Multi-beam x-ray source array based on carbon nanotube field emission

University of North Carolina at Chapel Hill
D. Spevak, Y. Cheng, F. Sprenger
XinRay Systems, LLC.

Support
NCI CCNE (U54CA119334)
NCI (R01CA134598)
NCI GO (RC2CA148447)
DoD CDMRP BC087505
TSWG ED-SR-2794 (for XinRay)

Thermionic x-ray

Spatial resolution: determined by focal spot size
Flux: limited by anode heat load

Alternative technologies
• Synchrotron Radiation
• Scanning electron beam
• Distributed source using multiple thermionic cathodes
• Laser
• Pyroelectric
• “Scotch tape”
• Field emission x-ray source

Electron Field Emission

\[ I = aV^2 \exp(-bF^{3/2}/\beta V) \]

- Room temperature
- Electronically controlled
- Instantaneous response

CNT Based Field Emission X-Ray Source

With Jinping Lu
U.S. 6,553,096, U.S. 6,850,595, U.S. 6,876,724, U.S. 7,085,351
**CNT Based Field Emission X-Ray Source**

Multi-beam field emission x-ray source array


**Promises of the CNT x-ray source technology**

- **Flexibility in source configuration**
  - 1D, 2D, straight, curved…
- **New possibilities for system design**
  - Stationary CT, tomosynthesis…
- **Electronic control**
  - Synchronization/gating

**Challenges**

- High current and current density
- High voltage stability
- Consistency
- Lifetime under non-ideal vacuum
- System integration…

**Example 1: “Jordan” linear x-ray source array**

**Target spec:**
- 160kVp
- 30mA (tube)
- 49 beams
- Short pulse
- Passive cooling

**SEM showing arcing induced damage on the cathode**

**XinRay**

**XinRay/Siemens**

**G. Cao et al. Med Phys 2010**
Focal spot size and spot-to-spot variation

<table>
<thead>
<tr>
<th>Emitter Number</th>
<th>Width (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.7</td>
<td>0.5</td>
</tr>
<tr>
<td>11</td>
<td>1.5</td>
<td>0.6</td>
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<tr>
<td>21</td>
<td>2.0</td>
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<tr>
<td>31</td>
<td>1.9</td>
<td>0.5</td>
</tr>
<tr>
<td>41</td>
<td>2.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Width average = 1.9mm ± 0.1, Max = 2.3mm, Min = 1.6mm
Length average = 0.5mm ± 0.1, Max = 0.9mm, Min = 0.3mm

Consistency test at 160kV @ 43mA
- 225us pulse width
- Variation from nominal current <5%
- 0.05% duty cycle per emitter

Lifetime test from a single x-ray beam at 160kVp
- One emitter 0.5% duty cycle, 225us pulse, 14mA cathode current, stable at 160kV

Example 2
CNT distributed x-ray source array for stationary digital breast tomosynthesis
Digital breast tomosynthesis (DBT)
- Limited view tomography
- Better detection for mass
- Hologic (FDA approved)
- GE and Siemens systems under clinical trial

Digital breast tomosynthesis
- Less successful in detection of microcalcification
- Long scanning time
- Motion blurring due to patient and x-ray source motion

Stationary DBT: First proof-of-concept bench-top system
- 25 x-ray beams over 48 degrees
- Similar geometry as the Siemens system

3rd generation stationary DBT scanner (Argus 3)
Targeted specifications:
- CNT source array
- Hologic Selenia Dimension detection system
- 15 – 31 views
- 100mAs total dose
- Increase spatial resolution by removing source motion blur

In collaboration with Yiheng Zhang, Don Kennedy, Tom Farbizo, Zhenxue Jing
Hologic, Inc.
Hologic Selenia Dimension Tomosynthesis
Scanner integrated with the CNT x-ray source array

Effective focal spot size

- Width avg = 0.64 mm
- Length avg = 0.61 mm
- Stdev = 0.04
- Stdev = 0.05

Experimentally measured values for all 31 beams
Anode Heat Load Simulation

- Results and Conclusions:
  - Anode is safe under the simulated 25kVp x 25mc operating condition.
  - Various simulations suggest the max temperature is proportional to the input power.

Accelerated lifetime measurement at 30kVp

- Cathode current: 40mA; Pulse width: 250ms
- Over 7 yrs service lifetime (60 patients/day, 200 days/yr)

Higher current at reduced pulse width

- Labview_IV: cathode current: 43mA; Pulse width: 250ms
- MPE_IV: cathode current: 43mA; Pulse width: 250ms
- Labview_IV after DC conditioning: cathode current: 43mA; Pulse width: 250ms

All 31 beams reached targeted 43 mA cathode current

- Wgc @ 43mA and 250msec pulse width
Synchronization of the source and detector

Improved MTF along the scanning direction

Initial reconstructed phantom images

Summary

• Nanotube field emission x-ray offers unique capabilities and opportunities for diagnostic x-ray imaging and radiotherapy

• The distributed multi-beam x-ray technology can potentially lead to new tomography scanners with high resolution and fast scanning speed, and new therapeutic devices for cancer treatment.