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

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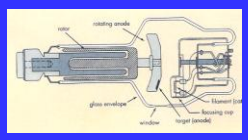
Support

NCI CCNE (U54CA11934)
NCI (R01CA134598)
NCI GO (RC2CA148487)
DoD CDMRP BC087505
TSWG ED-SR-2794 (for XinRay)

Thermionic x-ray



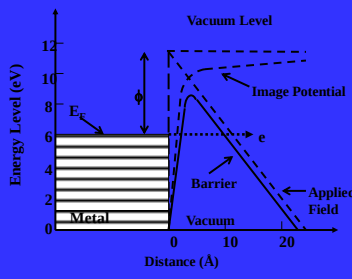
Spatial resolution:
- determined by focal spot size

Flux:
- limited by anode heat load

Alternative technologies

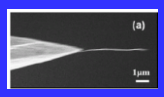
- Synchrotron Radiation
- Scanning electron beam
- Distributed source using multiple thermionic cathodes
- Laser
- Pyroelectric
- "Scotch tape"
- Field emission x-ray source

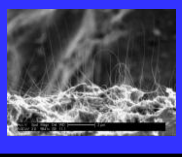
Electron Field Emission



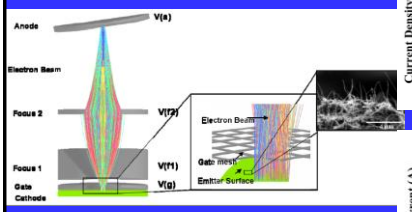
$I = aV^2\exp(-b\Phi^{3/2}/\beta V)$

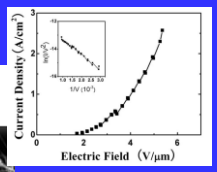
- Room temperature
- Electronically controlled
- Instantaneous response

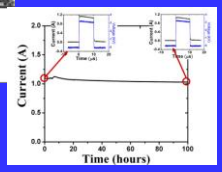




CNT Based Field Emission X-Ray Source





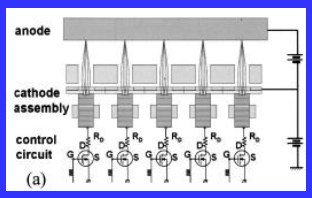


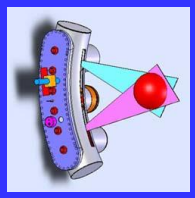
With Jianping Lu

U.S. 6,553,096, U.S. 6,850,595, U.S. 6,876,724, U.S. 6,980,627, U.S.7,085,351 . . .

CNT Based Field Emission X-Ray Source

Multi-beam field emission x-ray source array





J. Zhang et al , Appl Phys Lett 2005, SPIE Medical Imaging 2006

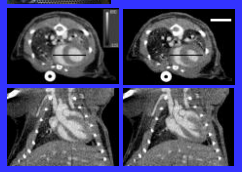
U.S. 6,553,096, U.S. 6,850,595, U.S. 6,876,724, U.S. 6,980,627, U.S.7,085,351…

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

XinRay

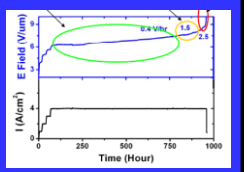
XinRay/Siemens

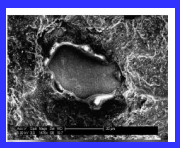


G. Cao et al. Med Phys 2010

Challenges

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



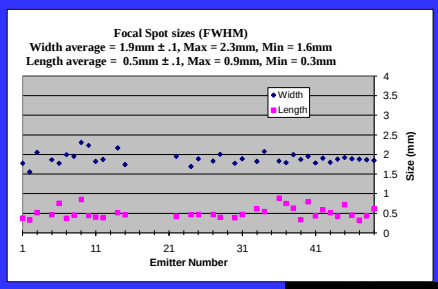


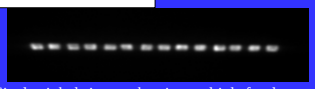
SEM showing arcing induced damage on the cathode

Example 1: "Jordan" linear x-ray source array

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

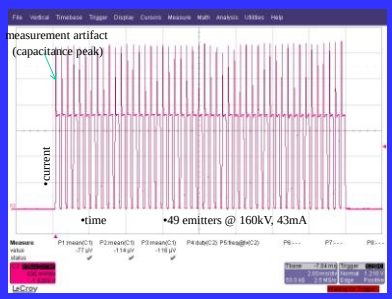
Focal spot size and spot-to-spot variation





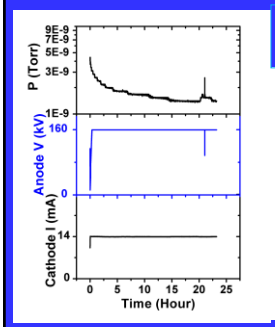
Single pinhole image showing multiple focal spots

Consistency test at 160kV @ 43mA

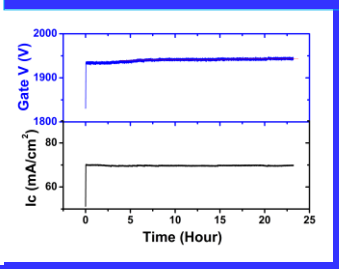


- 225us pulse width
- Variation from nominal current <5 %
- 0.05% duty cycle per emitter

Lifetime test from a single x-ray beam at 160kVp



One emitter 0.5 % duty cycle, 225 us pulse, 14mA cathode current, stable at 160kV

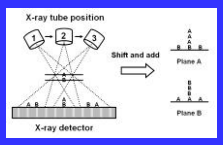


Example 2

CNT distributed x-ray source array
for
stationary digital breast tomosynthesis

Digital breast tomosynthesis (DBT)

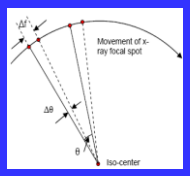
- Limited view tomography
- Better detection for mass
- Hologic (FDA approved)
- GE and Siemens systems under clinical trial

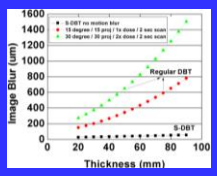


Hologic Selenia Dimension Tomosynthesis scanner

Digital breast tomosynthesis

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





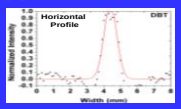
Tube motion during exposure

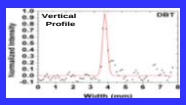
- enlarges the effective focal spot size
- degrades the image quality

Stationary DBT: First proof-of-concept bench-top system

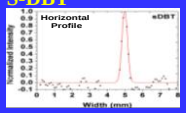
- 25 x-ray beams over 48 degrees
- Similar geometry as the Siemens system

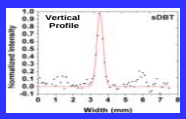
DBT





S-DBT





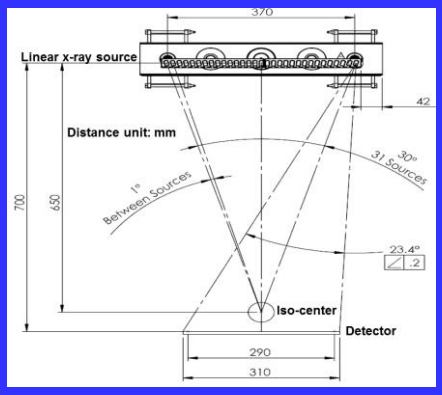
G. Yang et al, SPIE 2008;
X. Qian et al. Med Phys 2009

3rd generation stationary DBT scanner (Argus 3)

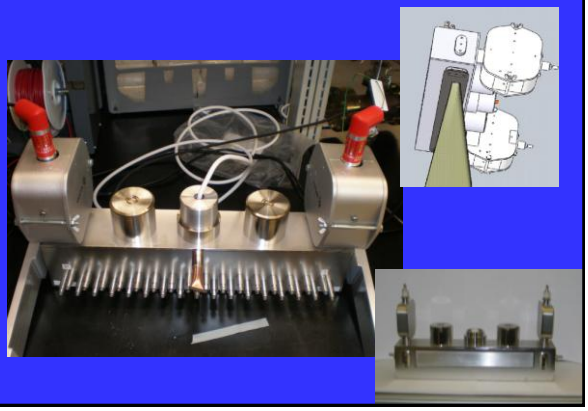
Targeted specifications:

- 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.

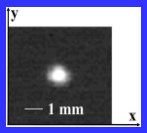


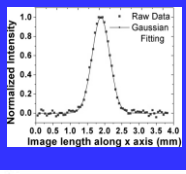
CNT x-ray source array for s-DBT

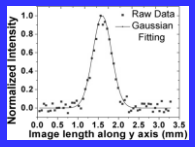


Hologic Selenia Dimension Tomosynthesis
Scanner integrated with the CNT x-ray source array

Effective focal spot size



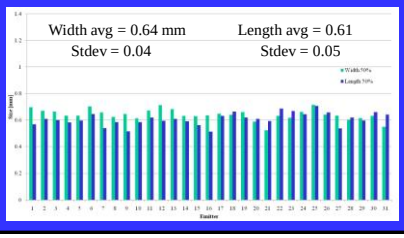




Experimentally measured values for all 31 beams

Width avg = 0.64 mm
Stdev = 0.04

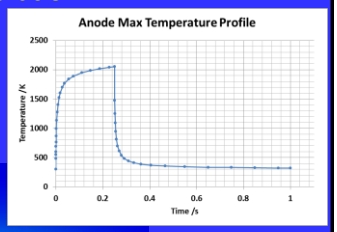
Length avg = 0.61
Stdev = 0.05

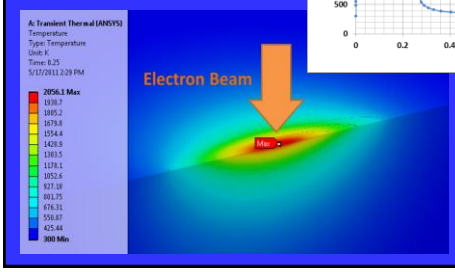


Anode Heat Load Simulation

•Results and Conclusions:

- Anode is safe under the simulated $28kVp \times 28mA$ operating condition.
- Various simulations suggests the max temperature is proportion to the input power.

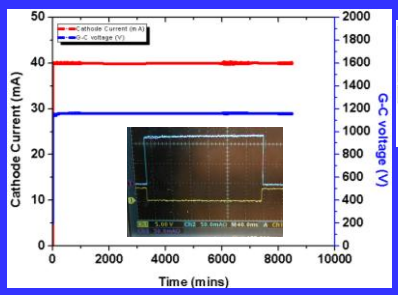


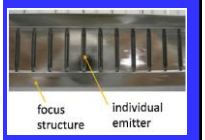


•↑Top Right Figure: Anode Max Temperature Profile for the $28kVp \times 28mA$ operating condition with 250ms exposure time.

•←Bottom Left Figure: Temperature distribution on the anode body for the $28kVp \times 28mA$ operating condition.

Accelerated lifetime measurement at 30kVp

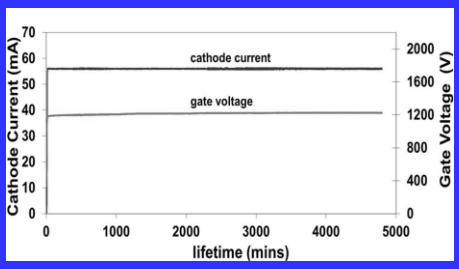




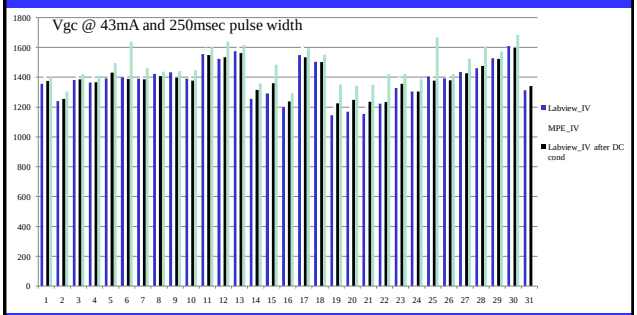
Cathode current: 40mA; Pulse width: 250ms

Over 7 yrs service lifetime (60 patients/day, 200 days/yr)

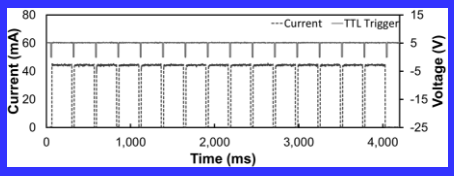
Higher current at reduced pulse width

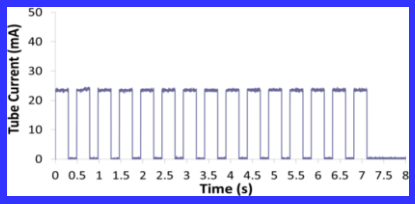


All 31 beams reached targeted 43 mA cathode current

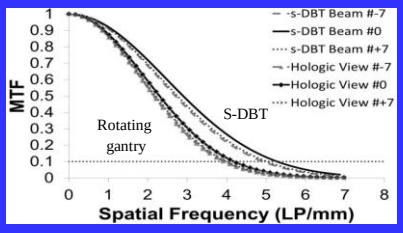


Synchronization of the source and detector





Improved MTF along the scanning direction

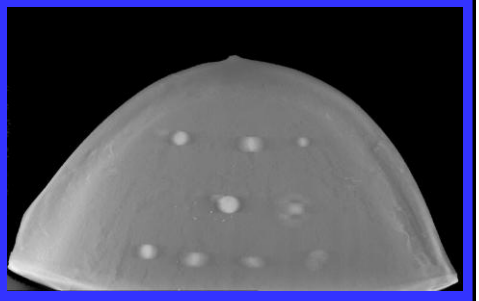


15 view, 14 degrees, 100mAs

Initial reconstructed phantom images

Condition: 15 views, 14 degree, 100mAs, 28kVp anode.

Breast phantom



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 tomogaphy scanners with high resolution and fast scanning speed, and new therapeutic devices for cancer treatment.