A NEW LINEAR DETECTOR ARRAY CONCEPT FOR ACCELERATOR BASED DIGITAL RADIOGRAPHY OF THE FINAL DISPOSAL CANISTERS FOR SPENT NUCLEAR FUEL

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ABSTRACT
The final disposal canisters for spent nuclear fuel consist of a cast iron insert with channels for the spent fuel bundles. The cast iron insert will be placed inside a copper cylinder that acts as a corrosion barrier when the canisters have been embedded in the bedrock at a depth of about 400 meters. The copper canisters have a wall thickness of 50 mm and they will be sealed by welding a copper lid to the canister once they have been filled with spent nuclear fuel. The sealing weld needs to be absolutely tight and it will therefore be inspected using several NDE methods. Digital radiography is one of them.

The thickness of copper, which X-rays have to penetrate during weld inspection may be up to 120 mm and therefore a 9 MeV linear accelerator is needed as X-ray source. The canister is rotating during the inspection while the accelerator and the linear detector are stationary. During one full rotation about 3 m of weld will be inspected. Because of the radiation from the spent fuel inside the canister, the inspection needs to be fully automated and this is one reason why only digital radiography can be used. The goal is to be able to observe volumetric defects as small as $0.5 \times 0.5 \times 0.5 \, \text{mm}^3$.

To minimize the effect of scattered radiation a collimated line detector will be used where the width of the collimator is 200 µm and the length is about 100 mm. This novel line detector will consist of 512 direct conversion Gallium Arsenide (GaAs) strips with a pixel pitch of 200 µm manufactured by Oxford Instruments. There are several reasons for choosing GaAs as detector material: It has good stopping potential for MeV energy photons (similar to that of Germanium), but it does not need cryogenic cooling. GaAs also has good radiation tolerance for photons in the MeV energy range. Further, the technology for manufacturing detector strips out of thick layers of high purity epitaxially grown GaAs wafers is relatively well mastered. Due to the high sensitivity of the GaAs and rapid readout electronics it will be possible to capture the X-ray picture and the background in one single measurement run without the need to use a trigger signal to synchronize the accelerator X-ray pulses and the readout.

The conventional way of building an X-ray line detector is to use a scintillator, which generates light out of the X-ray photons. The light photons are then captured and converted to an X-ray picture by an array of photodiodes. The main progress beyond the state-of-the-art in using GaAs technology is to eliminate the light conversion phase and thereby increase the spatial resolution and the sensitivity. The final detector will be composed of three line detectors to facilitate stereoscopic radiography. This technique will help to localize and size defects in the direction of the X-ray.

INTRODUCTION
The high radioactive waste produced in nuclear power plants must be isolated from the organic nature until its radioactivity has decreased to harmless level. This isolation is called geologic disposal. This geologic disposal planned by Posiva Oy on assignment by its Finnish nuclear plant owners, Fortum Oyj and Teollisuuden Voima Oyj, is called EBS - Engineering Barrier System. The EBS- system consists of a multibarrier system: Finnish bedrock, bentonite clay around the disposal canisters and a cast iron insert inside the copper canister. The spent fuel assemblies are placed inside the massive cast iron insert in the copper canister. The canister's cast iron insert provides the required strength and protects the fuel from mechanical stress and pressure. The use of pure copper, a metal known to retain its properties well in the oxygen free conditions within the bedrock, ensures the tightness of the canister. The canister is placed into
a disposal hole bored in the bedrock. The sealing weld between the copper lid and the copper tube is possible to weld by electron beam or friction stir welding. The sealing weld needs to be absolutely tight and it will therefore be inspected using several NDE methods: ultrasonic testing, eddy current testing, remote visual testing and radiographic testing. Digital radiography is used to detect and characterize defects in the weld volume as well as ultrasonic testing. For digital radiography a proper detector is essential for reliable inspections.

In this study the construction of a digital semiconductor detector is considered for us in accelerator based radiography of the EB-sealing (Electron Beam) weld of the copper canisters for final disposal of spent nuclear fuel. The detector is a collimated line detector based on direct conversion instead of the more traditional scintillator detectors. A direct conversion detector will give a better spatial resolution as compared to a scintillator detector with the same pixel pitch. This is very important because we want to observe volumetric defects as small as 0.5 × 0.5 × 0.5 mm$^3$. The detector materials considered here are GaAs and CdTe, with some brief comparisons to Ge, Si and CdZnTe. GaAs is chosen as detector material for the new linear imaging detector.

**X-RAY SETUP FOR INSPECTION OF THE EB-WELD IN THE FINAL DISPOSAL CANISTER**

The measurement setup is illustrated in Fig. 1 were the accelerator is seen to the left, the canister in the middle and the detector to the right. The yellow fan-shaped area illustrates the x-ray beam. This setup is that of SKB in Oskarshamn, Sweden. The Varian Linatron used in this system delivers a dose rate of 30 Gy/min at one meter from the focal spot.

The detector is composed of a detector housing and a collimator for minimizing the scattered radiation. The geometry based spatial resolution and the detectability can be analysed using the schematic test setup shown in Fig. 3. Here $L_s$ is the size of focal spot of the linear accelerator, $L_d$ is the pixel size of the detector, $D$ is the distance from the focal spot to the defect in the EB weld and $d$ is the distance from the defect to the surface of the pixel.

![Figure 1. The canister in the middle is rotating during the inspection. The accelerator is seen to the left while the detector is the grey part to the right. The fan shaped X-ray beam is illustrated in yellow /1/](image)
Figure 2. A schematic view of the weld inspection setup shown in Fig. 1. The Source Detector Distance (SDD) was 2180 mm and the active height of the collimated line detector (rightmost) was 100 mm. The length of the collimator in the beam direction was 150 mm.

Figure 3. The origin of the geometry based restrictions in spatial detection and resolution. $L_s$ is the focal spot size and $L_d$ is the detector pixel size.

According to /2/ the spatial detection $LF$ can be approximately calculated using Eq. (1):

$$LF = \frac{d}{D} \sqrt{L_s^2 + \left(\frac{L_d D}{d}\right)^2}$$  \hspace{1cm} (1)

Further, the spatial resolution limit $\sigma$ is given by Eq. 2:

$$\sigma = 2 \times LF$$  \hspace{1cm} (2)

In the X-ray inspection of the EB weld the parameters in Eq. (1) has the following values:

$D = 1880$ mm  
$d = 300$ mm  
$L_s = 2.0$ mm  
$L_d = 0.2$ mm

As already mentioned, $L_s$ is the focal spot size of the accelerator (9 MeV Varian Linatron), which gives a dose rate of 30 Gy/min at a distance of 1 meter from the focal spot. The spot size is < 2 mm /3/.

These parameter values give us the following values for the spatial detection ($LF$) and the spatial resolution limit ($\sigma$) respectively:

$LF = 0.32$ mm  
$\sigma = 0.65$ mm

No scattering or electron spreading has been accounted for in this geometric model. The properties of the accelerator such as energy, spot size, pulse duration and dose rate are important for the performance of the radiographic system. Another important property of the system is the X-ray spectrum of accelerator. An estimated spectrum of a 9 MeV linear accelerator is given in Fig. 4.
CONSTRUCTION OF THE DETECTOR AND THE COLLIMATOR
The length of collimator in the X-ray direction is expected to be 15 – 20 cm and collimator slit width is 200 µm. The height of the collimator is 100 mm. The height and width directions are mutually perpendicular to the X-ray direction see Fig. 2. A suitable material for the collimator is Densimet® as it has high density (17.0 – 18.5 g/cm³), high modulus of elasticity and has good machinability and mechanical properties. This Tungsten alloy is also harmless to the health and the environment.

Each of the detector strips should be individually oriented along the line-of-sight towards the focal spot of the accelerator. This is a consequence of the high energy used; the strips need to be long in the X-ray direction to provide enough stopping power. The alignment of the individual strips is illustrated to the right in Fig. 5. This means that once the detector strips have been built the distance between the focal spot and the strip detector cannot be changed. Further, the accuracy of the alignment of the individual strips with the X-rays will become more critical with increasing length of the strips in the direction of the radiation. If this alignment is not properly done, direct radiation will leak into the neighbouring strips and this will lead to image blurring. It can be seen from Fig. 5 that a straight strip detector is functional only if the strips are very short in the X-ray direction. As the sensitivity of the detector increases with increasing strip length, a minimum length is needed to fulfil the needs. The needed length is dependent on the detector material used (about 50 mm for GaAs). Some radiation will in any case scatter in the strips themselves and leak into the neighbours, but this cannot be avoided. To minimize the latter kind of blurring the height of the strips should not be larger than the height of the collimator slit.

The strip arrays in the detector can be either scintillators or direct conversion semiconductors. In the first case the incoming X-rays are first converted to light, which is lead to an array of photodiodes using waveguides and possible other optical components. In the second case the X-rays produce electron-hole pairs directly without the intermediate step of light production. This is considered to be an advantage from the point of view of spatial resolution and perhaps also with respect to detection efficiency.
Figure 5. The individual strips have to be aligned (right picture) towards the focal spot to avoid loss of resolution (left picture) due to geometric spread of the signal into neighbouring strips /5/.

The detector used in the setup shown in Fig. 1 (the SKB setup) was based on scintillator technology and the scintillator material used was CdWO₄ (Cadmium tungstate). CdWO₄ is a high density, high atomic number scintillator with relatively high light yield. The emission maximum is at 475 nm and the total light output is 12 to 15 photons/keV. The light yield relative to NaI(Tl) on a bialkali PMT is 30 to 50% (see Internet Address, Cadmium tungstate). Here are some features and benefits of CdWO₄:

- Low afterglow
- Withstands high energy radiation damage
- High density, high Z scintillator
- Suitable for low activity counting applications
- Relatively high light yield

In this detector the CdWO₄ strips had a height of 5 mm (in the X-ray direction) and there were 2048 strips with a width of 0.05 mm. Eight strips were, however, connected together to form an effective strip of width 0.4 mm. Therefore the useful number of strips was 256. The collimator slit was also 0.4 mm so we can say that the pixel size was 0.4 mm.

A deeper study of the scintillator detector concept is out of the scope of this work because the detector to be manufactured for Posiva Oy will be based on direct conversion technology and there will be 512 strips with a total length of about 100 mm. The collimator slit will be 0.2 mm. The pixel size will be 0.2 mm, and therefore the surface of the pixel will be one fourth of that of the surface of the scintillator pixel depicted above (the SKB setup). For the Posiva-setup, there are also plans to introduce two extra detectors on both sides of the detector shown in Fig. 1. By this arrangement it will be possible to make stereoscopic radiography /6/. In the next chapter an overview of some possible direct conversion materials will be given.

DEFECT DETECTION

In this chapter an example defect detection using the using the accelerator and detector setup shown in Fig. will be given. In evaluation of the defect detectability a copper reference specimen containing a lot of artificial defects were used. Most of the defects were inserted in the EB-weld area, see Fig. 2. All the artificial defects were observed together with some natural defects that accidently were present in the specimen. One set of artificial defects were holes extending from the top of the weld to the root of the weld, i.e. vertically in the weld area in Fig. 2. The diameters of these holes were 0.5 mm, 1.0 mm, 1.5 mm and 2.0 mm. The area of the X-ray picture containing these defects have been processed into the colour
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coded map shown if Fig. 6. Red corresponds to the highest grey values while dark blue represents the lowest grey values. As can be seen also the smallest hole with diameter of 0.5 mm can be observes almost all the way from the top of the weld to the root.

The performance of the X-ray system was also analysed by using Image Quality Indicators (IQI) and the results were compared to standards /7/. The results were very encouraging and it seems probable that the new direct conversion GaAs detector described below will further improve the defect detectability.

Figure 6. The X-ray picture of the area containing holes (diameters 0.5 mm, 1.0 mm, 1.5 mm and 2.0 mm) from the top to the root of the EB-weld has been processed into a colour coded map. Also the smallest 0.5 mm hole is observed.

POSSIBLE SEMICONDUCTOR MATERIALS FOR A LINEAR ARRAY X_RAY DETECTOR
The X-ray source used for the inspection of the EB weld in the final disposal canister will probably be a 9 MeV linear accelerator. The mean energy of the X-rays photons leaving such a device is somewhere between 3 and 4 MeV. This makes the detector design a bit trickier than for X-rays in the keV range. Enough radiation need to be absorbed in the detector material to give a good signal, however, the absorption coefficient goes steeply down for increasing photon energy. The absorption coefficient is higher for high density materials, so the detector material needs to have high density in order to have a good stopping power. Some materials satisfying this demand are Germanium (Ge), Cadmium Telluride (CdTe), Cadmium Zinc Telluride (CdZnTe) and Gallium Arsenide (GaAs). Ge can be excluded from this application because it will need to be cooled to cryogenic temperatures because of its small bandgap (Takahashi & Watanabe, 2001). Further, the semiconductor properties (mobility of electrons and holes, electron-hole lifetime etc) and the possibilities of manufacturing the needed strips will influence the choice of material.

Properties of some detector materials
The material should also be highly homogeneous so that the individual detector strips will have as similar X-ray detection properties as possible. Table 1 gives some properties of six detector materials.
The X-ray path length in different materials to reach absorptions of 30%, 60% and 90% has been calculated in Table 2 for 3 MeV photons to illustrate the difference in stopping power. The mass attenuation coefficients used are from NIST /9/, except the linear attenuation coefficient for CdZnTe is from Amptek /8/. Note that Ge and GaAs are quite similar in this respect. CdTe and CdZnTe are a bit better than Ge and GaAs. Remember, however, that Ge will need cryogenic cooling and is therefore not an option in this application. Silicon (Si) has a quite poor stopping power for this energy and is therefore not suitable.

Table 1. The properties of some detector materials. Those with the highest density (or Z) have the best stopping power. The radiation length ($X_0$) is the length in which the intensity of a monochromatic beam drops to $1/e$ /10/.

<table>
<thead>
<tr>
<th>semiconductor</th>
<th>density [g/cm$^3$]</th>
<th>Z</th>
<th>$E_{\text{gap}}$ [eV]</th>
<th>$\epsilon$ [eV]</th>
<th>$X_0$ [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>2.33</td>
<td>14</td>
<td>1.12</td>
<td>3.6</td>
<td>9.37</td>
</tr>
<tr>
<td>Ge</td>
<td>5.33</td>
<td>32</td>
<td>0.67</td>
<td>2.9</td>
<td>2.30</td>
</tr>
<tr>
<td>CdTe</td>
<td>5.85</td>
<td>48,52</td>
<td>1.44</td>
<td>4.43</td>
<td>1.52</td>
</tr>
<tr>
<td>CdZnTe</td>
<td>5.81</td>
<td></td>
<td>1.6</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>HgI$_2$</td>
<td>6.40</td>
<td>80,53</td>
<td>2.13</td>
<td>4.2</td>
<td>1.16</td>
</tr>
<tr>
<td>GaAs</td>
<td>5.32</td>
<td>31, 33</td>
<td>1.42</td>
<td>4.3</td>
<td>2.29</td>
</tr>
</tbody>
</table>

$E_{\text{gap}}$ : band gap energy  
$\epsilon$ : an ionization potential  
$X_0$ : radiation length

Based on this we are left with only GaAs, CdTe and CdZnTe (with some reservations for very recent developments). The use of CdTe as imaging detector material has also been investigated in Finland by for example VTT and Oxford Instruments Analytical /11/. The scintillator material Cadmium Tungstate (CdWO$_4$) /12/ is included in Tab. 2 because the first measurements were done using a detector of this type. The performance of this material cannot, however, be compared to the direct conversion materials using the stopping power because mechanism for signal production is different.

Table 2. The X-ray path lengths in mm needed for 30%, 60% and 90% absorption as calculated from the linear absorption coefficients at 3 MeV photon energies. Copper is included for comparison.

<table>
<thead>
<tr>
<th>Energy absorbed</th>
<th>Si</th>
<th>Ge</th>
<th>GaAs</th>
<th>CdTe</th>
<th>CdZnTe</th>
<th>CdWO$_4$</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>41.6</td>
<td>19.0</td>
<td>18.9</td>
<td>16.8</td>
<td>15.8</td>
<td>11.7</td>
<td>11.1</td>
</tr>
<tr>
<td>60%</td>
<td>107.0</td>
<td>48.8</td>
<td>48.7</td>
<td>43.1</td>
<td>40.5</td>
<td>30.0</td>
<td>28.5</td>
</tr>
<tr>
<td>90%</td>
<td>268.8</td>
<td>122.6</td>
<td>122.3</td>
<td>108.4</td>
<td>101.9</td>
<td>75.3</td>
<td>71.6</td>
</tr>
</tbody>
</table>

According to /13/ there still seems to be some technological problems with CdTe and CdZnTe. These relate to homogeneity of the material, to the maximum area of the grown layers and to defect concentration. A large enough area is needed to build a large detector and a good homogeneity is needed to get equal response from the individual strips. According to Sun et al. epitaxial GaAs is still superior in these aspects. For CdTe, however, new techniques for growing detector grade materials are under
Comparison between direct conversion and scintillator detectors

CdWO₄ has higher stopping power than semiconductor materials. However, if linear strip detector is used to detect the light then X-ray path length shall not exceed 5-10 mm in order to avoid geometrical spread of the signal. This limitation can be avoided by using 2-dimensional pixel sensors. The advantage of them is that the measurement geometry can be flexible. The problem is that the number of photons detected by individual pixels is very low compared to the optical signals these sensors are designed for and the image will be granular. The scintillating effect is rather inefficient, only a very small fraction of the energy of the incident quanta is used to generate the signal. The signal in direct conversion detectors is much larger.

The other disadvantage of the scintillator detectors is the optical blurring: the light is spreading to the neighbor pixels. For example if the thickness of a scintillating layer on a linear strip sensor equals to the pitch of the strips the 50% of the light go the neighbor pixels that causes blurring. The situation can be sometimes improved by using reflective/absorbing walls between pixels or by using structured scintillators (CsI).

The disadvantage or challenge of the usage compound semiconductor detectors, like GaAs and CdTe detectors, is their industrial non-maturity in this kind of applications and the technology requires further development.

CONSTRUCTION OF THE GaAs-DETECTOR

The strip detector will be produced by using high purity GaAs material grown by CVPE method (Chloride Vapour Phase Epitaxy). The material is grown on n⁺-type bulk GaAs wafers in a quartz tube. The concentration of the free carriers in the high purity “intrinsic” (actually slightly n-type) layer is less than 1·10¹³ cm⁻³ and the thickness of the layer is about 200 µm. At the very end of the growth, a 1-2 µm thick p⁺-type layer is grown on the top of intrinsic material by feeding Zn dopant in to the quartz tube. In this way a GaAs PIN structure is formed.

The GaAs wafers are then processed by using normal lithographical patterning techniques developed for GaAs semiconductor devices, based on the use of photoresist, etching, and metal deposition by sputtering and evaporation. The different strips are separated electrically from each other by etching the p⁺ layer between them and then passivating the etched surface with silicon nitride.

The GaAs detector has 512 strips that are not parallel but they are focused to a point that is 2180 mm from the detectors. The pitch of the strips is 0.2 mm and length of the strips was selected to be 25 mm in the first prototype. Figure 7 shows a GaAs strip detector produced earlier.
Figure 7. A GaAs wafer with one strip detector and test devices on the edges. The strip detector is placed at the centre region of the wafer since the edge regions contain typically different kind of defects. The direction of x-rays has been marked with red arrow.

The active radiation detecting volume in the GaAs strip detectors is the intrinsic layer. The signal is generated when x-rays interact with GaAs material by mainly by Compton, but also by photoelectric and pair production effects and create energetic electrons and positrons that lose their energy along their path causing electron-hole pairs inside the intrinsic layer. The signal is detected as a photocurrent in the PIN diode strips when the strips are reverse biased. Typically the bias voltage is of the order of 100 V. The leakage current of one detector is anticipated to be about 1 nA, based on similar detectors produced earlier. The plan is to reduce the leakage current on order of magnitude by cooling with a TEC down to -5 °C -10 °C, which also ensures the full depletion of the intrinsic layer. Because of the cooling the GaAs detector is inside a hermetic chamber. It prevents the condensation of moisture on the detector surface.


Figure 8 shows a schematic illustration of our system. The charges generated in the strips are read by special multi-channel ROICs (Readout Integrated Circuit) or readout ASICs. We are planning to use
XCHIP devices (STFC, RAL). Each of them has 128 input channels, so four XCHIPs are enough. The XCHIPs are placed on a XSTRIP board containing voltage regulators and other auxiliary components, and they multiplex the 512 detector channels into 16 analogue outputs. The XCHIPS are controlled and read by UltraDAQ, a high-speed standalone data acquisition system that performs the analogue to digital conversion and forwards the data to a PC via UDP over Gigabit Ethernet. The data are received and stored using a LabView application, which can also do some online processing of the data. Most processing and image reconstruction will be done offline with specialized software.

XCHIPs shall be protected from the radiation passing through the detector or from the scattered radiation. For this reason, the XCHIPs are placed to a few cm apart from the detector-radiation plane and they are protected with Densimet shields, see the figure 8. This can be done by using flexible polyimide cable that can be formed to S-shape.

In addition, the pitch of the input pads in the XCHIPs is 44 µm and in order to connect the strips of the GaAs, pitch 200 µm, a fan-in structure is needed. Unfortunately, the 44 µm was too fine for polyimide cables and the fan-in structure will be made on a glass plate. So the strips of the GaAs detector are first connected to the flexible polyimide cable, then to the fan-in glass plate and then to XCHIPs.

The GaAs detector is mounted carefully on its place so that it is parallel with the collimator and in the same plane so that the detector would be fully exposed.

SUMMARY AND CONCLUSION
Several techniques for improving the accelerator based digital radiography of the final disposal canisters are presented in this study. On central aspect is the use of Gallium Arsenide (GaAs) as a direct conversion material instead of a scintillator material. This will eliminate the optical blurring and thereby increase the spatial resolution. The spatial resolution is further increased by using a pixel pitch of 0.2 mm instead of 0.4 mm used in the scintillator based detector. The sensitivity of the GaAs material and the rapid readout circuits make it possible to capture the X-ray picture and the background radiation in a single measurement run without any need to synchronize the readout with the X-ray pulses from the linear accelerator. A software routine will use calibration measurements to correct for slight differences in sensitivity between different GaAs strips. The same software routine will also correct for beam hardening and hence linearize the defect vs. grey value curve. Finally, the GaAs detector are much smaller than the corresponding scintillator elements and this will make it possible to place two or three GaAs line detectors in the same detector housing assembly to facilitate stereoscopic radiography.

REFERENCES
9) NIST (National Institute of Standards and Technology). Internet address 2011-05-26:

