Compact Radio Frequency Technology for Applications in Cargo and Global Security

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STFC Daresbury Laboratory
CLASP Security Event
Tuesday 5th July 2011, London
Compact RF Technologies

- **S-band (2 - 4 GHz):**
  - Linacs (medical and security) for x-ray scanning (~10 cm)
- **C-band (4 - 8 GHz):**
  - Linac-driven compact FELs (science) and THz imaging (security)(~5 cm)
- **X-band (8 - 12 GHz):**
  - Linacs and RF technology (medical, defence and security) for tumour ablation, x-ray scanning and radar (~2.5 cm)
- **W-band (75 - 110 GHz):**
  - Linacs and technology (defence) for radar and active denial systems (mm)
X-Band RF Applications I

• **Low Energy, Low Output:**
  - 1 MeV, up to 2 cGy/min at 1m @ 100 Hz.

• **Air cargo screening ⇒ inspect a full ULD:**
  - No system currently exists to achieve the required penetration and spatial resolution,
  - A 1 MeV based LINAC inspection system has the potential to open up this new market sector.

• **Mobile screening with a small exclusion zone:**
  - Current mobile screening systems require 40m x 40m exclusion zone ⇒ protect public.
  - A low energy and dose rate LINAC can:
    - significantly reduce the exclusion zone footprint,
    - allow scanning in public areas i.e. sporting events, car parks, concerts, etc.
• **High Energy, Medium Output:**
  - 6 MeV, up to 80 cGy/min at 1m @ 100 Hz.
• X-band competes directly with existing S-band systems.
• Key advantage of X-band is the significant weight reduction:
  – Also reduces the cost/weight of surrounding lead and tungsten shielding.
• The X-band size reduction enables the device to be packed more efficiently into smaller standard-sized cargo containers.
• For mobile scanners, reducing the rear axle weight of a LINAC by 500 kg is a significant advantage over existing S-band systems.

http://www.rapiscansystems.com/
Cargo Screening Accelerators

• X-band technology chosen due to:
  – availability of technology
  – compactness
  – technological limits to robustness
  – tolerances at high power in micromachining and brazing.

• Existing Linac suppliers:
  – Varian (USA) – 65% market
  – Siemens (USA)
  – Nutech (China)

Linear Accelerators account for 90% of the sources used in high energy cargo screening.

It is expected that the global market is ~few hundred units/year.

In 2007, 250 units were sold internationally.

Data provided by Rapiscan Global Sales and Marketing (2007)
CLASP Ph-I Collaboration Team

- **STFC, ASTeC Daresbury Lab:**
  - Ian Burrows (Mechanical Eng.)
  - Peter Corlett (Project Manager)
  - Andrew Goulden (Cooling Sys.)
  - Paul Hindley (Installation)
  - Peter McIntosh (ASTeC PI)
- **Rapiscan Systems:**
  - Ed Morton (Rapiscan PI)
  - Imran Tahir (Magnetron Controls)
- **E2v:**
  - Stuart Andrews (Gun/Magnetron)
  - Cliff Weatherup (e2v PI)
- **Lancaster University:**
  - Graeme Burt (Project Leader)
  - Praveen Ambattu (Linac)
CLASP X-Band Scanner System

DC Electron Gun

e2V collaboration

Buncher and Accelerating Structure
(1 MeV)

Variable Accelerating Section
(1-3 and 4-6 MeV)

Magnetron

e2V collaboration

Variable Phase and Amplitude

X-ray Target

Rapiscan collaboration

CI Proposal Scope

Variable Phase and Amplitude

Automated Control System
(Energy, rep-rate, dose)
Proprietary Rapiscan Imaging and Data Analysis

Magnetron
(8-12 GHz, 1-2 MW, 100-200 Hz
Dynamic switching of amplitude and phase pulse-to-pulse)
CLASP 1 MeV System (Funded Phase-I)

- DC Electron Gun
  - e2V collaboration

- Buncher and Accelerating Structure
  - (1 MeV)

- Magnetron
  - e2V collaboration
  - (8-12 GHz, 1-2 MW, 100-200 Hz)
  - Dynamic switching of amplitude and phase pulse-to-pulse

- X-ray Target
  - Rapiscan collaboration

- CI Proposal Scope Phase-I

- Automated Control System
  - (Energy, rep-rate, dose)
  - Proprietary Rapiscan Imaging and Data Analysis
17 keV Electron Gun from e2v

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>sigma_X,rms</td>
<td>0.242 mm</td>
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<tr>
<td>sigma_Y,rms</td>
<td>0.235 mm</td>
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<tr>
<td>emitt_X,rms</td>
<td>0.141 π-mrad-mm</td>
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<tr>
<td>emitt_Y,rms</td>
<td>0.133 π-mrad-mm</td>
</tr>
<tr>
<td>div_X, rms</td>
<td>19.85 mrad</td>
</tr>
<tr>
<td>div_Y, rms</td>
<td>19.32 mrad</td>
</tr>
</tbody>
</table>

Gun activated at e2v before shipment to Daresbury.

http://www.e2v.com/
E2v Magnetron

- Model E2V MG6005.
- 1.3 MW peak power.
- 1 - 4 µs pulses.
- Peak voltage 43 kV.
- Peak Current 75 A.
• E2V engineers acceptance tested the magnetron at Daresbury, with only a few minor problems (modulator failure required repair).
• Maximum power achieved ~ 1.1 MW but not sustainable due to arcs.
• Stable operation at 1 MW.
• Operating at long pulse lengths (4 us) and high power (>1 MW) results in significant arcing within the magnetron.

• Operating frequency found to be low compared with the specification at 9.283 - 9.290 GHz.
• Cause for this is unknown, but under investigation.
• Does however coincide with the linac frequency!
An Automatic Frequency Control system has been produced.

Continually tunes the magnetron to keep maximum power transfer to the linac.

A sample of FWD power is fed through a cavity and its phase compared to a reference signal.

Any difference in phase represents a frequency shift.

The magnetron tuner motor is moved by a PID loop to compensate this phase error.
1 MeV Buncher/Accelerator

\[ \beta = 0.28 \quad 0.48 \quad 0.68 \quad 0.88 \quad 1 \quad 1 \quad 1 \]

\[ 17 \text{ keV} \]

\[ \begin{array}{cccccc}
0 & 0.02 & 0.04 & 0.06 & 0.08 & 0.10 \\
X_{\text{rms}}, \text{mm} & & & & & \\
\end{array} \]

\[ \begin{array}{cccccc}
0 & 0.02 & 0.04 & 0.06 & 0.08 & 0.10 \\
E_{\text{kin}}, \text{MeV} & & & & & \\
\end{array} \]

**cavity ON**

**cavity OFF**
1 MeV Linac Design

Parameter | Value
--- | ---
Energy | 1 MeV
Frequency | 9.3 GHz
Length | 130 mm
$R_{sh}$ max | 116 MΩ/m
$P_{in}$ | 433 kW
Pulse Length | 4 μs
Pulse Rate | 250 Hz
Peak Beam Current | 70 mA
Average Beam Power | 70 W

5 mm beampipe diameter
3.5 mm iris thickness
1 mm coupling cell thickness

Gradient (MV/m) | E (MeV) | $I_{beam}$ (mA) | Spot Size (mm)
--- | --- | --- | ---
20 (nom) | 1.08 | 70 | 1.6
+10 % | +11 % | -4 % | +58 %
-10% | -27 % | -33 % | -55 %

Voltage (kV) | E (MeV) | $I_{beam}$ (mA) | Spot Size (mm)
--- | --- | --- | ---
17 (nom) | 1.08 | 70 | 1.6
+10 % | +0.8 % | -3.5 % | +48 %
-10% | -7 % | -20 % | -15 %
Beam Tracking Analysis

• Collaboration with Tech-X UK to verify Linac electron beam capture and tracking.
• Using VORPAL code to validate PIC transport.
• VORPAL - simulate the physical behaviour of devices and processes for industrial and research applications:
  – laser wakefield accelerators
  – plasma thrusters
  – high-power microwave guides
  – plasma processing chambers

http://www.txcorp.com/products/VORPAL/
Linac Fabrication

- Fabrication commissioned with UK industry:
  - Shakespeare Engineering, Ltd
- Geometric tolerances of 10 µm required.
- Diamond machining and vacuum brazing processes employed.

http://www.shakespeareengineering.co.uk/
Implementation Status

First beam testing expected to start from 11/7/2011 at Daresbury Lab.
<table>
<thead>
<tr>
<th>Milestones</th>
<th>Expected</th>
<th>Achieved</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLASP Ph-I Initiated</td>
<td>1/7/2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetron Designed</td>
<td>20/10/2009</td>
<td>20/10/2010</td>
<td></td>
</tr>
<tr>
<td>Gun Manufactured</td>
<td>12/02/2010</td>
<td><strong>9/7/2010</strong></td>
<td>Based upon design delay as noted above</td>
</tr>
<tr>
<td>Gun Activated</td>
<td>12/3/2010</td>
<td><strong>9/7/2010</strong></td>
<td>Based upon design delay as noted above</td>
</tr>
<tr>
<td>System Integrated</td>
<td>16/7/2010</td>
<td><strong>30/5/2011</strong></td>
<td>Delayed hardware availability.</td>
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<tr>
<td>Beam Testing Completed</td>
<td>30/12/2010</td>
<td><strong>ETA 31/7/2011</strong></td>
<td></td>
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</table>
Conclusions I

• CLASP funded development of 1 MeV system has brought together a strong UK collaborative team:
  – STFC, ASTeC Daresbury Lab.
  – Lancaster University
  – Rapiscan Systems UK
  – E2v, UK
  – Shakespeare Engineering, Ltd
  – Tech-X, UK

• Challenging requirement to develop and demonstrate a gun, magnetron and 1 MeV linac system.
• Each of the sub-systems have been validated separately and expect to achieve 1 MeV beam generation.
Conclusions II

• Major development successes:
  – An optimised 17 keV, high peak current electron gun has been designed, fabricated and activated.
  – A highly compact combined buncher/accelerating structure has been designed.
  – High precision fabrication has been demonstrated for the complex linac geometry.
  – A 1 MW, 9.3 GHz frequency locked magnetron has been designed, fabricated and high power tested.

• Each of these successes strengthen the UK’s position for exploitation into wider security application areas .... but also for science, medicine, defence, and imaging sectors.
CLIC X-band Crab Cavity with CERN

UK design team funded by CERN for next 3 years!

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<th>Parameter</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>11.424 GHz</td>
</tr>
<tr>
<td>Equator radius</td>
<td>14.09 mm</td>
</tr>
<tr>
<td>Group velocity</td>
<td>2.95 % of c</td>
</tr>
<tr>
<td>R/Q</td>
<td>53.92 Ω</td>
</tr>
<tr>
<td>( E_{\text{max}} / E_{\text{trans}} )</td>
<td>2.726</td>
</tr>
<tr>
<td>( H_{\text{max}} / E_{\text{trans}} )</td>
<td>0.0095 S</td>
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