RF Sub-Systems for Cargo and Vehicle Inspection

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Presented by Trevor Cross, Group Chief Technology Officer
e2v Technologies (UK) Ltd.

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Founded in **1947**

>$300m annual sales

**1600** employees

**500+** engineers & scientists

**Operational facilities in** Europe, the US and Asia

![FY12/13 revenue ($m) by region](chart)
We aim to deliver enabling technology and vital services for critical systems.

Our business is built on our core high performance technologies rooted in:

- **Vacuum electronics** - generation and control of RF and microwave power
- **Silicon photonics** – image sensors & detectors
- **Specialist hi-rel digital IC design, manufacture, package, test and life cycle support**

Our strategy includes a move from a component to a sub-system scope of supply, with long term support and service.
Overview

1) Security Screening Market
2) X-ray Sources
3) Linac screening systems
4) RF Sub-systems
5) Summary
1) Security Screening Market

2) X-ray Sources

3) Linac screening systems

4) RF Sub-systems

5) Summary
Security Screening Market
Some significant specialist applications of X-rays and accelerators

Indicative system costs

- Hand Baggage Scanners: <$100k
- CVI Linac Systems: ~$1m
- Medical Radiotherapy Linac Systems: ~$4m
Security Screening Market
Some significant specialist applications of X-rays and accelerators

- Indicative system costs
  - Hand Baggage Scanners: <$100k
  - CVI Linac Systems: ~$1m
  - Medical Radiotherapy Linac Systems: ~$4m
  - Large Hadron Collider (LHC): ~$5bn
Cargo and Vehicle Inspection (‘CVI’) - a subset of security screening
• Over 90% of world’s non-bulk cargo transported in standardised containers.

• Over **600 million** container shipments each annum.

Container Shipments by Country

- **China** 46%
- **Europe** 28%
- **USA** 13%
- **Hong Kong** 7%
- **Korea Republic** 6%

Source: Containerisation International Yearbook, 2014.
What’s in the containers?

What it says on the paperwork?

OR

- Contraband?
- Terrorist material?
- ???
Container screening - the scale of the problem
...the containers shipped in one year..

Containers stacked 9 high .... would still reach the moon!

.... or lined up end to end they would go ~ 278,000 times around the LHC tunnel!

Image credits: Wikipedia; CERN
• The global X-ray security screening market is forecast to grow from $1.2 billion in 2011 to $1.9 billion by 2016.

• Over the next five years, analysts forecast a CAGR growth of 7% of the global X-ray screening market.

Source: Homeland Security Research Corporation 2011
Growth in X-ray security screening due to:

- Expansion of Asia Pac secure facilities and aviation security markets
- Replacement of more than outdated X-ray systems
- There is no modality on the horizon that can competitively challenge the cost-performance of X-ray based screening technologies.

Source: Homeland Security Research Corporation 2011
Security Screening Market
Baggage and Mail Scanning - examples

Image credited to Westminster International LTD. WS IS100X

Image credited to Smith’s Detection System

Image Credited to Lighthouse Global Technologies.

CX6040BI X-ray inspection system. Image Credited to Nuctech Company Limited

Image credited to L3 Communications Security & Detection Systems
Security Screening Market
- CVI Systems - examples

PB Series CVI System. Image credited to Nuctech MB series.[11]

High Energy X-ray Mobile Screening System. Image Credited to Smith’s Detection Systems.[14]

Image credited to Rapiscan. Eagle R60 Rail Scanning System.[10]

Image credited to American Science & Engineering Sentry Z portal System.[12]
Focus on security screening systems CVI.
  - which require a linac X-ray source, as these systems
  - Up to 10 MeV

Derived from the accelerators and RF sub-systems used in radiotherapy

Some unique cargo scanning imposes new requirements such as,
  - Portability, material discrimination
And,
  - higher throughput, leading to a shorter time between object screening.
1) Security Screening Market

2) X-ray Sources

3) Linac screening systems

4) RF Sub-systems

5) Emerging Technologies

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X-ray Sources for CVI

- Choice is dependent upon the X-ray photon interactions required to obtain contrast in a particular application and detector performance.

- X-ray sources affect the screening systems capability in terms of:
  - Material discrimination
  - Throughput
  - Reliability
  - Safety
  - Cost and space requirements
X-ray sources matched to systems

- **Cobalt-60 Source**: Photo Credits and Copyright 1999: Oak Ridge Associated Universities.
- **6 MeV S-band Linac**: Image credited to AET, Inc.
- **X-ray Vacuum Tube**: Photo Credits and Copyright 2007 Dorland’s Medical Dictionary for Health Consumers. by Saunders

**System example**

- **CX6040BI X-ray inspection system**: Image Credited to Nuctech Company Limited.
- **CVI Scanner**: Image credited to Kapri Corp copyrighted 2010-2011
- **Eagle M60 drive-by scan mode**: Image credited to Rapiscan Systems.
## X-ray Sources

### Variants [1]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Energy Range</th>
<th>Approximate Steel Penetration/mm</th>
<th>Method</th>
<th>Application</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Tubes</td>
<td>50 - 450 keV</td>
<td>38</td>
<td>Electron beam acceleration and rapid deceleration by an anode target to create Bremsstrahlung</td>
<td>Baggage and mail scanning</td>
<td>Poor penetration so not suitable for CVI</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Above 150 keV there are anode cooling issues</td>
</tr>
<tr>
<td>Cobalt-60 Source</td>
<td>1.17-1.33 MeV</td>
<td>63.5 - 229</td>
<td>Radioactive source emits gamma rays of different energies. The photopeaks for a scintillation counter occur at 1.17 and 1.33 MeV.</td>
<td>Vehicle inspection and non-destructive testing (NDT)</td>
<td>Source lifetime and output dose variation with half life</td>
</tr>
<tr>
<td>Linac Systems</td>
<td>2 - 10 MeV</td>
<td>133 - 390</td>
<td>Electron beam acceleration using a linear accelerator (linac) and absorption by a high-Z target to produce X-rays.</td>
<td>Heavy container and vehicle scanning</td>
<td>Above 6 MeV there is neutron production and more shielding required</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Poor penetration below 3 MeV</td>
</tr>
</tbody>
</table>
X-ray Sources
Electron Linacs are most often required for CVI
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X-ray Screening Systems

- Technology driven by user requirements for high throughput and accurate material identification. This is turn affects the RF sub-system and detector array.

- The X-ray screening systems in operation today currently using the following imaging techniques:
  - Transmission
  - Backscatter
  - Dual Energy
  - A combination of the above to improve material discrimination

- Transmission systems rely on the attenuation of X-ray photons as they pass through the object material. Denser materials appear brighter on positive contrast images, similar to X-ray imaging.

- Backscatter Systems can be used for luggage and personnel screening, and vehicle inspection. [9]

- Dual Energy Systems are used for CVI and border security applications.
Linac X-ray Screening Systems
Transmission Systems

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.
X-ray Screening Systems
Backscatter systems

- X-ray source and large area detectors on the same side to detect Compton scattered photons
- Strong signal received from low-Z materials, but poor penetration of denser materials.

Image credited to American Science and Engineering (AS&E) Inc.
X-ray Screening Systems
Dual Energy systems

- Linac used to interlace pulses of high and low X-ray energy for continuous imaging.

- Interaction mechanisms at different energies provided image contrast for organic and inorganic material.
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• The design skills required for RF power sub-systems in terms of specialised component design and manufacture mainly reside in companies.

• At present, some CVI system companies are demanding more integrated RF sub-systems.

• As such, e2v intends to not only drive the innovation in sources but provide sub-systems.
RF Technology
Typical magnetron source landscape and heritage

Frequency/GHz

Peak Power Output/W

Medical + Cargo
Linacs, Radar for big ships

Medical

Marine radar and radar for small boats

Military (anti-aircraft missile), Ground surveillance with low-flying helicopters to pick up telephone cables

Very high definition
Defence radar

Industrial Heating and Air Traffic Control

Military Radar (large missile guidance)

L-band (1 - 2GHz)
S-band (2 - 4GHz)
C-band (4 - 8GHz)
X-band (8 – 12GHz)

J-band (10 - 20GHz)
Q-band (33 - 50GHz)
W-band (75 - 110GHz)

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RF Technology
Global indicative annual volumes of Magnetrons

- Medical and Industrial: ~4k
- Defence: ~20k
- Marine: ~150k
- Domestic microwave ovens: ~150M
RF Technology
Magnetrons

- Magnetrons are efficient high peak power RF sources.

- Use a variety of anode designs for its magnetrons. These include:

1. Strap Vane
2. Long anode (L, S, C bands)
3. Coaxial (S, C, X, J, Q bands)
4. Rising Sun (J, Q, W bands)
5. Distributed Strap – an e2v patented design!
RF Technology
Extensive Magnetron Modelling

- Sidearm structural modelling
- S-band anode cooling
- S-band output modal analysis
- S-band sidearm transport random vibration

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RF Technology
Magnetron Product used for CVI

Magnetrons for X-ray screening arranged for clarity [14, 15 & 16].
RF Technology
Magnetron Development

- A higher peak power - more penetration power

- High Average Power (AP) - yields a faster PRF or longer pulse widths.

- Missing RF pulses attributed to magnetron arcing cause lost slices in an image.
  - Arcs can appear in bursts – could require a re-scan.
  - As system requirements become less tolerant of arcing, e2v is developing efforts to reduce the arc rate by two orders of magnitude.
RF Technology

Modulators

• Produces a pulse to drive the magnetron. Current trend toward solid state modulators as opposed to the older line-type devices due to size – as compact RF sub-systems are more desirable.

• e2v currently offer the AMM1 solid state modulator (>600 units fielded)

• AMM2 provides a number of benefits over its predecessor in terms of:
  o Smaller and lighter design
  o Field replaceable units and remote diagnostics
  o An improved pulse shaping - which improves magnetron starting performance.
  o Improved efficiency
RF Technology
RF Sub-System Development

- Future development for e2v building on our RF component technology.

- This will provide benefits to the user and system manufacturer in terms of:
  - Optimised Interfaces
  - Component and system compatibility
  - Integrated diagnostics
  - Fault reporting
  - Scheduled maintenance and service requests
RF Technology

e2v’s Linac Security Screening Portfolio

- Magnetrons
- Thyratrons
- Modulators
- RF Accessories
- X-ray Security Applications

Sub-systems

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Summary

- Linac based X-ray sources are the usual choice for CVI applications – because they can produce the required penetration.

- Development of RF sub-systems for linac screening applications has led to higher throughput and improved material discrimination – driven by user requirements.

- Demand for linacs will be driven primarily by cargo screening and border protection needs. Slated to grow at c. 7% CAGR (however this business is heavily influenced by governmental policies on homeland security, political change and government budgets etc.)

- Future systems will need to offer faster throughput with less false positives and improved material discrimination to compete in the market.

- e2v supplies is committed to the continued supply and development of RF equipment for CVI (magnetrons, thyratrons, solid-state modulators and passive waveguide components) and can offer microwave subsystems too.
Acknowledgments

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Thank you all for listening.

Questions ?