RF SUB-SYSTEMS FOR CARGO AND VEHICLE INSPECTION

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Abstract

X-ray screening for security is a well-established inspection technique. Whilst in terms of fielded systems the vast majority consist of low energy X-ray sources, typically used for hand baggage or mail screening. There is a smaller but high value niche market servicing the requirements for border security, and cargo and vehicle inspection (CVI). This latter application requires higher X-ray energies of up to 10 MeV using an electron linear accelerator (linac) source to penetrate fully loaded shipping containers. Increasingly, methods are required to improve throughput and provide a higher level of material discrimination during inspection. This paper will briefly review the elements required to make an effective X-ray source, whilst outlining the RF technology required to drive a linac-based X-ray security system. Following this, potential new developments in radiofrequency (RF) sub-systems will be discussed in the context of user benefits.

INTRODUCTION

Over 90% of the world's non-bulk cargo is transported by ship in standardised containers. The containerisation system was developed after World War II and its cost reduction has been a major driver of international trade and globalisation. There are well over half a billion container shipments per annum. China tranships about 25% of the total with Europe at 13% and the US at under 7% [1].

Security screening is a broad term which encompasses intelligent logistics, sniffer dogs and X-ray inspection at ports, airports, borders and mail depots. X-ray inspection systems offer rapid, non-invasive detection of contraband and explosive devices, and can be combined with other techniques to identify nuclear material. Although fast and effective, only a small fraction of container movements are X-rayed, as screening adds considerable time and cost to the industry. However, the recognition of the economic value in protecting customs revenue has driven additional growth in the market, since the detection and confiscation of contraband can quickly recover the capital cost of the system.

This paper will concentrate on security screening systems which require a linac X-ray source, as these systems produce the energies required for CVI. The accelerators and RF sub-systems used in radiotherapy markets have been established for many years, and thus act as a technology baseline for X-ray security systems. Despite this fact, cargo scanning imposes new requirements such as, portability, material discrimination and higher throughput, leading to a shorter time between object screening. So, it is likely that some of these technology developments will in turn offer real benefit back to the radiotherapy market.

X-RAY SOURCES

The choice of X-ray source is dependent upon the physics of X-ray absorption in materials and is strongly influenced by detector performance. These constraints need to be adapted to match requirements for object and material discrimination, throughput, reliability, safety and size. There are currently three main technologies used for security systems which are characterised by their penetration in steel, in Fig. 1.

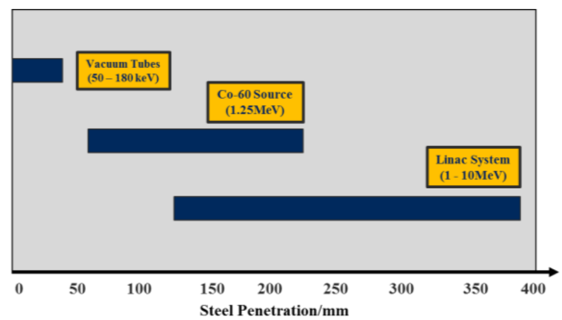

Figure 1: A diagram to show the approximate range of steel penetration for each type of X-ray source [2, 3, 4, 5].

Vacuum tube designs rely on the acceleration of an electron beam by an electric field and its subsequent absorption by a high atomic number (Z) anode target. The electron deceleration occurring during absorption produces a 'stopping' radiation, which is characterised by a Bremsstrahlung energy spectrum. Energies between 50 - 450 keV are achievable with this technique, however above 150 keV energies become difficult to attain reliably, due to a reduction in anode lifetime principally caused by cooling issues. These sources are typically used for baggage and mail scanning.

Radioactive isotopes such as Cobalt-60 and Caesium-137 are used to produce gamma rays with energies of 1.25 MeV[1] and 662 keV respectively [6]. These systems are widely used for vehicle inspection and non-destructive testing (NDT) [7].

Linac based systems for heavy container and vehicle scanning produce the 2 - 10 MeV X-rays required for increased penetration [5]. Although, Cobalt-60 sources offer a similar steel penetration to low energy linacs, it is unsuitable for imaging cargo containers. Most manufacturers typically design linacs in the range of 3 - 6 MeV to balance the trade-off between poor penetration at low energies, versus unwanted neutron production and shielding requirements at higher energies.

[1] The quoted energy is the average energy of the two gamma rays emitted by a Co-60 source. The individual energies are 1.17 and 1.33 MeV respectively [7].

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The pulse repetition frequency (PRF) of linac systems can be adjusted to match the speed of the cargo or vehicle under inspection. Higher repetition rates permit faster throughput, thereby decreasing scanning time. For example a PRF of 500 Hz, allows cargo containers to be scanned as they move at speeds of nearly 10 km/h, whilst achieving a 5mm horizontal resolution [5].

LINAC SCREENING SYSTEMS

The technology for linac screening systems is primarily driven by user requirements for high throughput, and accurate material identification. These requirements determine the choice of X-ray source, RF sub-system and the detector array. In the following section a range of imaging modalities is discussed in terms of their detection capabilities and the RF technology required to drive the linac and thus generate X-rays.

Most linac based systems operate in transmission mode, see Fig. 2. In this method X-rays are imaged after passing through the object under inspection, with photons being attenuated along their path. This technique is sensitised to denser materials which absorb more X-rays, and thus appear as brighter objects on positive contrast images.

Forward-scatter imaging is a key variant of the transmission imaging method, in that a pencil beam of X-rays is used to obtain spatial information for the object. This modality relies upon the same attenuation mechanism as the conventional transmission method [8].

X-ray Backscatter

A key requirement of the X-ray source for backscatter is that the energy range must match that required to observe Compton scattering for low-Z materials, see Fig. 3. This can be achieved using a low voltage vacuum tube for luggage and personnel screening to identify hidden threats under clothing, or with a linac system to scan vehicles using a large field-of-view [9]. Originally, backscatter systems were designed to address user requirements for single-sided detection, [10] in cases where access to the far side of an object was restricted.

These systems detect photons which have interacted with the object material via Compton scattering. The fan beam produced by the X-ray source is further collimated using a 'chopper wheel' - to create a pencil beam at the desired position to 'line scan' the object [9]. This process is repeated to create an image as the scattered photons are detected by a set of large area integrating detectors [8]. Backscatter system rely upon the strong signal received from low-Z materials, as scattering forms a significant proportion of the total interaction cross-section for this energy range. Hence, this method can be used to identify organic contraband i.e. narcotics and explosives [9].

However, due to the poor penetration of denser materials, many commercial systems now incorporate both forward and backscatter imaging modalities into a single system, using two sets of detectors, and in some cases two X-ray sources depending on the application. These complementary detection capabilities offer increased penetration and improved discrimination across high and low-Z materials.

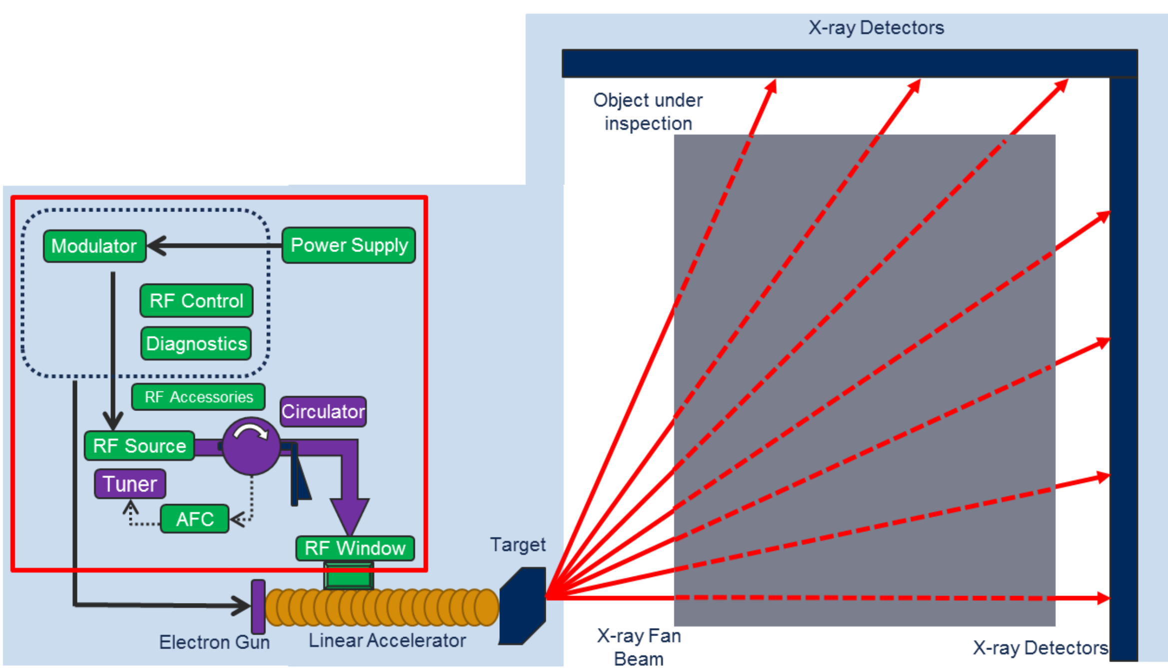

Figure 2: A schematic diagram to highlight the RF sub-system required for a typical fixed transmission linac screening system. The RF sub-system is highlighted by the components in the red box, items coloured green are currently offered by e2v and those in purple form future development work.

Dual Energy Systems

In this method, a linac is used to create interlaced pulses of high and low X-ray energies with a high PRF to provide a continuous imaging mechanism [11]. There are several methods available for dual energy switching at the RF sub-system level these include; dumping some of the RF power from the magnetron to create a low energy beam, using a modulator to create pulses of different amplitude in order to establish two different X-ray energies, or by designing a linac cavity to switch the RF power output in and out of phase to vary the output energy.

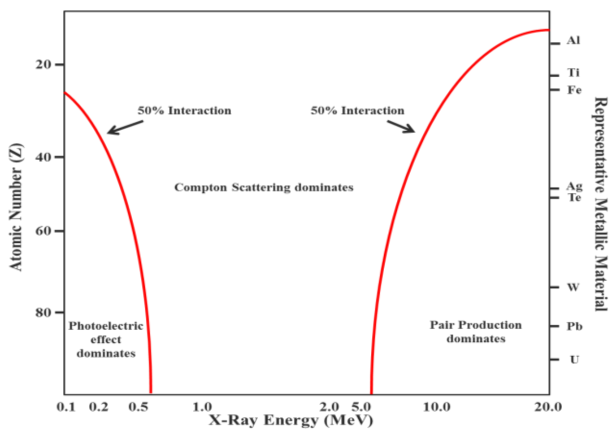

Figure 3: A graph to illustrate X-ray interaction mechanisms for different photons energies [12].

Dual energy systems rely upon the different interaction mechanisms shown in Fig. 3, which are associated with X-ray photons at different energies. At high energies of at least 9 MeV pair production is dominant, whereas at low energies of ~5 MeV photon interactions can be attributed to Compton scattering, and the photoelectric effect [11]. The ability to discriminate between organic and inorganic materials is realisable due to the large variation in atomic number between these materials. Therefore, the attenuation signal from the X-ray source can be related to the incident energy and the effective atomic number of the object materials.

Despite this fact, dual energy systems are currently unable to differentiate between materials of similar atomic number. This is effect is more prominent for low-Z materials, due to the large errors associated with weak attenuation signals [12]. Consequently, dual energy systems are a compromise between the energies required for full object penetration and the performance of the X-ray source/detector to aid material identification.

Detector Technology

Most X-ray screening systems currently use scintillator crystals, to convert scattered X-rays into light photons which are detected by photodiodes. The detector is designed to be sensitive enough to detect accurately the scattered photons within its dynamic range. Due to the inhomogeneity of object densities and orientations, a range of attenuation paths are created, which can vary as much as 100000:1 [5].

Detector technology is driven by the demand for high energy X-ray screening systems to provide higher throughput, and better object and material identification [13]. The design considerations for high energy detectors can be split up into the requirements imposed on the X-ray source and the desire for better image quality. In the former, the focus is on the ability to withstand X-ray damage and provide high sensitivity. Whereas in the latter case, the combination of pixel size and a higher dynamic range, can increase the detector's ability to detect variable signals from a range of attenuation paths [5].

RF TECHNOLOGY

The majority of the linear accelerators in operation today are produced by commercial organisations who continue to benefit from a strong relationship with the high energy physics community. However, the same is not true of the RF power subsystems that drive the linac cavities. Here the design skills for specialised component design and manufacture, as well as system design and integration, for low cost systems produced serially in quantity reside mainly in commercial companies. For example, there are a relatively small number of manufacturers of the magnetron RF source, shown in Fig. 4. There is an emerging trend for the linac system companies to demand more integrated RF sub-systems. Currently, e2v intends not only to drive the innovation and development of magnetron technology but, also offer integrated sub-systems up to the level indicated by the red outline, in Fig. 2.

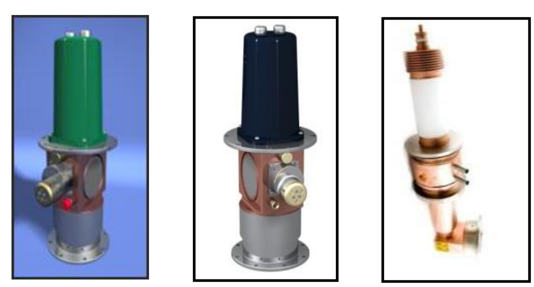

Figure 4: Displays the existing (MG5193), new technology (MG7095) and future high power S-band magnetron devices supplied by e2v for linac based X-ray security systems.

The Magnetron RF Source

Magnetrons emerged as efficient high peak power RF sources during WWII and became the baseline choice for compact, cost-effective, high power radar systems to support the subsequent rapid growth of commercial radar for the aviation industry. Ground based systems operated at S-band with reasonably high power, and these devices were rapidly adopted for driving medical linacs as a compact alternative to klystrons.

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Microwave circuit dimensions get smaller as frequency increases and mobile military platforms operated radars at X-band. These became standard in marine radar with a large global market today. Compact X-band systems are also attractive for cargo scanning from lightweight, mobile vehicles whose flexibility can significantly extend the application and market potential for X-ray cargo scanning, to include mobile spot checks at remote border roads and flexible deployment at ports and airports. However, the benefits of reduced size and weight come at the expense of much tighter manufacturing tolerances overall and relatively low power. The route forward is promising but further development is required. There has been some interest in taking an intermediate step to C-band. This is perfectly possible but the absence of a well-established market leaves a hole in the magnetron product range at C-band. The cost of new development and the more modest benefit in size and weight will probably make this an unflavoured choice for future cargo scanning systems.

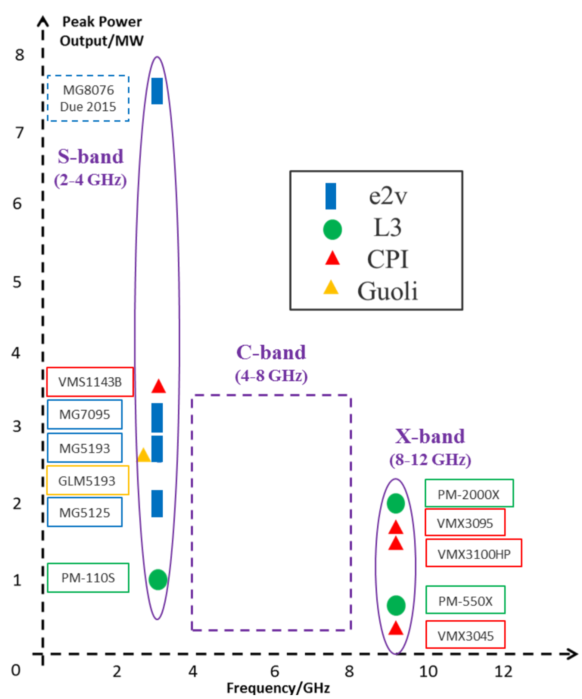

Figure 5: Magnetrons for X-ray screening arranged for clarity [14, 15, 16]. Please refer to device data sheets for definitive operating parameters.

Given the close link in application requirement between medical linacs and cargo scanning, it is not surprising that the vast majority of cargo scanning linacs use an S-band medical magnetron, with for example e2v's MG5193 series magnetron, shown in Fig. 4. This magnetron accounts for a high proportion of the installed base. Initially, magnetrons were used in single energy machines but the increasing demand for material discrimination has shifted the requirement to dual energy. Today it is estimated that more than half of e2v magnetrons go into dual energy machines. They are designed to meet very demanding minimal frequency shifts on a pulse to pulse basis, with the current adjusted by up to 50% between pulses.

As mentioned earlier, increasing throughput is a strong benefit for cargo scanning and the next generation of magnetron technology is already emerging to meet the demand. An example is the MG7095 shown in Fig. 4, with a 25% increase in peak and average power. A higher peak power provides higher X-ray energies and therefore increased penetration power, which also allows the OEM to choose a shorter linear accelerator for the same X-ray output dose. While, a higher average power permits a higher PRF or longer pulse widths. These characteristics meet user requirements for better image quality and thus faster throughput, as more images can be acquired each second. Magnetron power is limited by its design, and the design parameters are constantly being optimised to balance requirements for higher power output.

The magnetron design has been entirely revised to reduce the magnetron arc rate. By their nature all magnetrons are susceptible on an occasional basis to arcing effects. While not necessarily a problem any resulting missing RF pulse must be accommodated in some way. For cargo scanning, each arc and missing RF pulse will result in the loss of a slice in the image. Since the arcs can occasionally come in bursts, they could result in the need for a re-scan. So as system requirements become less tolerant of arcing, development effort at e2v is targeting reductions in the arc rate by two orders of magnitude. This will increase reliability and the magnetron useful lifetime.

The demand for throughput continues to increase, and the magnetron technology roadmap indicates the possibility of even higher power devices that embody all the performance benefits established to date. e2v plans a high power S-band magnetron with over double the power capability of existing cargo scanning magnetrons, while retaining record low arc rate levels for improved image performance.

The Modulator

Another key device in the RF sub-system is the modulator which produces a pulse to drive the magnetron. Many existing systems still use older line-type devices; however there is a trend toward solid state alternatives which are more compact.

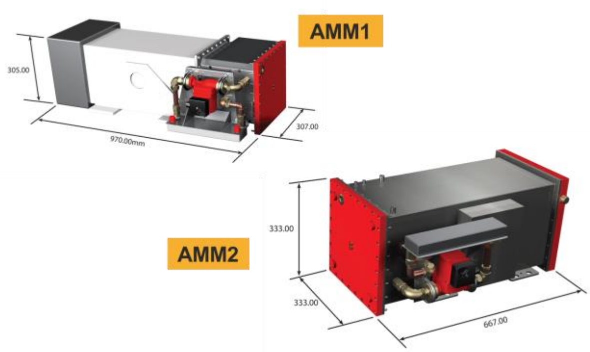

Figure 6: Displays e2v's solid state modulator range.

e2v currently offer the AMM1 solid state modulator and is developing a new generation of modulators, see Fig. 6. AMM2 which offers a number of user benefits over its predecessor. These include:

- A smaller, lighter design
- Field replaceable units and remote diagnostics
- An improved front edge to the pulse; which improves magnetron starting performance.
- The generation of a flat pulse at multiple magnetron operating points without changing the magnetic field; which maximises conversion of microwave power into x-ray output at the system level.

All the properties above provide a more compact RF sub-system.

RF Sub-Systems

A future development building on e2v's RF component technology will be in the manufacture and production of a complete RF sub-system, as shown in Fig. 7. This could provide benefits to the system manufacturer and user in terms of:

- Optimised interfaces
- Component and system compatibility
- Integrated diagnostics
- Fault reporting
- Scheduled maintenance and service requests

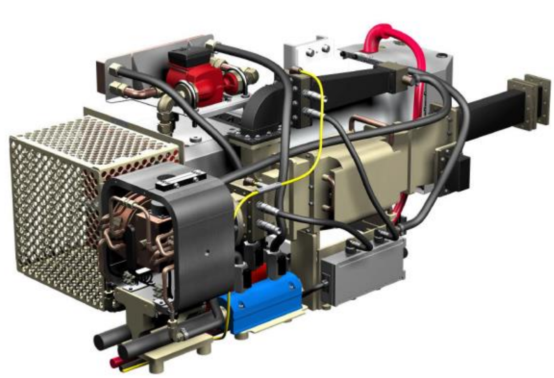

Figure 7: A schematic diagram of an RF sub-system offered by e2v for linac screening systems.

As a result, the sub-system offering will provide the user with a high level of performance control and pre-emptive maintenance, which should in turn allow key performance factors to be adjusted for a particular security application.

CONCLUSION

Security screening is now a baseline requirement for global transport systems and will continue to be so for the foreseeable future. Increased emphasis on the control of borders to protect customs revenues and reduce threats from illicit and potentially harmful materials, will drive innovation and cost reduction in future. Cargo scanning with X-rays is the only established non-invasive inspection technology available and is likely to remain so. The magnetron is the most effective RF source for this application and has headroom for performance developments that will address the emerging user requirements. e2v is concentrating its efforts on enhancing magnetron performance by at least a factor of 2 and in developing RF power systems that optimise overall system performance, reliability and serviceability to levels that help ensure that market potential can be translated into real growth.

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