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CHALLENGES FOR HIGH-ENERGY X-RAY SECURITY SCREENING LINACS

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Abstract

X-ray based Cargo and Vehicle Inspection (CVI) systems are used for security and customs inspections at a variety of locations. To provide the maximum flexibility many users require mobile CVI systems to allow vehicles to be screened efficiently for threats and contraband. The need for mobile systems means that the linear accelerator, and ancillary systems, used to generate the x-rays must be compact, rugged, and reliable. These systems must meet image performance tests specified by American National Standards Institute (ANSI) and the International Electrotechnical Commission (IEC). The IEC also defines a standard for material discrimination. The requirements of these standards mean that the x-ray output produced by the linac needs to be consistent during and between scans, with the stability and repeatability of the output being critical. The tolerances on the linac output to meet the performance standards combined with the need for a compact system gives an unusual challenge for the linac design. A review of how different stability measures impact the performance tests is presented. This is compared to current technologies and possible future linacs used for mobile CVI systems.

MOBILE CARGO AND VEHICLE INSPECTION SYSTEMS

Mobile Cargo and Vehicle Inspection (CVI) systems are an important tool for customs agencies, security services and military organisations. Mobile CVI systems allow for inspection points to be set up where needed. This allows the user to react to any intelligence they receive or to changes in traffic flow across borders and other inspection points. The typical design of linac based mobile CVI systems includes: an electron linac with a nominal energy of 3 to 7 MeV, a conversion target, slit collimator, detector array and x-ray beam stop. These are all mounted to a truck or trailer to allow the system to be moved as required. Figure 1 shows a Rapiscan Eagle M60 which is a mobile CVI system.

Figure 1: Rapiscan Eagle M60 in the deployed position ready for scanning.

This system uses a 6 MeV electron linac to produce x-ray pulses with a bremsstrahlung spectrum with an end point energy of up to 6 MeV. Figure 2 shows a typical x-ray spectrum from a 6 MeV linac used on a transmission imaging CVI system. The spectra is not ideal for transmission imaging as the majority of photons emitted have an energy of less than 1 MeV. Low energy x-rays contribute to some performance metrics however, they also cause a lot of scatter which adds noise to the final image. For transmission imaging a more uniform spectral distribution would be preferred.

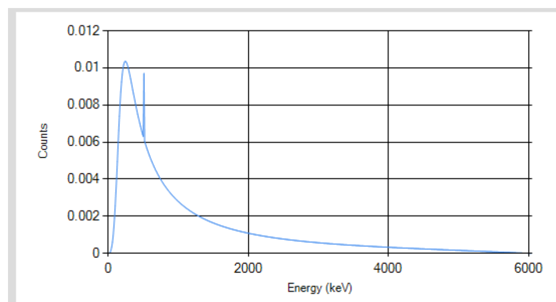

Figure 2: Typically 6 MeV x-ray spectrum used in transmission imaging systems.

The x-ray beam is then collimated into a fan beam which is used with an L-shaped detector array to image the cargo or vehicle under inspection. Figure 3 shows an outline drawing of the rear of the Eagle M60 with the linac, slit collimator and L-shaped detector array indicated.

The imaging methodology used by mobile CVI systems like the Eagle M60 require either the CVI system or the object under inspection to move through the scan tunnel between the linac and detector array. As the object under inspection passes through the imaging plane the linac is pulsed generating a series of x-ray pulses. The signal from each pulse is captured individually as a line, these lines are then stitched together to create an image of the object under inspection. Figure 4 shows a typical x-ray image of cargo imaged by a mobile CVI system. The pulse rate of the linac is determined by the geometry of the system and the speed at which the object passes through the imaging plane. For mobile CVI systems this is typically between 80 and 400 Hz.

IMAGE PERFROMANCE STANDARDS

The American National Standards Institute (ANSI) and the International Electrotechnical Commission (IEC) have

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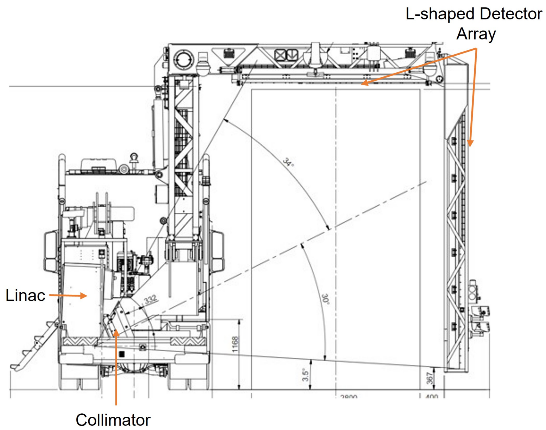

Figure 3: Outline drawing of the rear view of a Rapiscan Eagle M60 in the deployed position ready for scanning. The positions of the linac, collimator and L-shaped detector array are indicated.

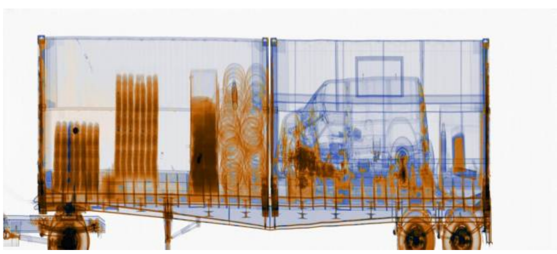

Figure 4: Transmission image from a mobile CVI system.

developed a series of image performance standards [1, 2] that transmission imaging CVI systems are tested against. The two standards specify four methods to quantify the image performance of a CVI system:

- Steel Penetration
- Spatial Resolution
- Wire Detection
- Contrast Resolution

The test methodology for the four tests above are slightly different between the ANSI an IEC standards. However, the methodologies for each of the four tests are similar enough that the tests for each standard can be analysed together. In addition to the image performance tests the IEC standard [2] also specifies a test methodology for material separation which is an important metric for CVI systems.

Steel Penetration

The steel penetration test measures the maximum thickness of steel through which a test object can be observed. For mobile CVI systems the typical steel penetration value is in excess of 300 mm. To achieve these steel penetration values the imaging system is operating close to the noise limit of the detectors. The useful part of the x-ray spectrum for the steel penetration test is the section above 4 MeV. This means that most of the x-rays emitted by the linac are not useful for achieving high values of penetration.

Spatial Resolution

The spatial resolution test measures the minimum separation where different the features of a test object can be distinguished. The spatial resolution of a mobile CVI system is determined by the line width of the system, the repetition rate of the linac and the speed at which the object under inspection passes through the imaging plane. The line width of the system is determined by the width of the detector pixels and the geometry of the system.

Wire Detection

The wire detection test measures the smallest diameter of wire visible in air in the x-ray image. As with the spatial resolution test the line width of the system is a key parameter in determining the wire detection limit of a CVI system. However, the wire detection limit is also driven by the x-ray dose output of the system. The wire detection limit is driven by the contrast of the wire to the air background in the image. This contrast between the wire and air is effected by the number of low energy x-rays emitted. This results in a different set of constraints on the x-ray output to the steel penetration tests.

Contrast Resolution

The contrast resolution test is used to determine the minimum increase in steel thickness that is visible in an x-ray image. These tests are usually done at a percentage of the total penetration of the system. Typical mobile CVI systems aim to achieve a 2% contrast at around 20% of the total penetration. As the aim of this test is to identify the smallest increase of steel possible the useful portion of the x-ray energy spectrum is very different to the steel penetration requirements. This means it is the photons below 4 MeV that contribute the most to the contrast resolution of the system.

Material Separation

Material separation is the ability of a CVI system to correctly identify the effective Z value of materials that it images. To determine the effective Z values two different x-ray spectra with different end point energies are used. The most common end point energies used for material separation are 6 MeV and 4 MeV. The cargo is imaged with both spectra and the difference in x-ray flux that is detected is compared to a set of calibration curves for different materials. The IEC standard specifies that the materials to be identified are graphite, aluminium, steel and lead.

QUANTIFYING X-RAY PERFORMANCE

The steel penetration, wire detection, contrast resolution and material separation tests require a consistent x-ray dose output from the linac. This means that the pulse to pulse variation in the total number of photons emitted across the x-ray spectrum needs to be small. The material separation and steel penetration tests are also very sensitive to the end point energies of the x-ray spectra. This introduces a constraint on

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how much energy variation in the electron beam is allowed on a pulse to pulse basis.

Material separation also introduces other constraints due to the need to use previously generated calibration curves. As these curves need to apply to every point in a scan this means the acceptable drift in x-ray output over the whole scan is very small. In addition the variation in the x-ray output between scans is also restricted as otherwise the same material could respond differently on different scans.

Therefore quantifying the x-ray output of a linac with metrics that can be directly linked back to the image performance tests is important. The main metrics that are considered in this paper are pulse to pulse stability, drift and scan to scan stability. These are measured using the imaging array which integrates the x-ray signal for each pulse.

Pulse to Pulse Stability

The pulse to pulse stability is measured over different time intervals during a scan. The time intervals depend on the scanning con ops used by the mobile CVI system. Pulse to pulse stability ϕ is given in Eq. (1).

$$\phi = 100\frac{\sigma_x}{\bar{x}} \tag{1}$$

σ_x is the standard deviation of the array responses for each pulse in a given time interval and $\bar{x}$ is the mean array response per pulse in a given time interval. The current achievable pulse to pulse stability for mobile CVI systems is less than 1%. The pulse to pulse stability is impacted by variations in electron beam energy, the energy spread of the beam and variations in the bunch charge.

Drift

The drift δ in the x-ray output of a linac is defined as the change in signal over time. Equation (2) defines drift using the mean array response between two different time intervals. $\bar{x}_1$ is the mean array response from the first time interval and $\bar{x}_2$ is the mean array response from the second time interval.

$$\delta = 100\frac{|\bar{x}_1 - \bar{x}_2|}{\bar{x}_1} \tag{2}$$

To achieve consistent material separation results across a scan the drift over the scan duration needs to be less than 1%. This is currently the limit for industrial linacs used in security applications with many linacs in use not able to achieve this value. The main cause of drift that needs to be controlled for good material separation results is the change in the electron beam energy over time. This causes the end point energy of the x-rays to fluctuate which results in inconsistent material separation during a scan.

Scan to Scan Stability

Scan to scan stability is the measure of how repeatable the x-ray output is between scans. There are two different ways to measure scan to scan stability. Equation (3) calculates the difference between the start of one scan and the start of the next scan. This provides a measure of how consistent the linac is at producing the same output when it starts pulsing. Equation (4) calculates the difference the end of one scan and the start of the next scan.

$$StS = 100\frac{|\bar{x}_{1A} - \bar{x}_{1B}|}{\bar{x}_{1A}} \tag{3}$$

$$EtS = 100\frac{|\bar{x}_{2A} - \bar{x}_{1B}|}{\bar{x}_{2A}} \tag{4}$$

$\bar{x}_{1A}$ is the mean array response at the start of scan A, $\bar{x}_{1B}$ is the mean array response at the start of scan B and $\bar{x}_{2A}$ is the mean array response at the end of scan A. For typical CVI systems $STS < 2\%$ and $ETS < 3\%$, the difference between STS and ETS is due to the allowable drift during a scan. The main drivers of STS and ETS are the stability of the RF when first turned on and the coupling between the cavity and the RF source. Most security linacs use a magnetron as the RF source which means that ensuring a good frequency match between the cavity and magnetron when power is applied is crucial.

AREAS OF DEVELOPMENT FOR FUTURE CVI LINACS

Increasingly difficult image performance criteria are being specified by end users of CVI systems. This is a particular challenge to mobile CVI systems where the linac and all the ancillaries for it need to be mounted on a road legal vehicle. The common limiting factor for pulse to pulse stability, drift and scan to scan stability is the variation in electron beam energy.

Therefore the key developmental area is the RF system and accelerating cavity. Optimising the stability of the electron beam energy and whilst minimising the energy spread within an electron bunch will provide an important increase in image performance. For the next generation of security linacs the aim is to reduce the current limits on pulse to pulse stability and drift by an order of magnitude.

Other areas of development for future CVI linacs include intra-pulse [3] and dose optimisation. However, while these will drive improvements in performance they will not provide the overall impact that optimising the electron beam energy stability and energy spread. Therefore Rapiscan are concentrating on driving improves to energy stability primarily.

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