Novell design of high resolution imaging x-ray detectors

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Abstract
An x-ray imaging detector, based on scintillating fiber optics, was developed for high energy industrial radiography 1996. The detector was optimized for the highest possible spatial resolution at high energy (450 kV) and large wall thicknesses (equivalent to 40-60 mm steel). It was at that time proven to give superior radiographic sensitivity compared to fine grained industrial x-ray film. This even though the design, at that point, wasn’t optimized to protect the CCD from primary radiation.

A new imaging detector has now been built based on simulations and experiences from that first generation camera. The objective of this paper is to show how Monte-Carlo simulations were used to optimize spatial resolution and minimize radiation induced noise. Results from various tests of the new detector will be presented which also confirms the simulations at the design stage.

Keywords: X-ray, detector, scintillation, fiber optics

1 Introduction
Scintillating screens with directional structures has been used for many years and CsI, with structurally grown crystals, is the most common solution. Compared with conventional screens with powder scintillators is this a major step forward with respect to the spatial resolution. Typically, the thickness is approximately 200-300 µm and it is possible to increase the thickness up to 700 µm but then decreases the spatial resolution. The reason is
that the crystals are not perfect and because of that the lateral light scatter increases.

Scintillating glass fiber optic faceplates (SFOP) are another solution to increase the detection efficiency, while maintaining the spatial resolution. The first published reports of SFOP came more than 30 years ago [3] and in the mid 90's they were commercially available. The first system (see Figure 1) was built and qualified for the testing of two welds on one of the main circulation pumps of the Oskarshamn (unit 2) nuclear power plant (BWR reactor) [1].

The radiation source used was a 450 kV Philips and the imaging detector was based on a commercially available camera, XIOS, with fiber optic input window (Photonic Science). The lens in the XIOS-detector was a straight fiber optic image conduit with a length of 100 mm and the scintillator was 10 mm thick with statistically embedded extra mural absorber (EMA) fibers.

To understand why this type of detector was chosen and how the system was optimized, it is essential to describe the of the nondestructive testing (NDT) problem for which the system was developed. The system was developed for detection, but most of all for characterizing and sizing of service induced defects in primary systems in nuclear power plants. The defect type to be detected was typically intergranular stress corrosion cracking (IGSCC) which normally occurs in the heat affected zone (HAZ) close to weld joints. The total wall thicknesses in these piping components were in the range of 30-60 mm or more. The materials were exclusive stainless steel or nickel base alloys. This requires energy of at least 450 kV in order to provide good contrast and because of the geometry can’t micro-focus technique be used.

2 Detectors
Since x-rays neither can be seen nor be measured without being detected and converted to some measurable signal, a detector must be used. The photographic film was already in use when x-rays were discovered and it is still today the dominating detector type within mobile radiography. Very early scintillating materials were used, sometime along with photographic film as intensifying screen. Image intensifier then began to be used as x-ray detector. More recently modern semi-conductor materials such as silicon and selenium are used in the electronic detectors.

After screening various types of detectors and compared various properties, the following conclusions have been made. Conventional X-ray film and CR have been excluded in this application since the fixed pattern noise is limiting. All detectors based on direct detection have also been excluded given that the design limits possible energy levels. The exception is CdTe, but it does not meet the requirement on the spatial resolution which is too low. Only indirect detection using different scintillation materials remained as suitable detection method.
<table>
<thead>
<tr>
<th>Physics</th>
<th>Type</th>
<th>Pixel size (μm typ.)</th>
<th>Active area (mm² max.)</th>
<th>SNR (max.)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog</td>
<td>Film</td>
<td>-</td>
<td>350x420</td>
<td>&lt;200</td>
<td>Fixed pattern noise limits SNR</td>
</tr>
<tr>
<td>CR</td>
<td>Phosphor</td>
<td>40-50</td>
<td>350x420</td>
<td>200-350</td>
<td></td>
</tr>
<tr>
<td>Semiconductor</td>
<td>α-Se</td>
<td>127-400</td>
<td>400x400</td>
<td>&gt;10000</td>
<td>Only for low energies</td>
</tr>
<tr>
<td>-</td>
<td>CMOS</td>
<td>50-100</td>
<td>100x100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>CCD</td>
<td>10-25</td>
<td>25x25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>CdTe</td>
<td>100</td>
<td>100x100</td>
<td>&gt;3000</td>
<td>Limited resolution</td>
</tr>
<tr>
<td>Scintillation</td>
<td>α-Si</td>
<td>127-400</td>
<td>400x400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>CMOS</td>
<td>50-100</td>
<td>100x100</td>
<td>3800</td>
<td>Only for medium energies</td>
</tr>
<tr>
<td>-</td>
<td>CCD</td>
<td>10-25</td>
<td>25x25</td>
<td>&gt;6000</td>
<td>Small active area</td>
</tr>
</tbody>
</table>

Table 1. Different detectors.

Detectors based on the scintillation effect work excellent at lower energies (<100 keV) but the detection efficiency drops rapidly at higher energies. In order to increase the detection efficiency the thickness of the screen must be increased but at the expense of the spatial resolution. In conventional screens the scintillating material is in the form of a powder and applied with adhesives. The light that is produced when x-rays are absorbed is emitted isotropically and only photons within an angle less than α can be detected (see Figure 2). The reminder is reflected back into the screen again. The spatial resolution is thus proportional to the thickness of the screen.

![Figure 2. Light spread in powder screen.](image)

One way to solve this problem is to guide the light through the scintillating screen. This can be done on several different ways but in practice it is two methods that are applicable. One way is to use structurally grown CsI-crystals and another is to use scintillating glass fiber optic faceplates (SFOP). Screens made of structural grown CsI(Tl) are produced through chemical vapour deposition in a standard vacuum chamber. The crystal diameter can vary from 1 to approximate 30 μm and the screens can be up to 3 mm thick. A really thin screen (10-40 μm) can reach a spatial resolution as high as 30 lp/mm (MTF 10%) but then detection efficiency is very low.

When the thickness of the screen is increased this inevitably increases the crystal diameter. For a screen that is 1.5 mm thick the crystal diameter is about 30-40 μm. The detection
efficiency is significantly higher but the resolution is only 2 lp/mm (MTF 10%) [2]. Since the crystals are not entirely perfect the light guiding ability is neither. Despite that the crystals lead the light fairly efficiently a significant part of the light is spread laterally. The light spreading problem increases with increasing thickness of the screen due to the fact that crystals become less perfect the longer the crystals are grown. A solution to this problem is to use the SFOP (see Figure 3).

A big advantage with SFOP is the high detection efficiency along with the spatial the resolution. Calculations show that the difference in detection efficiency (at 400 kV) between glass SFOP (10mm) and structurally grown CsI (300μm) is about a factor ten.

### 3 Fiber optics

A fiber optic light guide is a conductor of light and can be produced very thin. It consists of a core with a high refraction indices and a cladding with a lower. The diameter varies from a few µm up to some millimeter. They can be produced in different types of glasses qualities assumed that they have good light conducting properties and high transmission of the actual wavelengths. It can be used as an x-ray detector if the core glass has scintillating properties. It can also be used as an image conduit which transports light and is then considered as a perfect lens, without aberrations. A glass fiber optic image conduit is a solid unit of glass fibers which is sintered together [3].

![Figure 3. Conventional screens compared to structured screen.](image)

An incoming light beam that hits a phase boundary against optic thinner medium will be totally reflected within a certain angle. In Figure 4, a light beam comes in from outside within the acceptance angle, \( \theta_a \). When it enters into the core, which has higher refraction indices, it is bent according to Snell’s law. When the beam hits the cladding it will be totally reflected if the angle is less than \( \theta_c \). How much light that can be transmitted is thus governed by the numeric aperture (N.A.) which is defined as:

\[
N.A. = \sqrt{\eta_{\text{core}}^2 + \eta_{\text{clad}}^2}
\]  

(1)
Light that are lost or is unguided continues its way into neighbouring fibers. To reduce crosstalk and improving spatial resolution black glass or extra mural absorber (EMA) are inserted between the scintillating fibers.

The new and the old SFOP were made with different scintillation (radioluminescent) core glass (both manufactured by Collimated Holes Inc [4]). The first SFOP, here denoted as CHI, had a core glass were the main material was terbium with a relatively high content of strontium. The second, here denoted as LKH-6 [5], have a core glass were the active material are terbium and gadolinium with high content of barium. The new SFOP with LKH-6 glass should produce 1.6 times more light photon per detected x-ray compared to the one with CHI-glass.

Also the EMA differs between the new and old SFOP. In the old SFOP the EMA was inserted interstitial placed black glass fibers. The new SFOP has EMA as a second cladding of black glass around each single fiber (see Figure 5). Earlier studies show that increasing amounts of EMA gives increased spatial resolution and already with 10% EMA the resolution has increased considerably [6]. Since the new SFOP has 20% EMA and also surrounds each individual fiber, the lateral scattered light negligible.
4 Experiments

The conducted experiments, described below, were time-consuming and required a large amount of preparations but can be described fairly easily. The experiments consisted of two parts was the first part is to redesign of the camera in order to minimize the amount radiation induced noise [7]. This was done by bending the fiber optic lens (image conduit) which moved CCD-chip out of the primary beam. The second part of the experiment was a measurement of how much the spatial resolution can be increased by increasing the amount of EMA. For this purpose a new camera was constructed with a curved fiber optic lens and with the new SFOP. The old camera configuration has previously been described in detail [1] and a more explicit description of the new camera design has also previously been published [7].

The new concept is based on a front illuminated full frame CCD (EEV CCD42-40) with pixel size of 13.5 x 13.5 µm [8]. It’s Peltier cold down to -30ºC and is equipped with fiber optic input window. The input window is a fiber optic lens with fiber diameter of 4.5 µm and the length is 50 mm (see Figure 6, 2a-2c). In the front of the camera, the bended fiber optic lens with the scintillating screen is mounted (see Figure 7). By comparison, the old camera, had a straight fiber optic lens and similar type of CCD (EEV CCD05-30) but with a pixel size of 22.5 x 22.5 µm [9] (see Figure 6, 1a-1c).
The new scintillation screen is square (see Figure 7), while the old one that was circular. This is a consequence of the CCD being square and the improvement of the light guiding properties of the fiber optic lens.

![Figure 7. Scintillating screen (left) and bended fiber optic lens (right)](image)

All tests were made with a defect free (forged) test block. A thickness of 20 mm was used with the IQI mounted on the source side (see Figure 8). The focus distance of 800 mm made the geometric unsharpness less than the detector unsharpness. In both cases a focus size less than 1 mm was used.

![Figure 8. Tests with the new camera. Test block (20 mm Fe) and IQI 462-5.](image)
5. Results

The tests were done at 300 kV with the new system and at 400 kV with the old system. The focus distance was 800 mm in both cases. To achieve about the same SNR, 20 s. exposure time at 400 kV and 150 s. at 300 kV was used. The large difference in exposure time is explained due to the different sampling (pixel size). The difference in area ratio is close to 2.78 between the pixels of two cameras. If this difference is compensated for exposure time of 54 s. is obtained. Since exposure time will be reduced with a higher level of energy, the images can be treated equivalent in respect of SNR.

The resolution was quantified with a double wire IQI (462-5) and revealed that the unsharpness is reduced in the new system. The modulation on the 13:th wire (d=0.05mm) is in the range of 60-70% (see left side of Figure 9 and upper part of Figure 10). The old system could hardly reach 20%. The radiation induced noise was reduced significantly as well and it is actually visible as black and white spots in the left image (see Figure 9).

Figure 9. New system (left) and old system (right).

Figure 10. Upper line profile shows the new camera compared with result from the old below.
4. Collimated Holes Inc., 460 Division Street, Campbell, CA 95008, USA
8. Princeton Instruments, 3660 Quakerbridge Road Trenton, NJ 08619 USA