Impact of Collimation on Line Scan X-Ray Images

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ABSTRACT

Various methods and techniques are used in the x-ray industry to improve the imaging quality of line scan x-ray detectors: increasing x-ray power, increasing the dynamic range of the imaging sensor, using longer integration time, etc. Other methods also include mechanical design alternatives such as optimized x-ray acceptance angles, sufficient shielding and radiation scatter guards, and collimation inside and outside the detector housing. This presentation will focus on the more economical way of improving imaging quality of line scan x-ray detectors: sensor side collimation. By simply placing two pieces of high-Z metal plates strategically above the sensor boards, imaging quality can be improved greatly in terms of crosstalk reduction and contrast sensitivity elevation.

Keywords: imaging quality, shielding, radiation, Compton scattering, collimation, line scan x-ray detectors, crosstalk, contrast sensitivity

Challenges in Imaging with Line Scan X-Ray Detectors for NDT

Line scan x-ray detectors are highly customizable in terms of their sizes and functionality to fit not only rigid mechanical requirements but also strict integration time constraints. Contrast sensitivity is the number one element influencing x-ray imaging quality in NDT applications. Line scan x-ray detectors are not known for having extraordinary contrast sensitivity due to its image capturing method. This unique image capturing method is essentially exposing one single line of sensors to x-ray radiation while moving in sync with the objects on a conveyor and building a 2D image in real time. Line scan x-ray detectors are ideal for scanning objects in motion or moving along side of heavy or long objects in relatively high speed.

Obstacles of Improving Contrast Sensitivity

Scattered Radiation vs Contrast Reduction

When an incident x-ray beam passes through the objects and then reach the sensor boards sitting inside the line scan detector housing, radiation absorption by the objects isn't the only event that happens. Some x-ray will penetrate through the material and some will be absorbed. The penetration or attenuation of the x-ray can manifest in several different mechanisms: Photoelectric process, Compton scattering, Pair production and Thomson scattering, etc. Compton scattering is a regularly occurring event accompanying penetrating radiation especially for NDT applications where radiation energy usually doesn't exceed 1Mev (figure 1). It is necessary and helpful to know what exactly Compton scattering is. Compton scattering is when an incident photon changes path due to an interaction with an electron (see figure 2). The electron in question gains energy and is ejected from its position. The x-ray photon loses energy because of the interaction with that electron but continues to travel through the objects/material along a changed path.

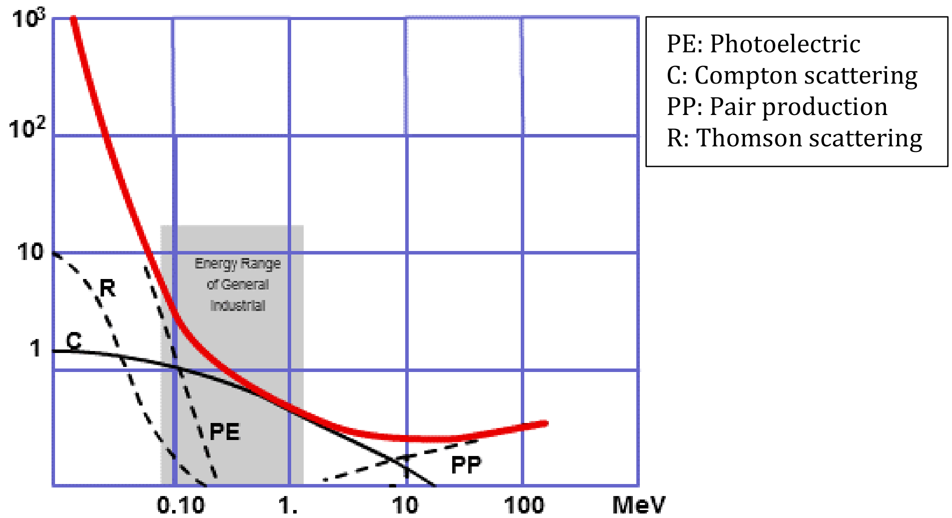


Figure 1. Sources of attenuation across different energy levels [1]

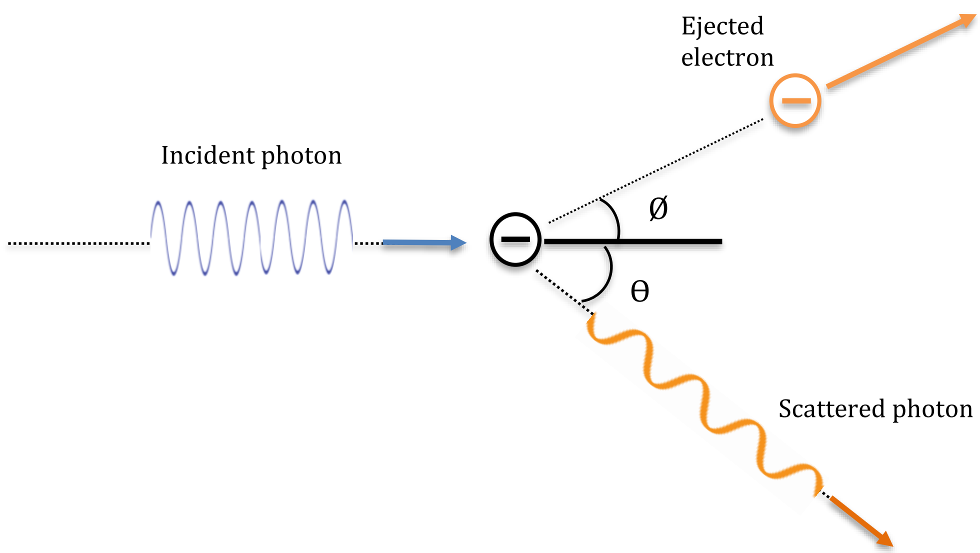


Figure 2. Compton Scattering

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta) \qquad \textbf{(Eq. 1)}$$

where

λ' = wavelength of scattered x-ray photon

λ = wavelength of incident x-ray photon

h = Planck's Constant

m_e = the mass of an electron at rest

c = the speed of light

θ = scattering angle of the scattered photon

$$E = \frac{hc}{\lambda} \qquad \textbf{(Eq. 2)}$$

Where

E = photon's energy

The directions and energies of the scattered photons can be approximated by using the Klein-Nishina formula [2] and figure 2. The conservation of energy and momentum is applied in equation 1 where the scattered photon's wavelength is longer than that of the incident photon. Because of the inverse proportional relationship between photon's energy and wavelength shown in equation 2, scattering photon will carry less energy than the incident photon.

With typical NDT inspection conducted within 1Mev range, the scattered radiation generated largely come from Compton scattering (figure 1). Even though the scattered radiation has less energy than incident radiation, the negative impact it has on contrast sensitivity is far from being insignificant. For example, live theater production uses spotlight to track and bring out the main speaking character to help the audience know which actor to concentrate on. Similarly, the features to be detected in a radiograph are like the speaking actor among all the other background actors, they need to stand out from the background for engineers and technicians to interpret defects. Scattered radiation gives the background of the feature too much exposure or illumination for it to stay mute in a radiograph. As a result, the overall contrast sensitivity of the image is reduced. (figure 3)

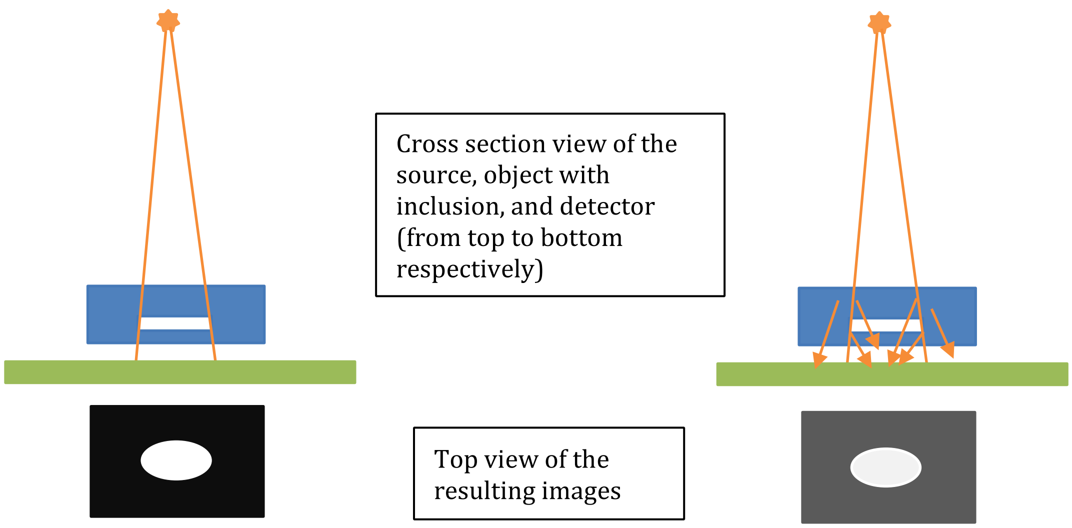


Figure 3. Scattered radiation reduces image contrast sensitivity on the right side (assuming there is no scatter radiation on the left)

Collimation

Collimation is a technique often used together with x-ray and gamma ray sources to make the beam more focused on the line scan x-ray detectors' linear sensing area. A collimator is usually a thick metal plate either made with lead or tungsten with a small slit or shutter in the middle. The collimators are commonly placed right in front of the tube emitting window. These source side collimators prevent excessive radiation by filtering through only the rays that travel parallel to the collimator slit/shutter. Most peripheral rays are shielded within the collimator and will not reach the objects nor image receptors. Figure 4 illustrates how a tube side collimator helps cut down the unwanted radiation. The light gray area represents the peripheral rays stopped by the collimator.

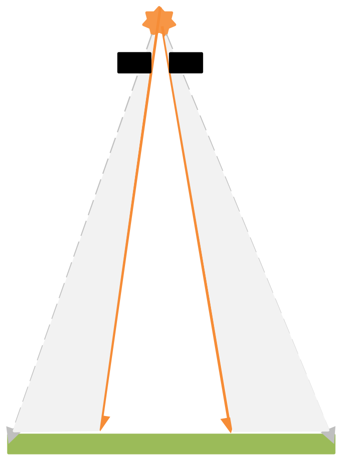


Figure 4. The collimator on source side reduces the beam size

Primary collimation vs secondary collimation

Detector side collimation is the secondary collimation if we call tube side collimation the primary collimation. A primary collimator device is typically a beam narrowing device. It narrows the beam coming out of the x-ray tube or gamma source exposure position opening so unwanted radiation is not "seen" by the detectors. A secondary collimator located close to detector sensing area further cuts down the radiation volume and narrows down the incoming beam even more. (figure 5)

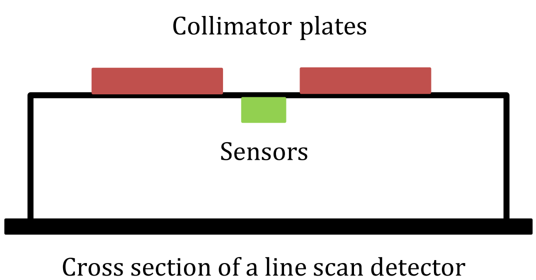


Figure 5. Sensor side collimator plates sitting on top of a line scan detector housing right above the sensing area

Intermediate collimation

Collimation that locates in the middle of tube side collimation and sensor side collimation can be considered as the intermediate collimation. Intermediate collimation can cut down more scattered radiation even with the existence of both primary and secondary collimation (figure 6).

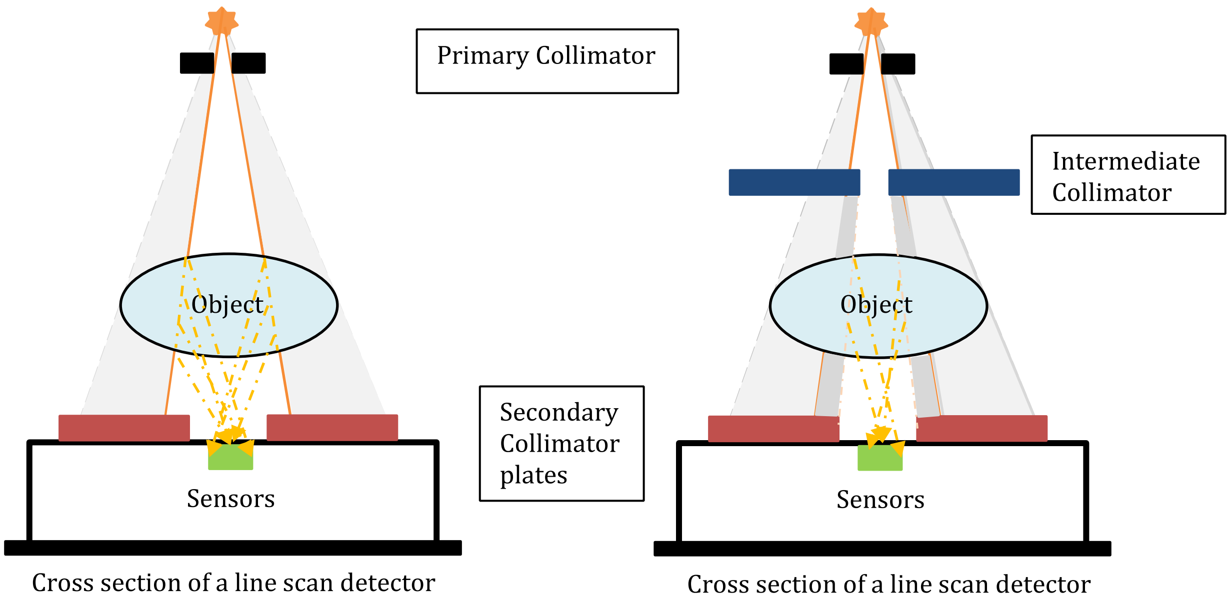


Figure 6. Intermediate collimation on the right side in comparison to just primary collimation and secondary collimation.

Ways to Improve Contrast Sensitivity

Secondary collimation helps to increase contrast sensitivity.

After evaluating various methods to improve contrast sensitivity, we have found that adding a set of Lead or Tungsten collimator plates to the existing inspection system can quickly increase the contrast sensitivity significantly. Additionally, some extra Lead (Pb) or Tungsten (W) plates of a few millimeter-thick cost anywhere from around 100 dollars to a couple of hundred dollars. It is a very small amount of money comparing to if the user were to change one of the main components of the inspection system, namely to a more powerful x-ray source, a fresher isotope, or a more sensitive detector.

To verify the theory that we had about the secondary collimation, we conducted a series of tests with a CMOS line scan detector in 3 different setups: no collimator, collimation plates with 3 mm gap, collimation plates with 1.7 mm gap. Figure 7 illustrates the 3 setups in a simplified fashion where the green rectangle represents the line sensor in a cross-section view, and the red bars are the two separate pieces of collimation plates. We choose tungsten over lead in making the collimator plates because tungsten is more rigid, denser, and more durable. Tungsten plates have fine, straight edges that will not be corrupted easily. The reason for using two pieces of tungsten plates instead of one with a slit in the middle is to easily adjust the gap size of the “slit” for exposing the sensing area to limited radiation. By reducing the collimator gap from infinity (no collimator at all) to 3mm gap then down to 1.7mm gap, the received radiation beam gets reduced respectively to smaller and smaller sizes.

The same testing conditions were applied to all three setups to scan a few imaging targets: square resolution test pattern Type 41, a steel cross-talk target, and an aluminum step wedge (figure 8).

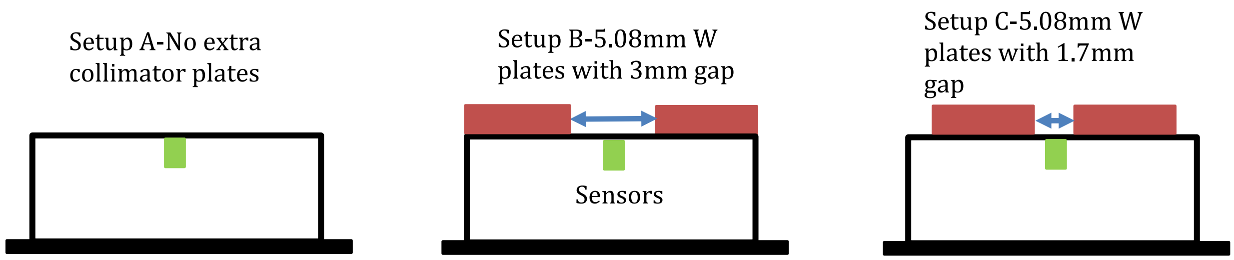


Figure 7. Three collimation test setups, setups B and C both use the same set of collimator plates which are 5.08mm thick Tungsten plates

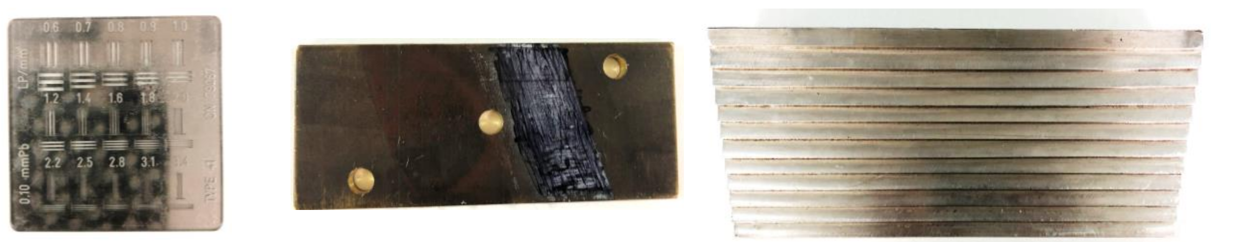
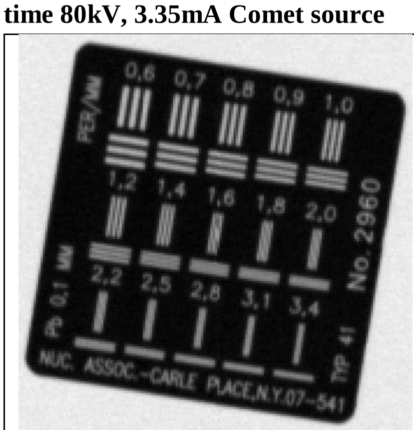
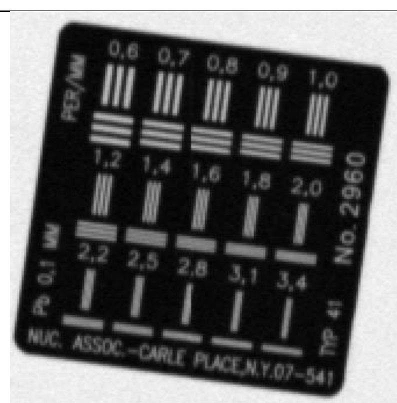
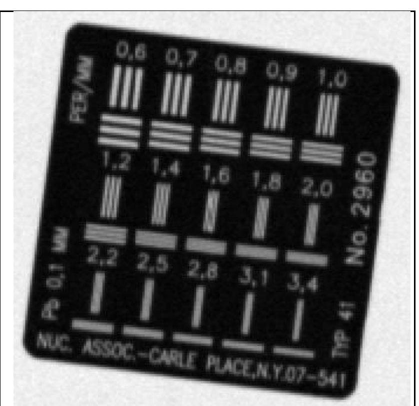


Figure 8. Left to right in order are the scanning targets of square resolution test pattern, steel cross-talk target, and aluminum step wedge

The square resolution test pattern in figure 8 is made of a 0.1 mm thick lead foil sandwiched in between two thin sheets of plastic. The thicker the material radiation penetrates; the more scattered radiation will occur. As a result, thinner objects tend to yield radiographs with good contrast sensitivity. The scanned images of the square resolution test pattern in table 1 demonstrates that the sensitivity of the 3 setups doesn't necessarily improve since thin metal objects already display good contrast sensitivity. It also shows that the usable resolution of the line scan detector doesn't change with or without the collimator on sensor side.

Table 1: These are the resulting images from the square resolution test pattern scans with 2ms integration time 80kV, 3.35mA Comet source

		
Setup A	Setup B	Setup C

On the contrary, table 2 of the 6.7 mm steel cross-talk target scans demonstrates that sensor side collimator with smallest gap results in the best contrast sensitivity out of the 3 setups. Setup A image in table 2 is the worst in image quality because of the negative influence from scattered radiation. The solid part of the cross-talk target shows "transparency" from all the scattering which verifies the theoretical results in figure 3. Table 3 summarizes the results in a quantitative matter where the ratio of the "white" part of the object and the "black" part of the object increases with respect to the addition of collimation and the reduction of collimator gap size.

The object scanned in table 4 is a 12-step aluminum step wedge with 3.75 mm step size. The resulting images show that sensor side collimator improved the visibility of the thinner steps (top part of images in table 3). It is also a result of less scattered radiation.

Table 2: These are the resulting images from the cross-talk target scans with 2ms integration time 80kV, 3.35mA Comet source. The same brightness and contrast leveling was used for all 3 images.

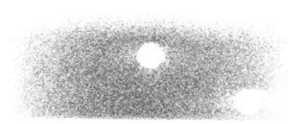
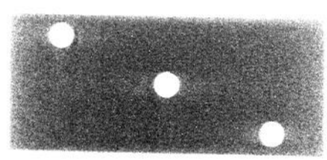
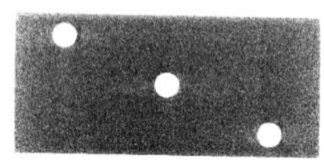
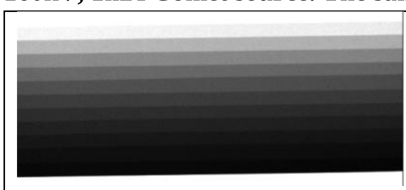
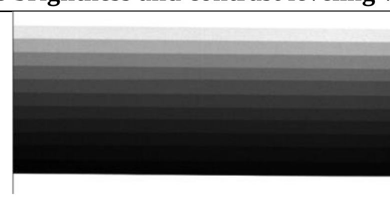
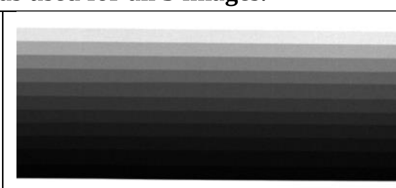
		
Setup A	Setup B	Setup C

Table 3: Cross-talk hole signal response value to body signal response value ratio

Setup	A	B	C
ratio	116	169	180

Table 4: These are the resulting images from the aluminum step wedge scans with 2ms integration time 160kV, 1mA Comet source. The same brightness and contrast leveling was used for all 3 images.

		
Setup A	Setup B	Setup C

Conclusion

Line scan detectors can get a boost in contrast sensitivity by adding some secondary collimation on the sensor side as we demonstrated in this paper. This relatively easy and economical addition to the detector may bring benefit to various NDT applications such as weld inspection, pipe inspection and others where dense and thick objects are to be inspected for defects.

Future Work

After establishing secondary collimation improves contrast sensitivity by cutting down scattered radiation, one might explore more about intermediate collimation that could advance the improvement even more.

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(2) Klein, O; Nishina, Y (1929). "Über die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac", Z. Phys. 52 (11–12): 853 and 869.