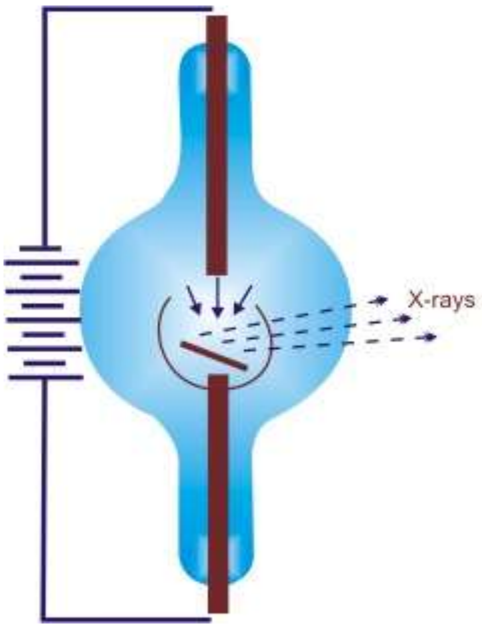
What are x-rays and how are they generated?

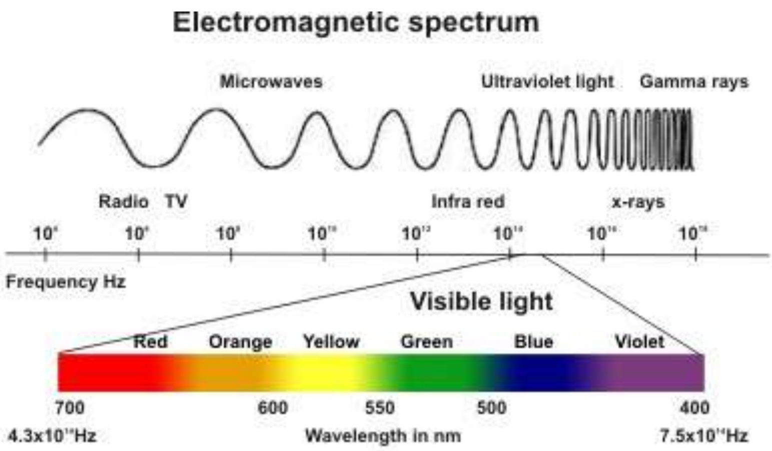


What are x-rays?

X-rays are part of the electromagnetic radiation spectrum. This spectrum includes radio waves, microwaves, infrared, the visible spectrum, ultra violet and gamma radiation. X-rays have a wavelength of the order of 10^{-10} metres, which is much shorter (or inversely a much higher frequency) than visible light. X-rays are also called ionizing radiation because of the way they interact with matter.

How are x-ray generated?

X-rays are produced by means of a cathode ray tube, which is similar to the tube of a television. Electrons are accelerated from a cathode at high speed towards a metal anode. As they hit the metal anode, they release energy. Over 95% of this energy is released as heat and less than 5% of the electrons' energy is converted into x-rays.



The principle constituents of an x-ray tube are:

Glass Envelope Provides a vacuum for the electron beam.

Electron Source A filament, which operates at a high temperature. The current through the filament provides control on the quantity of the electrons emitted.

High Voltage Applied between the filament (the cathode) and the anode. This high voltage controls the x-ray energy, and the force of the penetration of the x-rays.

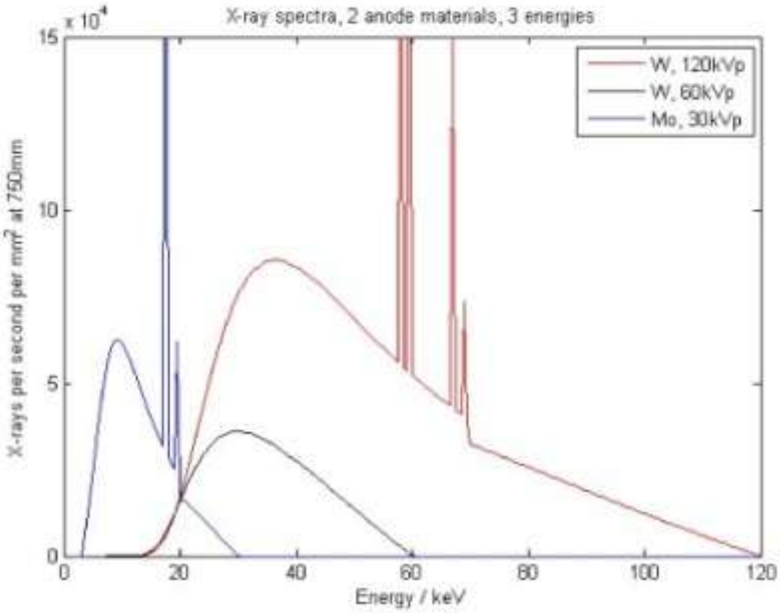
Anode A piece of metal (typically tungsten) that is hit by the electrons, (sometimes called the "target").

There are various types of x-ray tube.

- Oil Filled The entire tube is immersed in oil, shielded in lead, and contained in a tank. The oil is there to cool the tube and help insulate the high voltage supply within the tank.
- Gas Filled The tube is filled with gas and shielded with lead. As heat transfer in gas is much lower, the voltage levels are limited because of insulation issues. The energy of the x-rays produced by this type of tube is restricted to approximately 200 KeV.
- Rotating Anode An alternative method of dissipating the heat is to rotate the anode so that the heat load is spread evenly over a larger area. The whole assembly is then immersed in oil. This enables higher powered generators to be designed as a much higher heat load can be dissipated.

X-rays can be produced by other methods, particularly from cyclotron-style equipment using the Bremsstrahlung effect. Additionally some radioactive sources produce x-rays. However, these are not generally suitable for security or industrial applications.

What affects the characteristics of the x-rays?



A number of parameters affect the characteristics of the x-rays produced by an x-ray tube and determine the spectrum. The characteristics affected are:

X-ray energy

This is determined by the KV across the x-ray tube. Increasing KV leads to increasing x-ray energy and results in x-rays that are more penetrating.

Flux density

The number of x-ray photons produced is determined by the current (amps) through the x-ray tube.

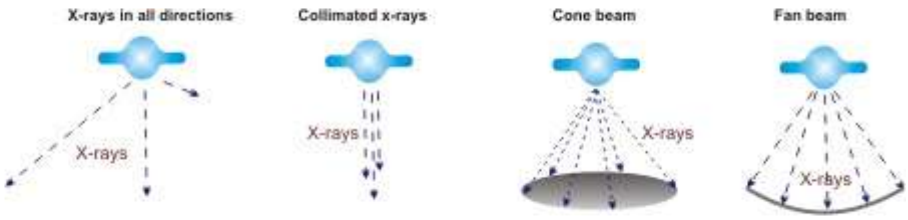
X-ray spectrum

When electrons hit the anode, the energy is absorbed. 95% is dissipated as heat, but the remaining 5% produces x-rays from the anode material. The material from which the anode is made will determine the spectrum, or distribution, of x-ray energies emitted. Anode materials typically used in x-ray tubes are copper, tungsten, molybdenum and silver.

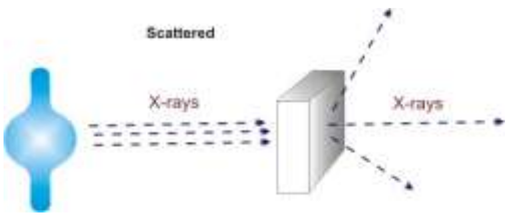
X-rays range in wavelength from10 to 0.01 nanometres, corresponding to frequencies in the range 30 to 30 000 PHz (1015Hz)

X-ray beams and how they are created

When x-rays are produced in an x-ray tube they travel in many directions depending on the shape of the anode (sometimes called the target, but not to be mistaken with the intended subject to be inspected by the x-ray, which can also be termed "target"). The x-ray tube is put in a steel or lead container to stop the x-rays escaping, in random directions, and a small hole (aperture or collimator) is introduced which releases them (collimates) in the required direction to form the primary beam. The shape of this aperture will determine the shape of the primary beam. Many different types of shape can be created, but the ones most commonly used in security and industrial applications are cone beams and fan beams.



When the x-ray beam enters an object it will interact with the material in one of three basic ways. It could pass through it completely unhindered, it may become totally absorbed or it may in some way interact with the material and be scattered, that is leave the material at a different angle and energy to that of the incident primary beam. The proportion of x-rays that pass through, are absorbed or are scattered will be dependent on the energy of the x-rays and the material they pass through.



In general scattered x-rays are created by any material that the x-ray beam hits, the target, air, x-ray shielding such as steel or lead, and travel in all directions. As a result, any x-ray system will produce x-rays from a number of points and surfaces. These scattered x-rays are important, because they can affect the quality of the x-ray image. They are also a safety issue as they can cause significant exposure to personnel. Therefore any system designed to screen items and personnel from exposure to the primary x-ray beam may also have to consider screening of these scattered x-rays.

Containing and stopping x-rays

Different materials absorb x-rays in different amounts at different energies. This principle is used in x-ray imaging. In general absorbtion increases with density so materials such as lead, which absorb x-rays very effectively, are widely used to shield people against harmful effects.

X-rays with more energy (KV) are harder to stop and so require more lead to effectively contain them. Therefore the thickness of lead required is dependent on the x-ray energy.

How are x-rays detected?

Different types of x-ray detector

Historically, photographic film was the most widely used detection medium in x-ray imaging applications. It has been used since the discovery of x-rays at the end of the nineteenth century. However, the principal disadvantage of x-ray film is its low sensitivity due to poor absorption. Only about 1% of the incoming x-rays are absorbed in the film and hence imaged. In addition the film needs to be chemically developed before it can be viewed. A major advantage of film, of course. is that the detection area can be comparatively large.

Over the last 30 years a wide range of electronic (digital) x-ray detection devices have been developed which are now steadily taking over from film in many applications. The advantages of digital x-ray imaging systems compared to the photographic film are the higher sensitivity due to increased absorption and the avoidance of time and material consumed in chemical processing. The image is immediately available in digital systems, which allows real-time operation of equipment. Because the image is available digitally, it can be processed on the computer, for example, adding colour to identify areas of interest, or measure specific features.

There are many ways to detect x-rays, all of which detect incoming photons by their interaction with the detector material. That interaction produces a signal which can be in the form of an electric current, a low-energy photon (typically visible light) or heat. The most widely used types of detectors are described below.

Proportional counter arrays

Proportional counters are large area detectors. They are filled with gas that produces an electrical charge when an x-ray passes through. The photon's energy is determined from the strength of the electrical signal; its time from the arrival of the x-rays and the shape of the electrical signal.

Microchannel plates

Microchannel plate detectors are also large-area detectors. They are basically x-ray photomultipliers (a device which detects dim light by producing a cascade of electrons). They are composed of layers of reactive material divided into narrow channels. The energy and location of incoming x-ray photons are determined by the strength, channel location and time of the electrical signal produced by the photon's interaction with the detector.

Charged coupled devices (CCDs)

In contrast to proportional counters and microchannel plates, CCDs are small-area detectors and require the photons to be focussed onto the detector plane. CCDs are made of silicon doped with impurities to create sites with different conductivities. Incoming x-rays then interact with the silicon and impurities to create a "cloud" of electrons. A voltage is applied across the CCD, and this cloud of electrons follows that voltage to the end of the CCD chip. From the charge of the electron cloud, the photon's energy is determined. Since regular readouts are performed, the timing can also be determined.

Properties of common x-rays detectors

Detector	Energy range (keV)	Δ E/E at 5.9 keV (%)	Deat time/event (μs)	Maximum count rate (s^{-1})
Gas ionization (current mode)	0.2 - 50	n/a	n/a	10^{11}*
Gas proportional	0.2 - 50	15	0.2	10^{6}
Multiwire & microstrip proportional	3 - 50	20	0.2	10^{6} mm^{-2}
Scintillation [NaI(T1)]	3 - 10,000	40	0.25	2×10^{6}
Energy - resolving	1 - 10,000	3	0.5 - 30	12×10^{5}
Surface barrier (current mode)	0.1 - 20	n/a	0.2	10^{8}
Avalanche photodiode	0.1 - 50	20	0.001	10^{8}
CCD	0.1 - 70	n/a	n/a	n/a
Superconducting	0.1 - 4	<0.5	100	5×10^{3}
Image plate	8 - 80	n/a	n/a	n/a

** Maximum count rate is limited by space - charge effect to around 10^{11} photons s^{-1} cm^{3}*

Semiconductor detectors

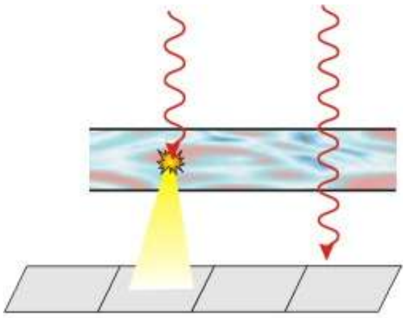
Several types of semiconductor detector exist, and more are under development. The main types include energy-resolving semiconductor detectors made from silicon or germanium detectors which are good as energy-resolving detectors of single photons (about 150 eV at 5.9 keV), and current-mode semiconductor detectors - semiconductor diodes used in current mode to measure x-ray flux, they offer very linear responses and thin entrance windows.

Amorphous silicon flat panel detectors

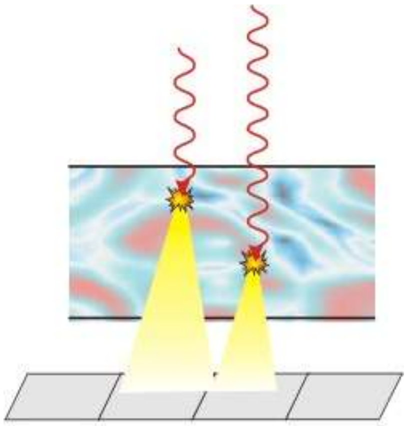
A further development of the CCD technology is large area flat panel image sensors based on amorphous silicon. These were originally developed for x-ray imaging in medical applications. As they provide both high resolution and high dynamic range, these expensive image sensors are well suited to certain high-end of industrial applications.

Scintillators - improving detector effectiveness

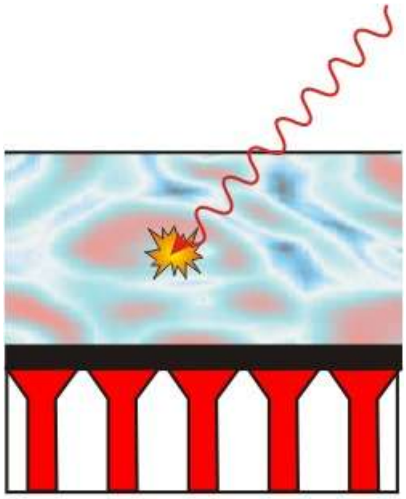
Several of the detectors above, such as amorphous silicon flat panels and CCDs, incorporate a scintillator screen in order to increase their efficiency in capturing x-rays. Scintillators are far more efficient at stopping x-rays than the semi-conductor or CCD which are far more efficient at absorbing light than x-rays. When an x-ray strikes the scintillator, it is converted to light. The light emitted (via a process called fluorescence) is then absorbed by the detector and converted to an electronic image.



Thin scintillator low sensitivity



Thick scintillator high sensitivity



Scintillator bonded to detector

Different types of scintillators are used depending on the energy of the x-rays to be detected. The scintillators can also be used in different configurations. In one possible configuration the scintillator is bonded directly onto the electronic device such as the CCD or amorphous silicon panel which increases the collection efficiency.

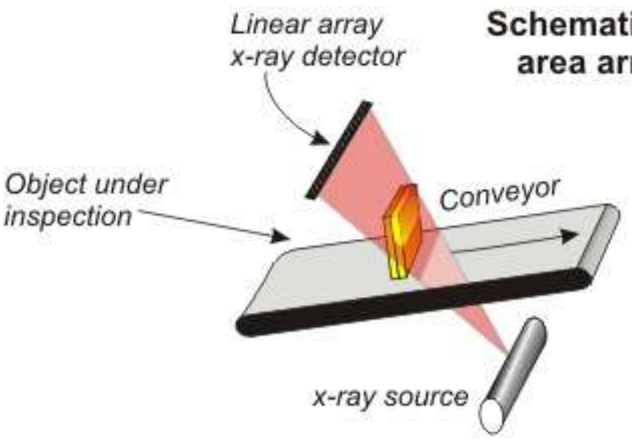
More traditionally, a fluoroscopic screen has been used. The x-rays are absorbed by the screen and turned into light creating an image, which can be captured using a standard 2D camera.

Different configurations of x-ray detectors

Detectors for digital x-ray imaging systems may have either linear (line scan) or area configurations.

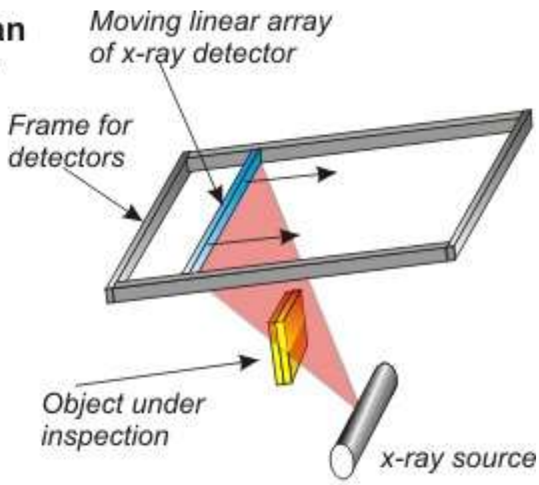
Line scan x-ray systems

Line scan technology uses a thin linear array of semiconductor detectors to acquire the image line-by-line either as the object passes by on a conveyor, or, in the case of some systems as the detector is moved across the target.



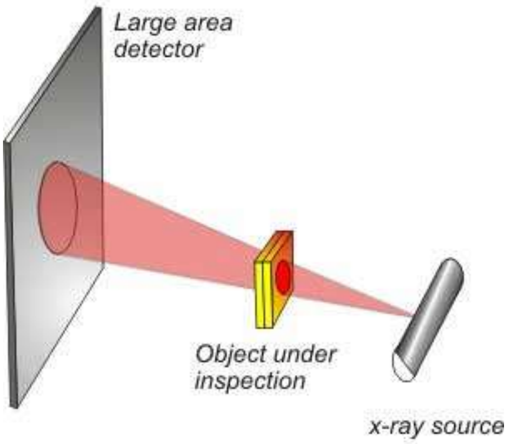
Schematic of a line scan x-ray imaging system with objects moving past on a conveyor

Schematic showing an area array detector



Schematic showing moving detector array, and stationary package

Producing an image using a line scan may use a thin curtain of x-rays to illuminate the detector array. As the object passes through the inspection area it is illuminated by the x-ray curtain and the resultant line image formed on the detectors is continuously read by the computer, building up a complete image of the object line-by-line. This technique also reduces the x-ray exposure to the object being inspected by around 98%.



Area detectors are two-dimensional and filled with rows and columns of detectors. They require no scanning procedure. They typically use large and expensive specialised “imaging” chips, similar to those used in conventional digital or movie camera.

The different configurations are suitable for different applications. For example, in baggage

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Technical Notes

inspection machines, linear detectors are used since the bags are transported past the detector on the conveyor belt. In medical applications, an area detector is normally used because a picture of an area of the body is required and the patient must remain still.