WEBINAR:
X-ray Technology for NDT Applications
(Nondestructive Testing)

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Bio

Andrew Fay is an Application Engineer at Hamamatsu Corporation US HQ in Bridgewater, NJ
Agenda

- Intro to X-rays
- Source Tubes
- Detectors
- Applications:
  - Industrial CT
  - Electronics Inspection
  - Food Inspection

~ 35 minutes
Agenda

- Intro to X-rays
- Source Tubes
- Detectors
- Applications:
  - Industrial CT
  - Electronics Inspection
  - Food Inspection
Advancements in X-ray Technology

Roentgen 1896

Industrial Cone Beam CT 2020

1895 X-rays Discovered

Courtesy: Pinnacle X-ray Solutions
X-ray: Properties

- Energy Range: “Soft x-ray” 5-50keV to “Hard x-rays” 150keV – 1MeV
- Wavelength: 0.01nm – 10nm
Principle of X-ray Generation

Basic structure of an X-ray tube

1. Cathode
2. Anode (Target)
3. Focal Spot

Thermionic Emission
X-rays: tube energy spectrum

Photon spectrum for x-ray tube operating at 150kVp
Factors affecting tube output spectrum: Target Material

Higher stopping power
(Need higher tube voltage to transmit)

Periodic Table of the Elements

Higher stopping power
(Need higher tube voltage to transmit)

Characteristic X-ray emission lines for some common anode materials:

<table>
<thead>
<tr>
<th>Anode material</th>
<th>Atomic number</th>
<th>Photon energy (keV)</th>
<th>Wavelength [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>74</td>
<td>59.3</td>
<td>0.0209, 0.0184</td>
</tr>
<tr>
<td>Mo</td>
<td>42</td>
<td>17.5</td>
<td>0.0709, 0.0632</td>
</tr>
<tr>
<td>Cu</td>
<td>29</td>
<td>8.05</td>
<td>0.154, 0.139</td>
</tr>
<tr>
<td>Ag</td>
<td>47</td>
<td>22.2</td>
<td>0.0559, 0.0497</td>
</tr>
<tr>
<td>Ga</td>
<td>31</td>
<td>9.25</td>
<td>0.134, 0.121</td>
</tr>
<tr>
<td>In</td>
<td>49</td>
<td>24.2</td>
<td>0.0512, 0.455</td>
</tr>
</tbody>
</table>

Photon spectrum for x-ray tube operating at 150 kVp
Factors affecting tube output spectrum:
Filters, Tube Potential, Tube Current

Add Filters at tube
Adjust tube Potential kV
Adjust tube current
X-rays interact with materials differently

Scatter and Sample Material Attenuation Coefficients

- X-ray source
- Sample
- Detector

X-ray Production / Spectra

incident X-ray
transmitted X-ray

Number of X-ray photon vs Energy
Factors for Image Quality: Tube Potential (Voltage kV) Variation

**Tube Potential (kV)**: Defines the intensity of X-ray energy

Change tube kV

- **30kV** 300uA
- **60kV** 300uA
- **90kV** 300uA

Higher Tube potential kV gives better material penetration
Factors for Image Quality: Tube Current (μA) Variation

**Tube current**: Determines the amount of x-ray photons ("Brightness" of image)

![Graph showing relative intensity vs. energy for different tube currents (200 mA and 400 mA).]

<table>
<thead>
<tr>
<th>Tube Current</th>
<th>S/N</th>
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<tr>
<td>80kV 100μA</td>
<td>114</td>
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<tr>
<td>80kV 300μA</td>
<td>200</td>
</tr>
</tbody>
</table>

**Signal to Noise ratio is improved by increasing tube current.**
Factors for Image Quality: Focal Spot Size, Image Sharpness and Magnification

Large Focal spot

Focal spot on target

Unsharpness

Unsharpness formula:

\[ U_1 = S_1 \times \frac{D_2}{D_1} \]

Small Focal spot

Object

Image

Magnification

Magnification formula:

\[ \frac{M_2}{M_1} = \frac{D_1 + D_2}{D_1} \]
Agenda

- Intro to X-rays
- Source Tubes
- Detectors
- Applications:
  - Industrial CT
  - Electronics Inspection
  - Food Inspection
Types of X-ray Sources: Conventional / Milli- / Micro- / Nano-

X-ray Source tubes are often characterized by the focal spot:

<table>
<thead>
<tr>
<th>Type</th>
<th>Focal Spot (Resolution)</th>
<th>App</th>
<th>kV</th>
<th>Res</th>
<th>Mag</th>
<th>Config</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Tube</td>
<td>&gt; 1mm</td>
<td>Medical</td>
<td>600kV</td>
<td>Low</td>
<td>No</td>
<td>Sealed Glass or Ceramic</td>
</tr>
<tr>
<td>Milli-focus Tube</td>
<td>0.4 - 1 mm</td>
<td>Industrial / Medical</td>
<td>600kV</td>
<td>High</td>
<td>Not Good</td>
<td>Sealed Glass or Ceramic</td>
</tr>
<tr>
<td>Micro-focus Tube</td>
<td>2–300 μm</td>
<td>Industrial CT</td>
<td>30-300kV</td>
<td>Very High</td>
<td>High</td>
<td>Sealed or Open</td>
</tr>
<tr>
<td>Nano-focus Tube</td>
<td>0.25-2 μm</td>
<td>High end Industrial / Scientific</td>
<td>30-300kV</td>
<td>Extremely High</td>
<td>High</td>
<td>Open</td>
</tr>
</tbody>
</table>

Microfocus X-ray Tube = MFX
Reflection Type and Transmission Type

Small FOD = high magnification

Reflection Type

Transmission Type

FOD: Focus to Object Distance

Min 6.8 mm

0.5 mm

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Sealed and Open-type MFX (Reflection or Transmission)

Sealed Type

- Electron gun (Cathode)
- Target
- Vacuum Bulb
- Anode
- HV Power Supply

Open Type

- Focusing coil
- Pump
- Cathode
- HV Power Supply

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Sealed and Open-type MFX (Reflection or Transmission)

**SEALED TUBE:**
- Typically oil cooled
- Rugged and Compact for 24/7 in-line and off-line inspection.
- Easy to use and integrate.
- Low maintenance.

**OPEN TUBE:**
- Target and Cathodes can be changed
- Typically water cooled
- Highest resolution and power achievable.
- Regular maintenance required.

Integrated Power Supply
No HV Cables
reduces maintenance
easy system integration
Advantage - High Resolution -

To achieve: **Stable and quiet environment is required.**

**Open-Type**

*(Transmission)*

**Nano Imaging**

**Sealed-Type**

*(Transmission)*

**Micro high resolution**
Agenda

- Intro to X-rays
- Source Tubes
- Detectors
- Applications:
  - Industrial CT
  - Electronics Inspection
  - Food Inspection
NDT Application: Energy Range

Energy Range:
- FLAT PANEL
- LSC
- XRII

Energy Levels:
- 20 kV
- 100 kV
- 150 kV
- 200 kV

Particle Sizes:
- 200 μm
- 150 μm
- 100 μm
- 50 μm
Detectors: Direct vs. Indirect

**INDIRECT X-RAY DETECTION**
- Csl:Tl (columnar structure)
- X-rays
- Secondary electrons
- Light
- ITO (indium titanium oxide)
- S = source
- G = gate
- D = drain

**DIRECT X-RAY DETECTION**
- High voltage
- Photoconductor layer
- Electron and hole pairs
- Top electrode
- Active matrix array
- Charge collection electrode (pixel)
- Capacitor
- TFT

\[ \text{NOT TO SCALE} \]
### Overview of Detectors: for NDT Applications

<table>
<thead>
<tr>
<th></th>
<th>Flat Panel</th>
<th>Line Scan Camera</th>
<th>Xray Image Intensifier</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Range</strong></td>
<td>Good</td>
<td>Good</td>
<td>300kV</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>$50\mu$m</td>
<td>$48\mu$m</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Size (active area)</strong></td>
<td><strong>Up to 43x43cm</strong></td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>Better</td>
<td>Best</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Low Dose Performance</strong></td>
<td>Good</td>
<td>Better</td>
<td>Best</td>
</tr>
<tr>
<td><strong>Ease of Use/ Interface</strong></td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Application:</strong></td>
<td>Food Inspection</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Industrial CT</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Electronics Inspection</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

*Note: The table provides a comparison of different types of detectors for Non-Destructive Testing (NDT) applications.*
Flat-Panel Sensors (FPS)
Intro to Scintillator and Deposition Types

Scintillator Material (Converts x-ray to light photon)

CsI Scintillator
- Needle Structure for High Resolution
- Deposition applicable

Scintillator Deposition or Coupling Methods:

1) “Flipped” Scintillator Plate Type: cost effective

2) “Direct Deposition” Type: eliminate light scattering on the contact surface and maintain better resolution
Compare CMOS and a-Si Flat-Panel

![Graph comparing pixel size and active area](image-url)
## CMOS vs. a-Si

Currently Only CMOS offered for NDT

<table>
<thead>
<tr>
<th>Attribute</th>
<th>CMOS</th>
<th>A-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation Hardness</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Cost</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Detector Size</td>
<td>30x30cm</td>
<td>43x43cm</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>✓ 50μm</td>
<td>100μm</td>
</tr>
<tr>
<td>Noise</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Low Dose / High Dose</td>
<td>✓ /</td>
<td>/ ✓</td>
</tr>
</tbody>
</table>

TFT on Glass Substrate vs. Silicon Wafer

Higher Charge Mobility in Crystalline vs. Amorphous
Line Scan Cameras (LSC)
Basic configuration of X-ray inspection system

General system consist of...

- X-ray camera (LSC)
- Milli- or micro- X-ray source
- Conveyers
- Shielding box
- PC
- Software

![X-ray inspection system diagram]

- X-ray source
  - Milli- or microfocus
  - 20kV to 160kV
- Object
- X-ray Line Scan Camera
  - Single Energy
  - Dual Energy
  - TDI

- Food
- Packages
- Electronics
- Tires
# Line Scan Camera Types

<table>
<thead>
<tr>
<th></th>
<th>LSC SINGLE Energy</th>
<th>LSC DUAL Energy</th>
<th>LSC TDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side view</td>
<td><img src="image1" alt="Side view" /></td>
<td><img src="image2" alt="Side view" /></td>
<td><img src="image3" alt="Side view" /></td>
</tr>
<tr>
<td>Top view (pixels)</td>
<td><a href="image4">Diagram</a></td>
<td><a href="image5">Diagram</a></td>
<td><a href="image6">Diagram</a></td>
</tr>
</tbody>
</table>

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More on Dual-Energy and TDI

**Dual-Energy**
- Rapid kVp switching
- Layer detector
- Dual-Source

**TDI (Time Delay Integration)**
- Improved sensitivity by $x \# \text{ lines}$
- SNR improved by $\sqrt{\# \text{ lines}}$
## LSC - Applications

<table>
<thead>
<tr>
<th></th>
<th>LSC SINGLE Energy</th>
<th>LSC DUAL Energy</th>
<th>LSC TDI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Applications</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Food inspection</td>
<td><img src="image1" alt="Food in glass jar" /></td>
<td><img src="image2" alt="Food in glass jar" /></td>
<td><img src="image3" alt="Food in glass jar" /></td>
</tr>
<tr>
<td>LiB inspection</td>
<td><img src="image4" alt="LiB inspection" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCB inspection</td>
<td><img src="image5" alt="PCB inspection" /></td>
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<td></td>
</tr>
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X-ray Image Intensifier (XRII)
**Operations in an X-ray image chain**

- **X-ray**
- **Metal vacuum bottle**
- **Output window**
- **Lens**
- **CMOS Camera**

**Components:**
- **G1, G2, G3 Anode**
- **CsI input screen**
- **Aluminum input window**
- **Phosphor output screen**

**Gain Calculations:**
- **Gain input screen = 200 el. / X-photon**
- **60 kVp Xray-quantum**
- **Gain output screen = 1000 photons / electrons**
- **Total gain = 200,000 photons / X-photon**
X-ray Image Intensifier + CMOS Camera

Features:
• Very Good Energy Levels 20 ~ 300kV
• CMOS Camera:
  • 2048 x 1544
  • 65 fps
  • USB 3.0

Applications:
• Electrical Comp and Boards
• Battery Inspection
Agenda

- X-ray Introduction
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Industrial CT Application: Examples

Electronics

Metal Parts

Composites

Material Sciences

Agriculture
Magnification allows the defect to be projected onto more pixels at the detector. Therefore better detectability.

MFX will allow good magnification of a sample/part onto the FPS:
- High Magnification
- Micro focus reduces Unsharpness
- Increases # pixels representing the sample

Flaw Detectability of System is increased.
Industrial CT Application : Image Quality – **Frame Averaging**

Random Noise intensity fluctuations can be reduced.

Noise drops by 1/the square root of the number of frames averaged.
Optimizing SNR is a balance of Signal Increase and Noise Reduction.

1. Confirm sample penetration, adjusting Tube Potential kV.
2. Add beam FILTER to remove unwanted low energy x-rays.
3. Collimate output of source tube to reduce scatter.
4. For given kV (i.e. part material density or desired penetration), drive signal as high as possible adjust Tube Current, and/or reducing geometric focal distance (Dose drops/increases by inverse square of the distance).
5. Adjust FPS frame rate and frame averaging.
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Electronic Inspection Application: Sample Dose and Magnification

- **X-ray tube FOD:** 7.3mm

- **FDD:** 300mm

- **Sample**

- **Geometric magnification = FDD / FOD = 30 times**

- **FOD:** 10.0mm (2.7mm from the X-ray window)

- **X-ray tube FOD:** 1.0mm

- **FOD:** 5.0mm (4.0mm from the X-ray window)

- **FDD:** 150mm

- **Sample**

- **4 inch X-ray II**

- **Pixel size of the input is 35μm**

- **Reflective**

- **Transmission**

- **L12531**

- **Pixel size of the input is 35μm**
Bidirectional Scanning

Focused fan beam onto small detector area
Agenda

- Intro to X-rays
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Food Inspection Applications

Hash brown potatoes

X-ray LSC
## Food Inspection Applications - Detectability

<table>
<thead>
<tr>
<th>Looking For:</th>
<th>Inside of:</th>
<th>Need:</th>
<th>LSC</th>
<th>Dual-Energy</th>
<th>TDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality and Safety Check</td>
<td>General</td>
<td>High Speed</td>
<td>BEST</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Organic Materials (Glass, Bone, Mineral Stone) or <strong>High Density</strong> Plastic/Rubber</td>
<td>Homogeneous (Yogurt, Butter)</td>
<td>Dynamic Range</td>
<td>BEST</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Organic Materials (Glass, Bone, Mineral Stone, <strong>Low Density</strong> Plastic/Rubber</td>
<td>Heterogeneous (Bag Hard Candy, Mixed Nuts)</td>
<td>Material Differentiation</td>
<td>Good</td>
<td>BEST</td>
<td>Better</td>
</tr>
<tr>
<td>Contaminants</td>
<td>Complex Packaging</td>
<td>Resolution and Material Differentiation</td>
<td>Good</td>
<td>BEST</td>
<td>BEST</td>
</tr>
<tr>
<td>Small Voids</td>
<td>Sealed Package</td>
<td>High Resolution</td>
<td>Better</td>
<td>Good</td>
<td>BEST</td>
</tr>
</tbody>
</table>
Food Inspection Application - Where

Single Energy LSC 🟢 ✓ ✓
Dual Energy LSC ✓ ✓ ✓
TDI LSC ✓ ✓ ✓

In from Field ➡ Bulk Food Process ➡ Processing Lines ➡ Packaged / Sealing
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<th>Talk #1 Date</th>
<th>Talk #2 Date</th>
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<tr>
<td>1</td>
<td>Introduction to Photodetectors</td>
<td>2</td>
<td>26-May-20</td>
<td>28-May-20</td>
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<tr>
<td>2</td>
<td>Emerging Applications - LiDAR &amp; Flow Cytometry</td>
<td>2</td>
<td>2-Jun-20</td>
<td>4-Jun-20</td>
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<tr>
<td>3</td>
<td>Understanding Spectrometer</td>
<td>2</td>
<td>9-Jun-20</td>
<td>11-Jun-20</td>
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<td>Specialty Products – Introduction to Light Sources &amp; X-Ray</td>
<td>2</td>
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<td>Introduction to Image Sensors</td>
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<td>02-Jul-20</td>
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<td>Image Sensor Circuits and Scientific Camera</td>
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<td>Mid-Infrared (MIR) Technologies &amp; Applications</td>
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<td>30-Jul-20</td>
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<td>Photon Counting Detectors – SiPM and SPAD</td>
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<td>10</td>
<td>Using SNR Simulation to Select a Photodetector</td>
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<td>18-Aug-20</td>
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