties of the performance of the scintillators to vary in finished arrays. With proper manufacturing techniques, we have shown that the properties of the scintillation materials are preserved in the final array, e.g. bulk transmission, afterglow. In BGO, we have measured the conversion efficiency of the bulk material and of the sub-millimeter arrays produced from it. The expected result was obtained—no change in conversion efficiency or decay time.

4.2 Images on a-Si Detector Arrays

The images shown in Figures 8 through 11 were obtained using 120 KeV X-rays and an a-Si array with a 127 micron pitch[13]. Figure 8 shows the image obtained using a recently produced, BGO array with: 0.5 x 0.5 x 10 mm^3 pixels, Aluminum/Epoxy separators of 0.05mm; overall size 27.5 x 27.5 x 10 mm^3. The radiation entered the 27.5 mm x 27.5 mm side most distant from the a-Si detector array. It is evident from the image, that the output of the pixels is quite uniform.

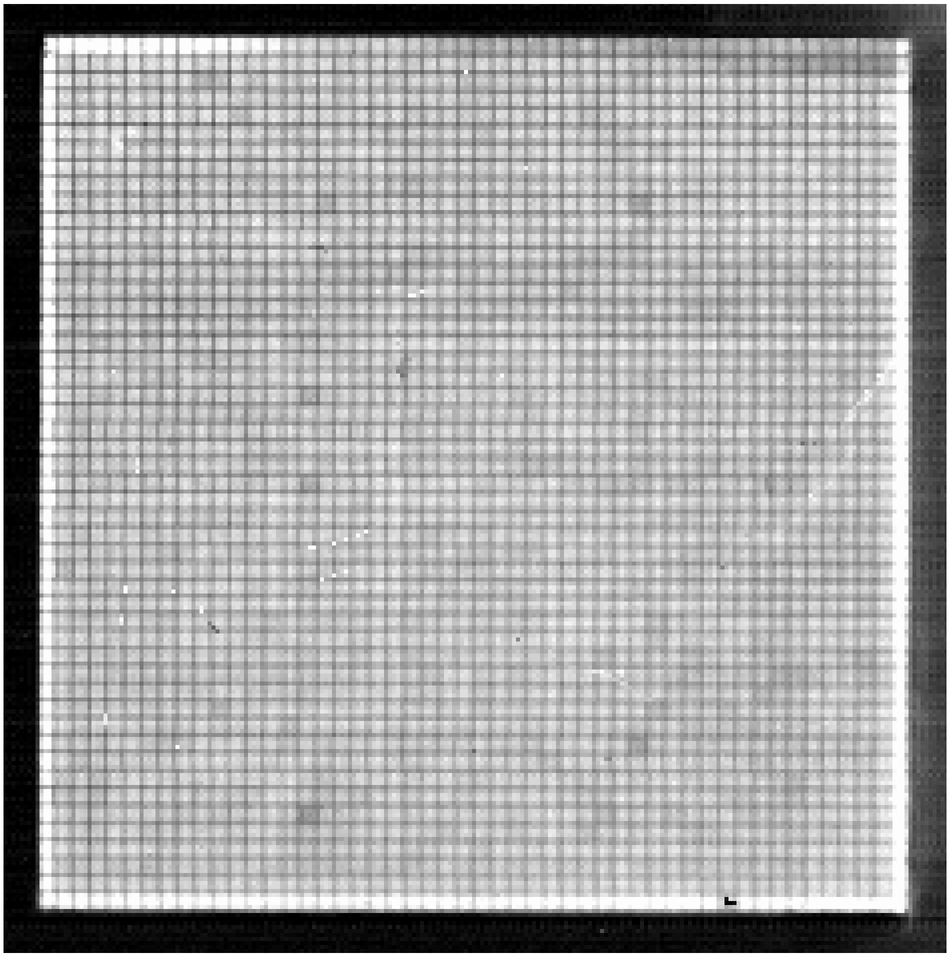


Figure 8. 120 KeV X-ray Image of 0.5 x 0.5 x 10 mm^3 Pixel BGO Array on 127 micron pitch, a-Si detector array[12]

The image shown in Figure 9 is from a CsI(Tl) array produced in 1996. The pixel size is 1 x 1 x 15 mm^3. The separators are white epoxy, thickness 0.23 mm. Overall array size is 170 x 170 x 10 mm^3. The image was made in the same manner as the image of the BGO array in Figure 8.

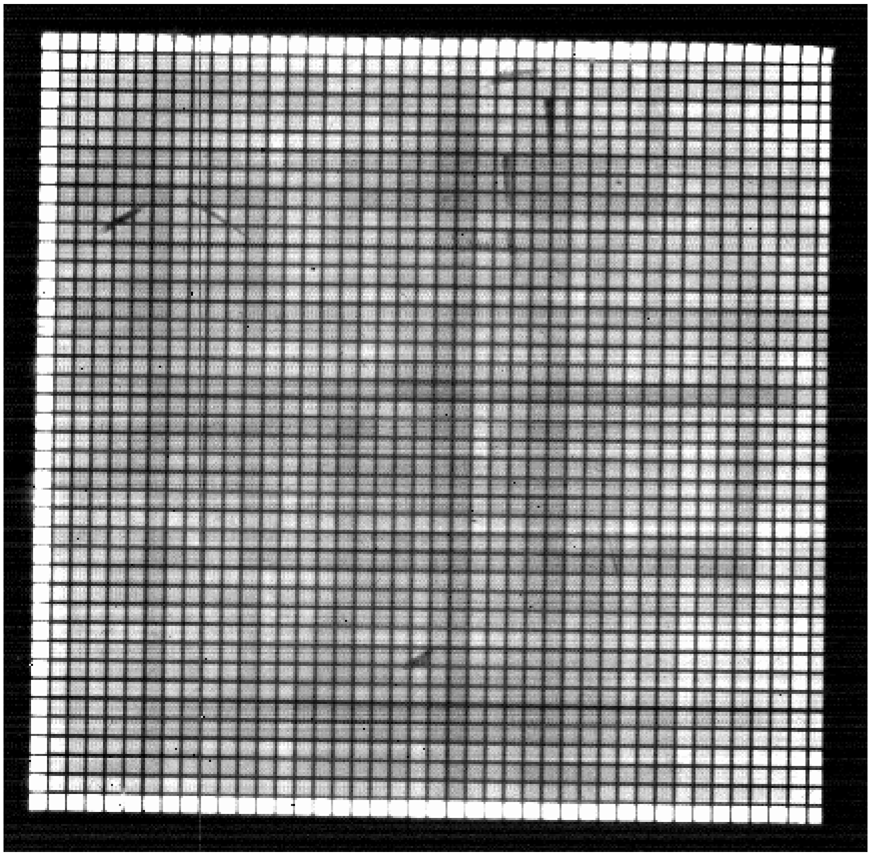
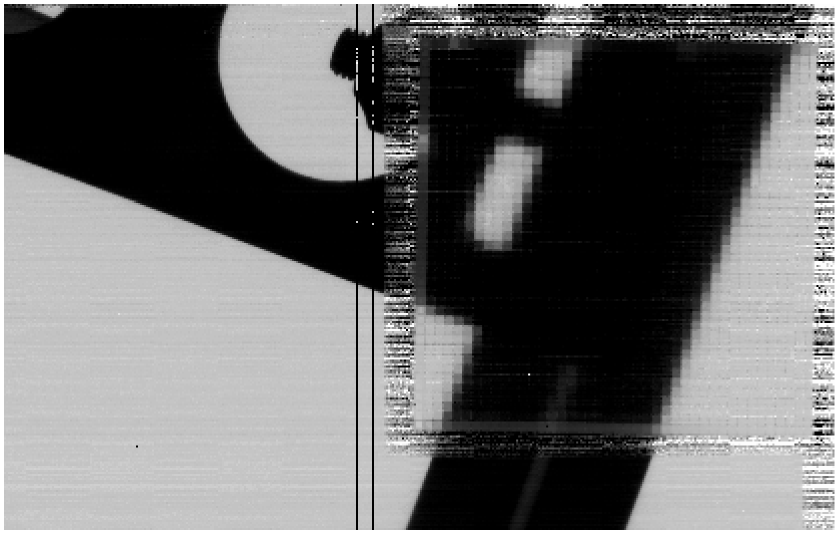


Figure 9. 120 KeV X-ray Image of 1 x 1 x 10 mm^3 Pixel CsI(Tl) Array on 127 micron pitch, a-Si detector array[13]

In Figure 10, a qualitative display of the resolution of the CsI(Tl) array is shown. An image of a simple tool (a carpenter's



square) was taken using a Lanex screen with a hole cut in it for the CsI(Tl) array. (The blurred edges result from the hole in

Figure 10. Image of a Tool using a 1 x 1 x 10 mm3 pixel CsI(Tl) Array surrounded by a Lanex screen[13]

the Lanex screen being slightly larger than the CsI(Tl) array.) While the resolution of an array is limited to pixel size, at higher energies than used here, the arrays provide better resolution than other modalities. For example, the Lanex screen only offers a shadow image; at higher energies the array could provide internal detail and structure.

Information on the effects of surface treatments on 2 x 2 x 10 mm^3 BGO crystals coupled to optical fibers, then to a multi-channel PMT is given in Reference 14. Data on the light output of various arrays using Co^{60} 1.2 MeV radiation and a lens-coupled CCD as a light sensor was obtained by Watson et al.[15] They investigated segmented arrays by several construction techniques from glass, plastic, CsI(Tl), BGO and LSO for a flash radiography application. The tests indicated that the light output of segmented scintillators is only slightly lower than the bulk material when used in a lens-coupled system.

5.0. SUMMARY

Precision pixelated arrays of scintillation crystals are available today in linear and 2D styles with pixel sizes of 0.3mm and radiation lengths of 40 mm or larger. The improvements in position-sensitive light sensors have been driven to great extent by medical radiography. These improvements coupled with the demand for higher resolution, real time imaging at higher energies is pushing the scintillation array technology toward smaller pixels and even more precise mechanical construction. Newer applications include multi-slice medical X-ray CT scanners, 300-400 KeV security container line scanners, MeV flash radiography and industrial real-time imaging.

There are choices of scintillator materials and separator/reflectors to optimize performance to a specific application. Even in small sub-millimeter pixel sizes, the performance of the arrays is consistent with the bulk properties of the scintillation materials when proper construction techniques are employed. We were somewhat limited in this paper by the proprietary designs, applications and results that we were unable to disclose. However, the examples and the basic X-ray images presented here show the potential for even wider use of precision pixel, scintillation arrays. Arrays with 0.5 mm and smaller square pixels can be obtained with precise spacing and good pixel transmission in different scintillation materials with radiation thickness from 0.3 to 44 mm. And, the technology is still evolving.

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