The new bounds of **flash radiography**

Capturing on the fly the changing state of materials such as those in nuclear weapons, in the very early moments of functioning, in the non-nuclear phase, entails making "X-ray photographs" of them in extreme conditions. Very brief exposure time, very high photon energy, very heavy attenuation by the objects are constraints that take radiography to the limits of its resources, at every point in the image acquisition and image processing chain. CEA's AIRIX installation, which has been operational since 2000, draws on the advances that have been achieved in this area.

CEA

Outside view of the AIRIX flash radiography installation, at the Moronvilliers site (Marne département, eastern France).

Radiography, as a technique that is quite familiar in the medical domain, allows the localization, inside a patient, of foreign objects, fractures, etc. It is also widely used in the industrial sector, for non-destructive control of component quality, or to scan the contents of packages. CEA's Military Applications Division (DAM) uses radiography to "characterize the state of matter subjected to powerful shocks, or major densification, under the effect of explosives," this being the situation for nuclear weapons, at the very outset of their functioning (see Table). The Division's AIRIX (Accélérateur à induction de radiographie pour imagerie X: X-ray Imaging Radiography Induction Accelerator) installation, which has been operational since 2000 at the Moronvilliers (Marne *département*, eastern France) site, is an essential component in the Simulation Program, which presently allows nuclear weapons to be designed without going through actual, full testing. A "firing," on this installation, consists in capturing on the fly the implosion, under the effect of the setting off of chemical explosives, of devices made of inert materials, simulating, in mechanical and thermal terms, nuclear materials. Flash radiography of objects of this type is characterized by very brief exposure times (less than 100 **nanoseconds** [ns]), very high **photon** energies (> 1 **MeV**), and very strong attenuation from the objects (> 10^5).

The principle of radiography is simple: penetrating radiation, consisting of very-high-energy **X** or **gamma** (γ) photons, passes through an object, being partially absorbed as it does so. **Absorption** varies according to the nature, density, and thickness of the materials tra-

domain	medical imaging	weld control	flash radiography
photon average energy	50 **keV**	500 keV	4 **MeV**
required dose at 1 m in air	1 **rad**	100 rads	500 rads
exposure time	100 ms	3 h	50 ns
dose rate at 1 m	10 rad/s	10^{-2} rad/s	10^{10} rads/s

Table.
Comparison of characteristics for three application domains of radiography.

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AIRIX accelerator hall. AIRIX (Accélérateur à induction deradiographie pour imagerie X: X-Ray Imaging Radiography Induction Accelerator) comprises 64 induction cells (to which high voltage is supplied via the red cables), bringing electron energy to 20 MeV

versed. Measuring this allows the characteristics of the object it has passed through to be arrived at.

The *exposure time* for the "X-ray photograph" thus achieved is related to the characteristic motion time of the radiographed object. For medical imaging, this time is set by respiration, or heartbeat: it stands at a fraction of a second or so. In the industrial domain, to detect a fault in a material (for weld quality control, for instance), this is related to the evolution time for this fault, which may range from a few minutes to several years. In that case, it is mainly device setting up time that influences optimum exposure time, which may range from a few minutes to several hours. At DAM, typically, analyzed materials may move at several kilometers per second! This entails exposure times of the order of a few tens of nanoseconds, if details of a few hundred **micrometers** (**µm**) are to be discriminated. Such an extreme characteristic time gives *flash radiography* its name, for this kind of measurement.

The *amount of radiation* (or **dose**) must be sufficient to make a mark on the detector – the device that converts the signal received to a form amenable to measurement – after attenuation in the object. In medical imaging, radiation must go through a medium equivalent to a few tens of grams per square centimeter of water, corresponding, for 50-**keV** X-rays (this being an energy level allowing good contrast), to attenuation by a factor 10, for 10 cm passed through. In the industrial field, the object to be radiographed may be thick, and heavy (e.g. 10 cm of steel), requiring more penetrating radiation than for medical imaging. A 500-keV X-ray flux undergoes attenuation by a factor 10 when passing through 3.5 cm of steel. The amount of radiation required for adequate detection is then achieved through use of exposure times of several hours. At DAM, the materials passed through are very dense, and attenuation of the more penetrating X-rays (4 MeV) may reach several hundred thousand. Further, pyrotechnical constraints(1) impose the interposition of shielding (ensemble of materials and structures shielding the source and detector from the projectiles and shockwave generated by the explosion), and removal of the object well away from the source and detector, this entailing a major falloff in radiation flux around the detector. Such heavy flux reduction, along the radiographic chain, results in the requirement to use *sources of extreme intensity*.

Detector sensitivity is a parameter of paramount importance, to guarantee good quality radiographic images. DAM teams do indeed draw on the advances achieved in medical or industrial imaging. However, owing to the steep attenuations encountered, the photon fluxes reaching their detectors needs must be very small, which has led them to develop specific, highly sensitive detectors, coupled with sophisticated image-processing **algorithms**.

After a brief rehearsal of the physics basis required for the understanding of the mechanisms of radiography, the following pages provide a survey of the components of a radiographic chain, in particular X-radiation flash sources, and imagers, and an outline of the basic principles of image processing.

The segments making up the radiographic chain

Radiography techniques are based on the physics of **electron** and photon interaction with matter (see Box). Their implementation involves a radiographic chain, comprising a *source*, inside which the X-radiation is generated, a *transport line* (along which are positioned

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(1) Pyrotechnic constraints: experiments on an object involving explosives entail shielding the diagnostics from the effects of detonation. Concrete blocks and metallic structures shield the source and detectors, contributing to the attenuation of the radiation used for radiographic purposes. Removal at a distance also provides good protection, imposing minimum distances between source, objects, and detectors.

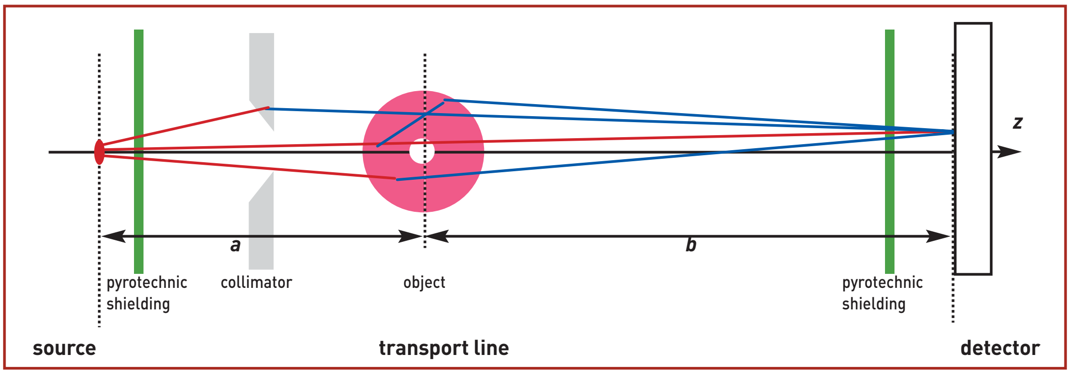


Figure 1. Principle schematic of a radiographic chain.

the object being radiographed, collimators made of dense, high-*Z* material, attenuating in calibrated fashion the photon flux in areas where it would be harmful, and pyrotechnic shielding), and a *detector–imager*, converting the distribution of incident particles into a usable digital image (see Figure 1).

Two types of photon reach the detector, and form the image: some are *direct*(2) photons, i.e. photons emitted by the source that have not interacted with the objects, the others *scattered*(3) photons, yielded by one or more interactions with these objects.

(2) Direct: this refers to the radiation flux coming from the source that has not interacted with components in the transport line (object, shielding, collimators). The *direct* flux carries the information on attenuation by the object.

(3) Scattered: this refers to the radiation flux that has undergone interaction with components in the transport line (object, shielding, collimators). The *scattered* flux causes lower image signal-to-noise ratio and poorer contrast.

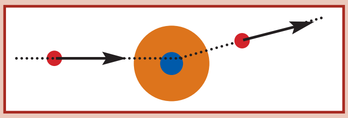
Particle–matter interactions

Particle–matter interactions playing a part in radiographic techniques involve, on the one hand, electrons, and, on the other hand, photons.

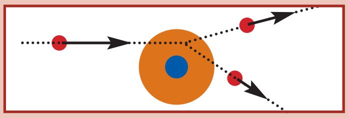
Electron–matter interaction

When a free electron penetrates into a material, it interacts with its atoms, according to three main reaction modes, respectively involving:

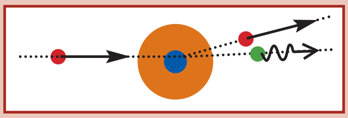
– *elastic collisions* with atom nuclei. The electron is deflected, with no loss of energy (elastic scattering);



– *inelastic collisions* with the atoms' surrounding electrons. The electron transfers energy to one of the bound electrons of the atom, which either becomes excited, or ionized (inelastic scattering);



– generation of bremsstrahlung. The electron emits photons as it is slowed down and deflected by the nuclei's electric field.

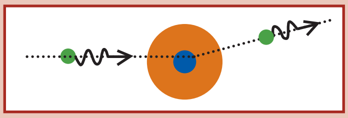


Bremsstrahlung is all the stronger, the higher the energy of the electrons involved, and the higher the *Z* of the atoms.

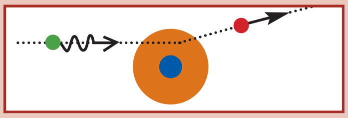
Photon–matter interaction

A photon may interact with atoms in a material according to four main reaction modes:

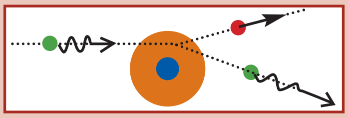
– *elastic collisions* (Rayleigh–Thomson scattering) with atoms;



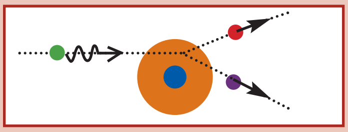
– *absorptions* (photoelectric effect) by the atoms' electron shells, resulting in electrons becoming exited, or being expelled;



– *inelastic collisions* (Compton scattering) with the atoms' electron shells. The photon is deflected, and loses energy. One electron from the electron shell is stripped from the atom;



– *pair production*. Under the effect of the atom's electric field, the photon materializes into an electron–positron pair.



Total attenuation is modeled by way of a photon mass attenuation coefficient (denoted μ/ρ), which varies depending on material type, and photon energy. The attenuation per unit length of a flux of N photons is:

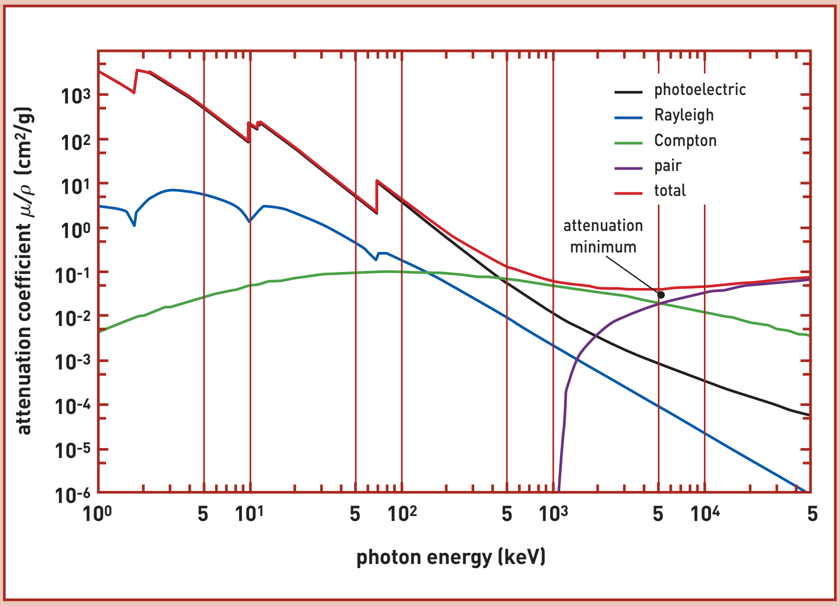
$$\frac{dN}{dz} = - \mu/\rho \cdot \rho \cdot N$$

where is the material's bulk density. The flux through material of thickness z thus stands at:

$$N(z) = N_0 \cdot e^{-\mu/\rho.\rho.z}.$$

At low energies, the photoelectric effect is dominant, and very swiftly arrests the photons. At high energies, it is pair production that is predominant. The positrons generated swiftly annihilate with electrons in the material, yielding two 511-keV photons. At intermediate energies, Compton scattering is dominant. In the case of heavy materials, total absorption stands at a minimum around the 4-MeV mark (as instanced in tantalum, see Figure).

Electrons generate photons, and photons generate electrons. The two particles play a *major, coupled* role in radiography.



Photon mass attenuation in tantalum.

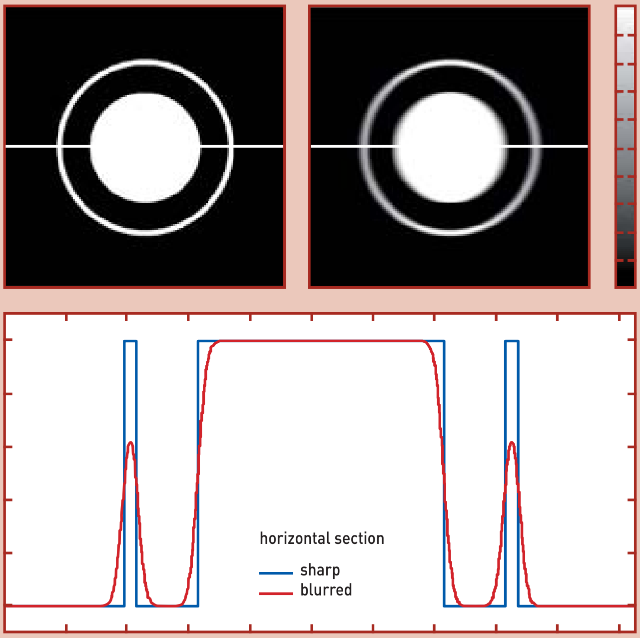


Figure 2.
Horizontal section.
The curve corresponding to the sharp image (shown at left) is shown in blue, that for the blurred image in red.

Information yielded by direct photons

As indicated in Box 1, the total absorption of a photon of energy E is characterized by an attenuation coefficient $\mu/\rho\ (E)$ for each material it passes through.(4) For a given material, the number of photons at the detector is all the lower, the higher the *surface density*(5) $\rho \cdot L$ of the object passed through (ρ being the material's bulk density, L the thickness traversed). Such direct photons thus contribute to the radiograph information that is directly usable through that attenuation, provided the properties of the flux emitted by the source be perfectly known, together with detector response and type of material involved.

Information yielded by scattered photons

At any given point of the detector, scattered photons arrive from all parts of the transport line. They thus carry no information as to the object's structure, while they do contribute, in the image, to a continuous, noisy background, lowering contrast and the *signal-to-noise ratio*,(6) thus making it less readily exploitable. As opposed to what holds for direct photons, there is no analytical expression of the transport function, for scattered photons. The simplest way (requiring however a large amount of computing power) to obtain this function is through use of **Monte-Carlo** type **codes**, taking on board paths and interaction probabilities inside the materials, on the basis of a statistical representation of the photons involved in the illumination of the object.

The design of a chain intended for the radiography of a given object involves the selection of the source (intensity,(7) spectrum,(8) size), detector (spectral response,(9) quantum detection efficiency [QDE], **resolution**), and positions, for the various component in the transport line, that will yield an adequate resolution, contrast,(10) and signal-to-noise ratio in the image to make apparent the details being sought for in the firing. For that purpose, the designer may draw on an ensemble of analytical models, Monte-Carlo simulation codes for the radiographic chain, and his or her own experience of radiography of equivalent objects, or dedicated mockups.

Resolution of a radiographic chain

The resolution of a radiograph is the minimum measurable size of a detail in the object, given perfect observation conditions, i.e. for an infinite signal-to-noise ratio. Thus, a point in the object plane shows up as a spot in the radiograph (see Figure 2). The resolution, expressed in meters, provides information as to the size of this spot. Ascertaining its shape may allow the minimum measurable dimension of a detail to be brought down, through use of appropriate *deconvolution* methods, these involving taking into account the deformation of information due to the measuring system, in order to extract the initial information. Conversely, the ability to measure, or even to distinguish, a detail will degrade, if contrast or the signal-to-noise ratio in the image are suboptimal.

In a radiographic chain, resolution in the object plane R_o is related to three characteristic spatial quantities: source point size $Ø_s$ (*source blurring*), detector resolution R_d (*detector blurring*), and the distance traveled by the object moving at velocity v during exposure time τ (*motion blurring*) (see Figure 3).

The influence of the first two processes depends on source–object distance a, and object–detector distance b, or on radiograph magnification M, this being

(4) Attenuation coefficient: as it propagates, X-radiation interacts with matter, and its flux falls off. Attenuation is then given by the exponential of the product of the attenuation coefficient by the surface density passed through. International unit: 1 m^2/kg. Common radiographic unit: 1 $cm^2/g = 0.1\ m^2/kg$. The coefficient is usually noted μ/ρ.

(5) Surface density: the amount of mass per unit surface that a penetrating radiation passes through. International unit: 1 kg/m^2. Common radiographic unit: 1 $g/cm^2 = 10\ kg/m^2$. When a single material is passed through, this is the product of the material's bulk density by the distance traversed. In the general case, it is the integral of the bulk density traversed along the photon's path.

(6) Signal-to-noise ratio: an image is composed of pixels. Ideally, every pixel holds a deterministic signal level, depending on its illumination. In actual fact, this information is affected by an error, which varies from one pixel to the next. The signal-to-noise ratio is the ratio of the theoretical signal to the standard deviation for the error affecting this signal.

(7) Intensity of a source: the quantity of photons per unit solid angle, emitted by the source. This is often characterized by the maximum dose deposited in air at 1 meter of the source.

(8) The spectrum is said to be monochromatic if all photons have the same energy.

(9) Spectral response of a detector: the amount of information yielded by a detector per incident photon, as a function of photon energy.

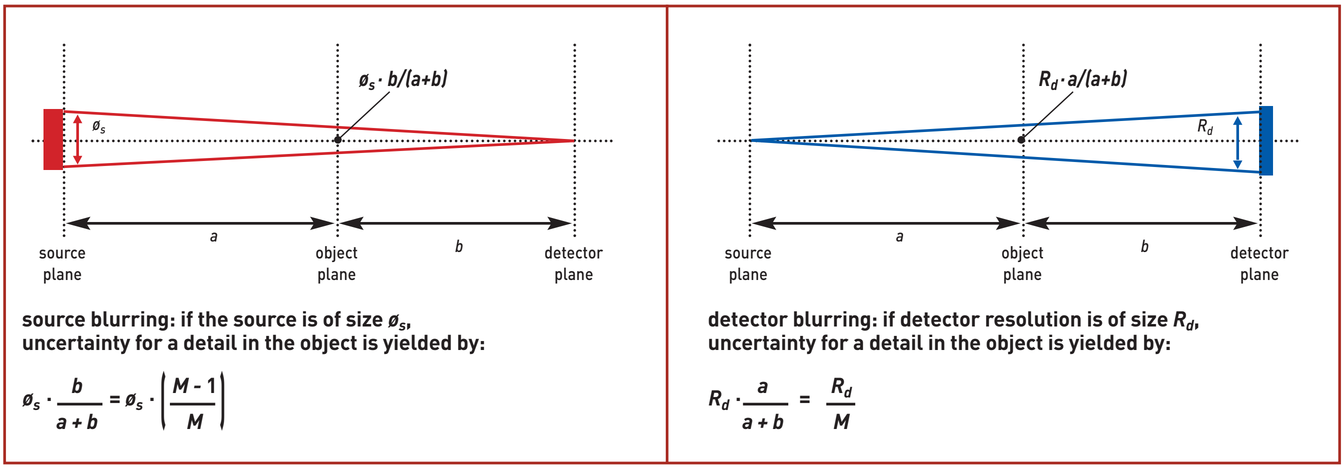
(10) Contrast (in an image): the difference in levels between two details in an image. If N_0 is the level for detail 0, and N_1 the level for detail 1, contrast is defined as:

$$C = \left| \frac{N_1 - N_0}{N_1 + N_0} \right|$$

Two details are highly contrasted (contrast tending to 1) if the level associated to one of them is much higher than that associated to the other. They are poorly contrasted if the levels are close to each other.

(11) $M = 1 + \frac{b}{a}$

(12) $R_0 = \sqrt{ø_s^2 \cdot \left(\frac{M - 1}{M}\right)^2 + \frac{R_d^2}{M^2} + (\nu.\tau)^2}$



source blurring: if the source is of size $\varnothing_s$, uncertainty for a detail in the object is yielded by:

$$\varnothing_s \cdot \frac{b}{a+b} = \varnothing_s \cdot \left(\frac{M-1}{M}\right)$$

detector blurring: if detector resolution is of size R_d, uncertainty for a detail in the object is yielded by:

$$R_d \cdot \frac{a}{a+b} = \frac{R_d}{M}$$

Figure 3.
Source blurring and detector blurring, referred to the object plane.

defined as the ratio between the size of the object as projected onto the detector, and true object size.(11) Overall chain resolution in the object plane is given, as an approximation, by the quadratic sum of the three contributions.(12) Resolution is all the higher, the smaller the source size, detector resolution, object velocity, and illumination time.

X-radiation sources

Photons having energies greater than a few tens of keV may be generated in two ways. The first consists in using **radioactive elements**, the nuclei of which emit gamma photons as they deexcite. The **dose rate** from radioactive sources, however, is not high enough, over the exposure time (~ 100 ns) required for the dynamic applications considered. In the second method, a brief, intense pulse of high-energy electrons is slowed down inside matter – in this case a target made from a heavy material – resulting in **bremsstrahlung** emission: photon sources for flash radiography are invariably based on this principle.

Two main types of machine allow such electrons to be generated, with low or high energies. At low energies (< 10 MeV), this is effected by way of a **diode**: the electron beam is produced by charges streaming between a **cathode** and an **anode**, in the form of a brief (~ 50-ns), high-voltage (300 kV–8-MV, depending on the machine) pulse. A small size for the anode guarantees small source size. High voltage is produced, as a rule, by the series discharge of powerful capacitors, charged in parallel. At high energies (> 10 MeV), generation involves a **particle accelerator**: the beam is produced in an electron gun, and accelerated along successive cavities, up to its final energy. It is then focused onto a heavy target, inside which bremsstrahlung is generated.

X-ray sources are characterized by way of five quantities: spatial distribution, angular distribution, intensity, spectrum, and duration.

The spatial distribution, or *focal spot* (the source size, for bremsstrahlung-generated X-photons) of the emission, in the source plane, relates to the spatial distribution of electrons at the target, and their scattering inside it. To achieve lower source size, and improve radiograph resolution, electron beam size, or the tar-

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A diode shown open.
Voltage breakdown occurs between the cathode (ring) and anode (needle).
Needle size determines source size.

get thickness or transverse dimension must thus be brought down, the two last-mentioned techniques resulting in reduced source intensity.

The angular distribution, or *lobe*, of the photons emitted by a source is the result of two contributions: the angular spread of the bremsstrahlung emission, which is inversely proportional to the energy of the incident electron beam, and the angular distribution of the electron beam itself, impinging on the target. The source's angular spread must be sufficient to ensure the radiographed object receives illumination of adequate homogeneity.

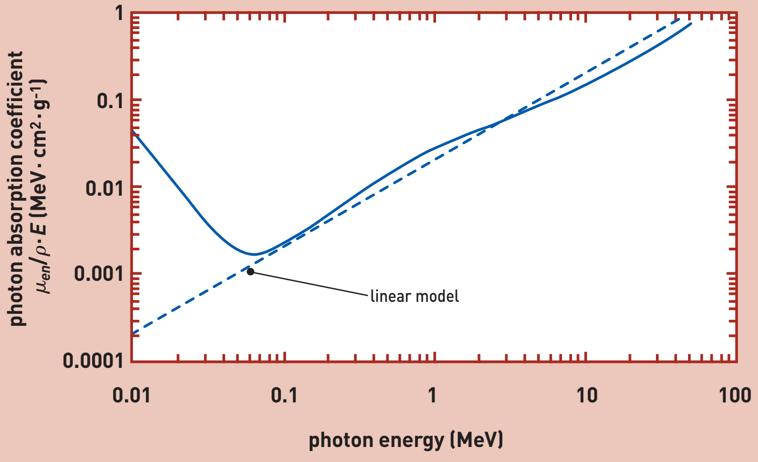
The source's intensity, or *dose*, is proportional to beam intensity, and is an increasing function of its energy. It is further dependent on target properties. Source intensity is characterized by the dose the source deposits *on axis, in dry air, at 1 meter of the source plane*. The dose is an expression of the energy deposited in a material. It is expressed in **grays**, or **rads**. To determine this, "radiologists" must take into account the evolution of photon absorption by dry air, as a function of their energy(13) (see Figure 4). The dose thus produced(14) must be all the higher, the more absorbent the radiographed object is, or the further away the detector, if an adequate signal-to-noise ratio is to be achieved in the image.

The energy distribution, or *spectrum*, is the fourth quantity that must be taken on board.

In high-surface-density, high-Z radiography, incident photons having energies of around 4 MeV are least absorbed by the object. This portion of the spectrum should be strongly represented in the source, this calling for energies, for the generating electrons, of at least 6–8 MeV. In low-surface-density, low-to-moderate-Z radiography, high contrast is provided by photons having energies around 100 keV, for which widely different absorption coefficients are exhibited, depending on materials. Photon sources of a few hundred keV are then highly suitable.

The time distribution, or duration, of the photon pulse, finally, is directly yielded by the duration of the electron pulse over the target. The shorter this is, the lower the motion blurring. Thus, for instance, a duration of 50 ns, to radiograph objects moving at 5,000 m/s, will result in 250-µm motion blurring.

Figure 4.
Energy deposited
in dry air.



X-ray imagers

Owing to the strong attenuation of the X-ray flux by the object, high-sensitivity, low-noise imagers must be employed, associated to highly sophisticated image-processing programs. The radiographic chain must be specifically optimized (choice of source, detector, collimators, and distances) for each object, to maximize the dose at the detector, contrast, signal-to-noise ratio, and resolution, on which image quality will depend. Specific developments are being carried through at CEA/DAM in this area, in response to the extreme context of flash radiography.

The *imager*(15) consists in a detector, which converts the X-ray flux (direct, and scattered) into a signal that may be read and converted into an image by a *reader–digitizer*.(15)

Detectors are characterized by eight properties, defined as follows:

Spectral response is the signal level induced in the detector by a photon, as a function of its energy. This response may vary widely, depending on detector type. These types may be optimized, to favor marking by low-energy photons (light objects), or conversely by high-energy photons (heavy objects).

Dose response is the signal level produced, as a function of incident dose, for a given spectrum. This is linear only for some detectors.

The *detection threshold* is the minimum detectable dose. Ideally, this should stand at zero. However, the imager may generate a background level, or noise, making detection of a weak incident signal impossible.

The *linearity range* is the dose range over which the imager yields a signal level that is proportional to the photon flux illuminating it. If that level is not proportional, while it does however simply vary in strictly increasing fashion, and is known, it can be taken into account.

The *saturation level* is the dose beyond which increased illumination induces no further increase in the image level. A saturated signal is not suitable for exploitation.

An *intrinsic noise level* is found, since, even if the detector is not exposed, the image contains a degree of noise introduced by the detector itself, but equally by the readout and digitization chain. The imager's detection threshold, related as this is to the noise level, should be as low as feasible.

Quantum detection efficiency (QDE) is the gain in the signal-to-noise ratio (SNR) achieved by the detector,

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(13) As given by the equation

$$\frac{dE}{dz} = -\,\mu_{en}/\rho(E) \cdot \rho \cdot E \quad \text{where : } \mu_{en}/\rho(E)$$

is the energy absorption coefficient of dry air (cm²/g) (see Figure 4).

(14) Dose is then given as $D = \int_{E_{min}}^{E_{max}} n(E) \cdot \frac{\mu_{en}}{\rho}(E) \cdot E \cdot dE$

where E_{min} and E_{max} are the bounding energies for the source spectrum, and n is the number of photons per unit surface and per unit energy on axis at 1 meter of the source.

(15) Imager: a device having the function of converting the transverse distribution of a received signal into a digital image. It comprises a detector, and a reader–digitizer. The latter converts a measurable signal into a digital image. The readout (conversion of the signal into an image) and digitization (conversion of an image into a digital image) functions may be carried out in one or two steps..

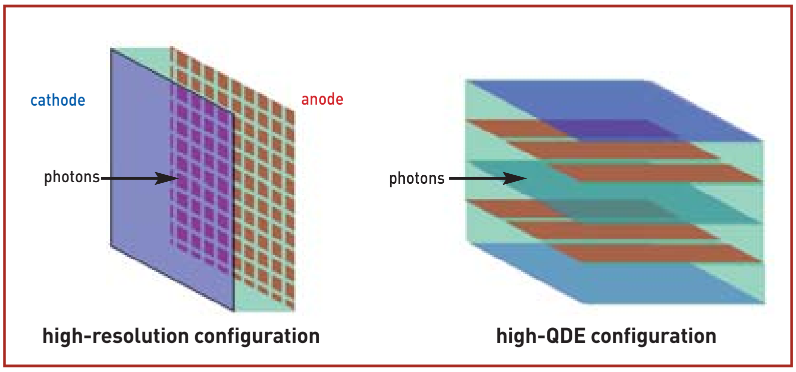

Figure 5.
Two configurations for CdTe detectors, high-resolution at left, high-QDE at right.

taken to be non-noisy.(16) This is always smaller than 1. Detector input signal-to-noise ratio (SNR$_{\text{input}}$) is the statistical quantum noise, induced by the theoretical number of photons N impinging on each **pixel** of the imager. There results the relation SNR$_{\text{input}} = \sqrt{N}$ (monochromatic model). The detector will not exhibit identical sensitivity for all of these photons. Some photons will not interact with the detector, while the others will not all produce the same signal level. The statistic will thus degrade, resulting in a lower image signal-to-noise ratio (SNR$_{\text{image,bw}}$). QDE reflects this degradation, and should be as high as possible. It may be raised, essentially, by increasing the number of photons interacting with the detector.

Resolution, the size of the detector's point spread function, finally, should be as small as possible.

Various types of detector

Four types of detector are used: screen–film combinations, photostimulable screens, CdTe (cadmium-telluride) semiconductors, and **scintillators** coupled to cameras.

Screen–film combinations

The marking of a photographic film corresponds to the blackening of silver halide crystals through a chemical reaction induced by the energy deposited by photons. When interposed in the flux, the film will be weakly marked, owing to its low thickness. On the other hand, it will exhibit sensitivity to photons of all energies, and the small thickness of the photosensitive layer (~ 10 µm) will ensure very good resolution. To improve detection threshold and QDE, it is used in conjunction with a plate of a few hundred micrometers of lead, or tantalum, generating showers of electrons that mark the film strongly. This allows all low-energy photons to be "cut off," these forming a major constituent of the scattered signal. To enhance further still detector sensitivity, a scintillator screen, in which X photons and electrons generate visible photons, which stream onto the film, may be interposed between plate and film. Such enhancements in sensitivity, however, are achieved at the detriment of resolution.

The detection threshold is determined by the fog, i.e. the intrinsic attenuation from the unmarked film. Saturation occurs once all crystals have been blackened. The linearity range for such films is small, however, specific calibration, for each experiment, does enable interpretation of radiographs. The measurement's signal-to-noise ratio may be enhanced through summation of the images obtained by stacking a number of screen–film pairs, placed inside one and the same cassette, digitized by means of a specific scanner.

Photostimulable screens

Photostimulable screens, or plates, are placed inside radiographic cassettes for use. When a high-energy photon or an electron interacts with the screen's sensitive surface, it causes excitation of **atomic levels**, which deexcite down to a metastable level, with a lifetime of several days. It is this level that stores information. The screen is subsequently read out by reexciting this **metastable** level by means of a **laser**, to a state which deexcites by emitting a photon, which is counted by the reader. The more excited atoms there are, the higher the signal collected. The linearity range is very large, and sensitivity very high. As with films, the signal is boosted by means of additional metal plates, and by stacking a number of screens. Scintillator screens, on the other hand, are ineffective, since photostimulables exhibit little sensitivity to visible photons. Screen readout is swift (a few tens of minµutes), resulting directly in a digital image. The low thickness of metal screens and photosensitive layer, together with small pixel size, allow high resolutions to be achieved.

CdTe semiconductors

CdTe detectors consist in crystals subjected to a high-voltage bias (~ 1 kV). Electrons yielded by photon interaction with the crystal are collected by way of anodes, or stored in an ASIC,(17) and counted. Two types of geometries are used (see Figure 5).

In *high-resolution detectors*, a large plate, of low thickness, is positioned perpendicular to the photon flux. The cathode is a plate, located at the front, the anode consisting in square electrodes, insulated from each other. Each anode electrode (pixel) is connected to the ASIC, placed downstream of the flux. This configuration allows high resolutions to be achieved, however it exhibits a low QDE.

In *high-QDE detectors*, CdTe plates several hundred micrometers thick and a few centimeters long form a multilayer sandwich with biased electrodes (the anode taking the form of strips at a pitch of a few hundred microns, with the cathode in the form of a plate). Anode bias ensures the electric charges generated by photons in the CdTe are delivered to the ASIC.

Scintillators + camera

Scintillators excited by X-rays release visible photons, collected by a **CCD** camera by way of an optical system. As with CdTe, two configurations are possible. In the *high-resolution* configuration, a large, thin scintillator plate is positioned perpendicular to the flux, at the optical system's object plane. Resolution is determined, essentially, by scintillator thickness,

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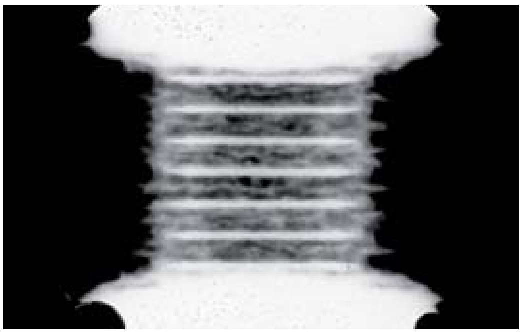
(16) $\text{QDE} = \dfrac{\text{SNR}^2_{\text{image, bw}}}{\text{SNR}^2_{\text{input}}}$

(17) ASIC (application-specific integrated circuit): an electronic component offering "customized" functions. With a CdTe detector, this stores the signal on each integrated pixel, over a defined exposure time, then transfers it to an electronic card on a PC.



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Radiograph of the magnetic implosion of a cylinder, the surface of which had been initially grooved. This allows the evolution of the cylinder's deformations – in particular Rayleigh–Taylor instabilities – to be seen, and compared with theoretical predictions.

and optical system blurring (CCD included). QDE is low. In the *high-QDE* configuration, scintillator needles several hundred micrometers in diameter, and a few centimeters long are positioned on a square grid, parallel to the photon flux. A reflecting medium allows any crosstalk(18) between needles to be precluded. Such a structure allows resolution to be kept from degrading excessively. Radiation is collected by a fiber bundle (image guide), or an optical system that transports it to the camera. To enhance sensitivity, the camera may be augmented by means of a brightness intensifier. To lower its detection threshold and noise, it may be cooled.

Image processing

The image obtained is characteristic of detector illumination. For *one and the same illumination spectrum*, the value of the signal, in each pixel, is an increasing function of dose. It is thus possible to determine the attenuation undergone by the incident flux, and to derive from this the object's surface density, for each line between source and detector. This requires knowledge of the source spectrum, dose, and lobe, detector spectral response and dose response, together with the type of material passed through.

Unfortunately, the dose response of some detectors (particularly for screen–film combinations) is far from linear, and it must be precisely measured. This is why, before every firing, a radiography is carried out of mockups, of well known composition and bulk density, and for which surface densities are close to those anticipated in the firing.(19)

Exploiting the radiographs thus obtained enables an estimate to be arrived at, of the surface density response curve for the chain as a whole, in the relevant attenuation range, which curve is then used for interpretation of the subsequent radiographs.

Once the surface density map is obtained for the object, a **tomographic** reconstruction of the object's interior is carried out.

Mathematical reconstruction

Working on the justified assumption of a symmetry of revolution for the objects, and parallel illumination, the problem of tomographic reconstruction is then amenable to mathematical solution, on the basis of the surface density map, obtained from a single view. The so-called "generalized inverse" algorithm yields the bulk density, through the resolution of simple linear systems, reconstructing the object's bulk density from the edge to the center, by successive analysis of surface densities closer and closer to the axis. Unfortunately, the presence of noise (the direct signal level may be very weak), of a high level of scattered signal, and considerable blurring results in uncertainty with respect to the bulk density obtained, which may be larger than the precision sought by the experimenters.

For that reason, they have developed more robust and more accurate algorithms, drawing on a considerable expertise, allowing tomographic reconstruction of the object's interior. From this reconstruction, they can determine precisely the contour of the interfaces between materials, and the volume occupied by each material, through use of specific algorithms, developed in collaboration with university laboratories. The position of these contours is then compared to that found with simulation codes, simulating the implosion of the object, and serves to validate these.

> Nicolas Pichoff*
Military Applications Division
CEA DAM Île-de-France

* In collaboration with the laboratories from the Experiment Design and Implementation Department (DCRE: Département conception et réalisation des expérimentations).

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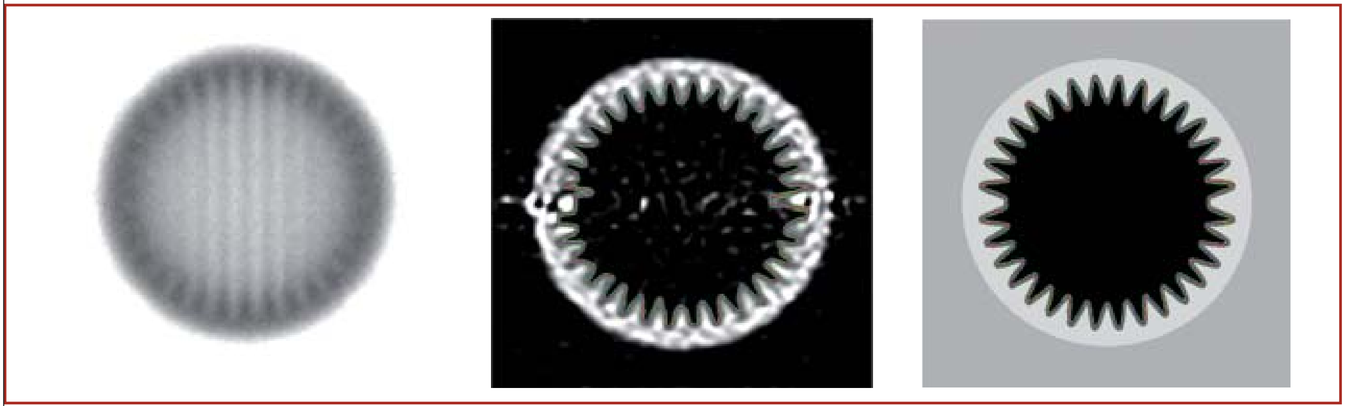
(18) Crosstalk: interference between one signal and another.

(19) The mockup is radiographed prior to the experiment, to assist in exploitation of the measurements carried out during the firing.



CEA

Reconstruction of the bulk density of a mockup, from a radiograph. At left, the radiograph; center, reconstructed bulk density; right, initial bulk density.