# CARBON NANOTUBE SENSOR FOR RADIATION DETECTION

John T.W. Yeow
Canada Research Chair in Micro/NanoDevices
Systems Design Engineering, University of Waterloo
ARTsensing Inc.
http://biomems.uwaterloo.ca
http://www.ARTsensing.com
jyeow@engmail.uwaterloo.ca

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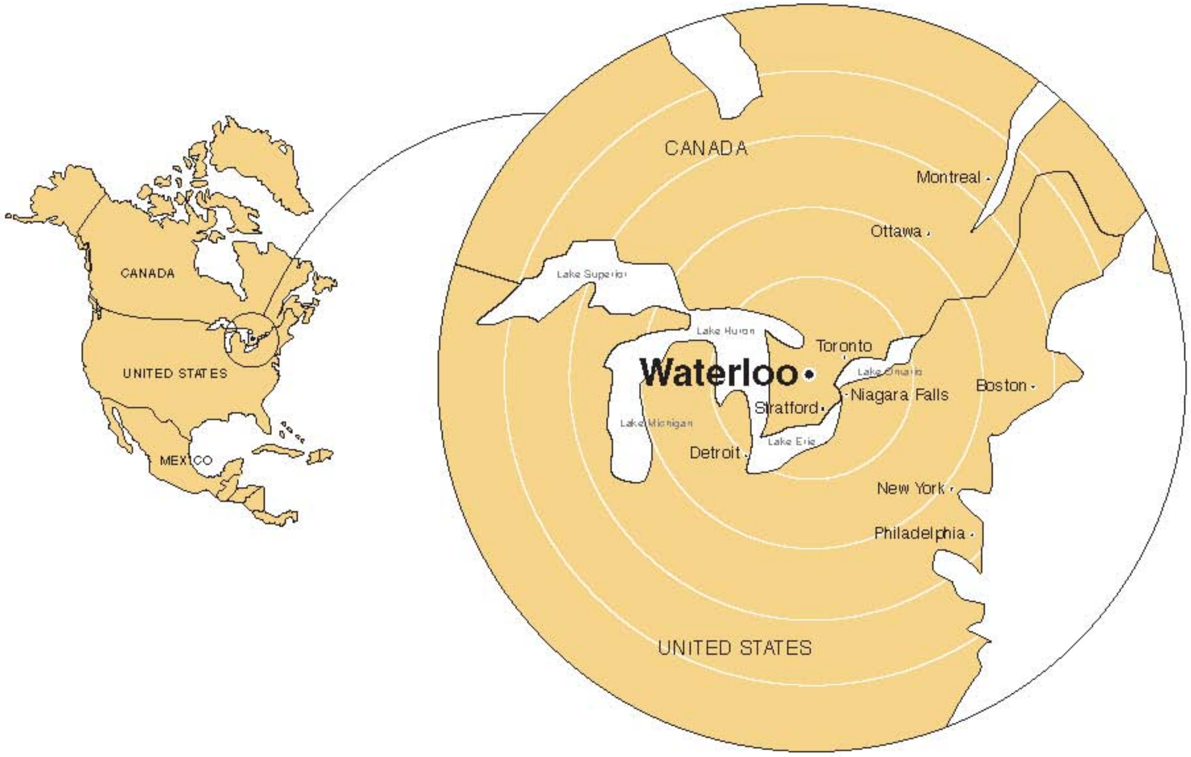
# Outline

- Space Dosimeter Requirements
- Current State-of-the-Art Technologies
  - Passive and Active Detectors

- CNT-based Dosimeter Technology (UW/ARTsensing Inc.)
  - Flexible & Transparent Dosimeter
  - Conformal Dosimeter (Wearable)
  - Experimental Data
- Conclusion

# Where is Waterloo?



# University of Waterloo Quantum-Nanotechnology Centre

Occupancy Date 2010

**$120M Quantum-Nano Centre (250,000 sqft.)**
- 50+ Quantum/Nanotechnology Researchers
- 150+ Quantum/Nano Graduate Students
- 500+ Nanotechnology Engineering Undergrad

**Tri-Cluster Nano Lab**
- NanoFabrication
- NanoMetrology
- NanoBiosystems

# Waterloo Research Park

RIM

ARTsensing

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# Promising Directions Identified at the 6th Canadian Space Exploration Workshop (CSEW6)

- astrobiology
- advanced life support
- Mars atmospheric studies
- operational space medicine
- planetary geology and geophysics
- radiation effects on humans
- solar terrestrial science
- space astronomy
- space life sciences
- space physical sciences

Radiation sensing has been identified to be important area of research in 9 out of 10 disciplines

# Space Dosimeter Requirements

- Low Power
- Small Mass
- Long Lifetime
- Real-time
- Time-resolved
- Sensitive
- Repeatable
- Robust
- Capability to measure all different particles over all energy ranges
- Function over wide dynamic range of dose rates and particle fluxes

# STATE OF THE ART

Passive and Active Detectors

# Passive Detectors

- Advantages: no power consumption, easy to use, safe, wide measuring range, high sensitivity, good stability, robust
- Disadvantages: no real-time and time-resolved data, analysis requires equipment on ground; Environmental effects
- Examples:
  - Thermoluminescent Dosimeter (TLD) and CR-39 Plastic Nuclear Track Detector (PNTD)
  - Pille TLD System
  - Bubble Detector

# Current Technologies

| Radiation Dosimeter | Advantage | Disadvantage |
|---|---|---|
| Film Dosimeter | • Films are self-developing.<br>• Portable | • Qualitative radiation measurement, rather than quantitative.<br>• Non-linear response to radiation dosage.<br>• Film is temperature and ultraviolet light sensitive |
| TLD | • Available in a wide range of materials, sizes and shapes.<br>• Easy to use. | • Sensitive to environmental conditions, handling procedures and heating conditions.<br>• Repeated use diminishes accuracy.<br>• Post radiation dose readout, TLD can no longer be used.<br>• Real-time and dose rate measurements not possible. |
| Plastic Nuclear Track Detectors (PDNTs) | • Light weight<br>• Accurate | • Passive<br>• Non re-useable |

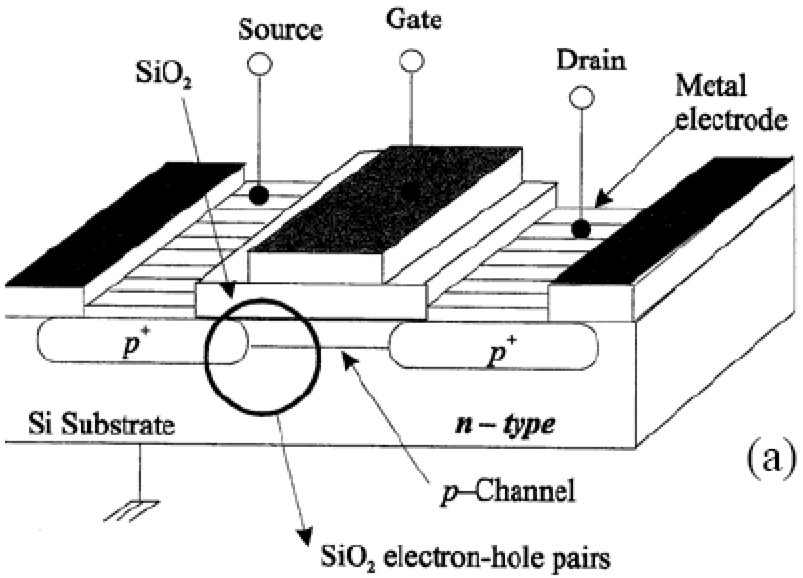
# Active Detectors

- Advantages: real time and time-resolved data
- Disadvantages: requires power consumption and data storage
- Examples:
  - Tissue Equivalent Proportional Counter (TEPC)
  - Silicon-Based Telescope Spectrometer
  - MOSFET

# Current Technologies

| Radiation Dosimeter | Advantage | Disadvantage |
|---|---|---|
| Ionization Chamber | • Accurate absorbed dose measurement, current gold standard. | • Requires high bias voltage (> 300V), increasing potential damage to patient and limiting portability of device.<br>• Large physical size with low spatial resolution<br>• Are not used for *in vivo* dosimetry. |
| Semiconducting Dosimeter | • Small physical size.<br>• Portable and can be placed on or within a patient.<br>• Provide real-time feedback | • Non-linear radiation dose response.<br>• Temperature and environmental dependent.<br>• Limited life span |

# Current Technologies



MOSFET detectors

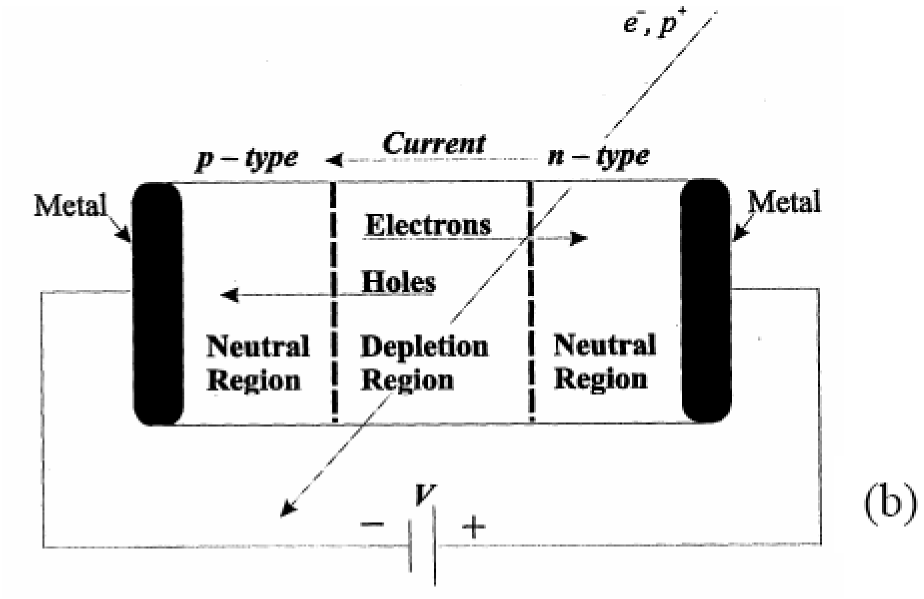


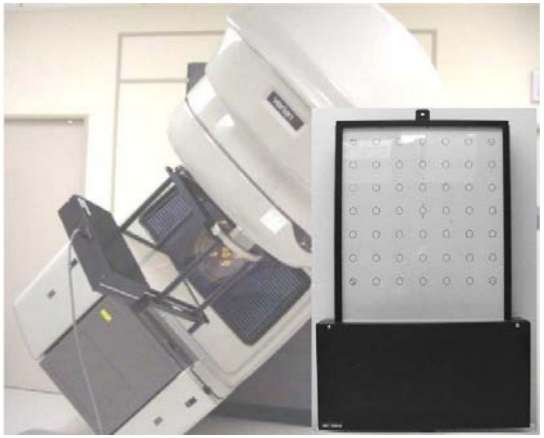
Photo-diodes

The absorbed dose measurement is based on MOSFET detectors, while the dose rate is determined with Hamamatsu photo-diodes. This device has an overall dimension of 12 cm × 12 cm × 6 cm and a mass of 2.7 kg (including the battery). The absorbed dose and absorbed dose rate resolution for the instrument is 0.4 mGy and 0.01 mGy $h^{-1}$, respectively, with a maximum absorbed dose capability of 2.8 Gy. The 0.3-W battery provides continuous operation for 28 d, while the 4-MB memory can store data for up to 41 d.

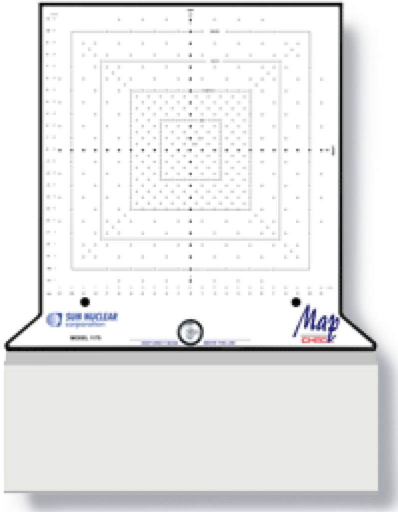
# Medical Radiation Dosimetry

- **Types of Dosimeters**

Ionization chambers, thermoluminescence dosimeters (TLDs), radiographic films, and semiconducting silicon diodes and metal-oxide-semiconductor field effect transistor (MOSFET) dosimeters



Array of Ion Chambers



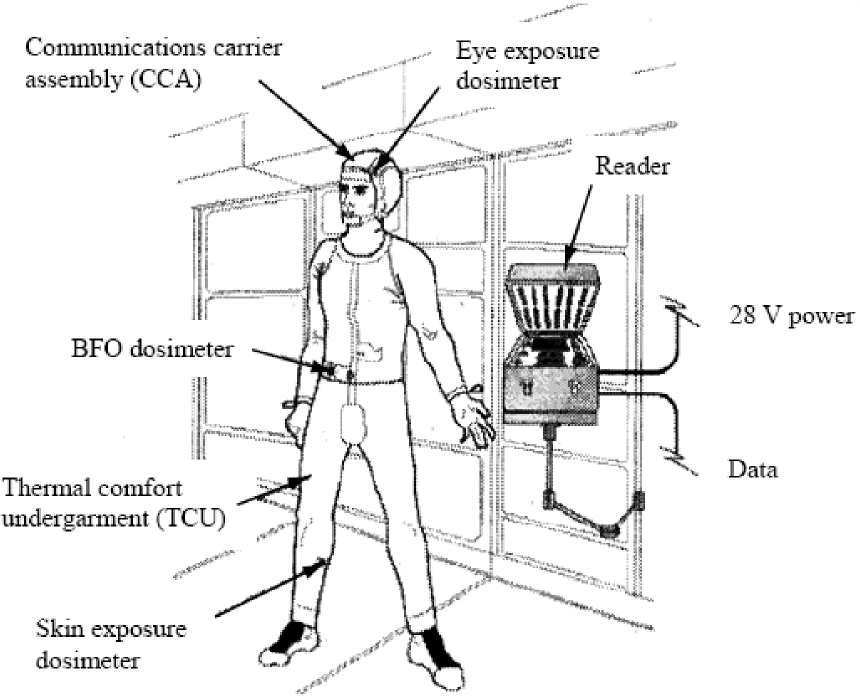
Sun Nuclear Corp. Profiler

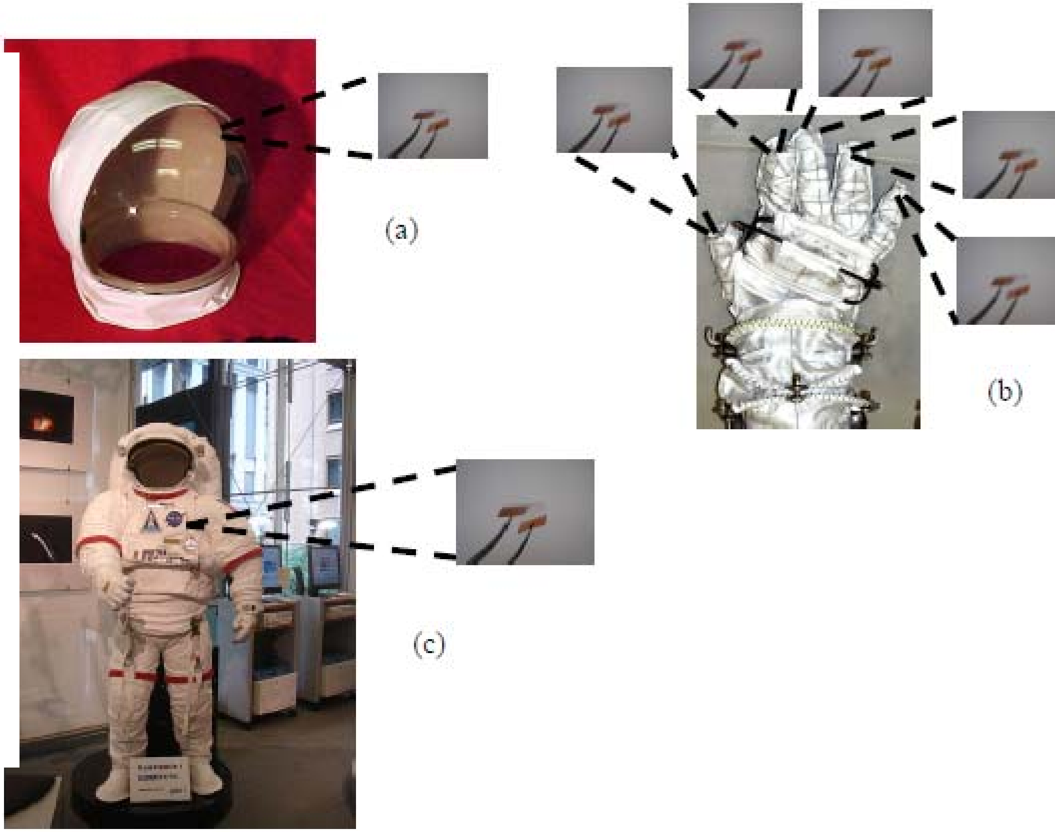
Sicel Technologies dosimeter

Problems:

1. High voltage, limited lifetime, bulky, large mass, non-conformal;
2. Do not provide real-time monitoring of the delivered dose.

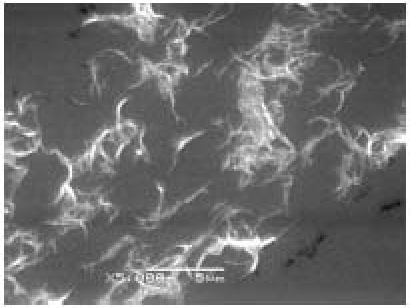
# Proposed Technology



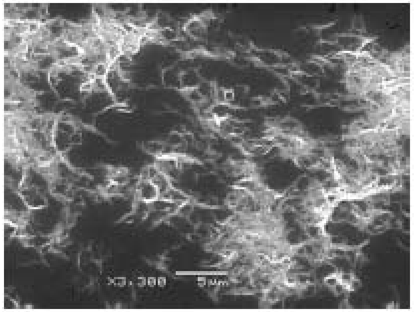


I. Thomson, "International Space Station Experiment E011, Study of Radiation Doses Experienced by Astronauts in EVA," presentation to NASA, 1999.

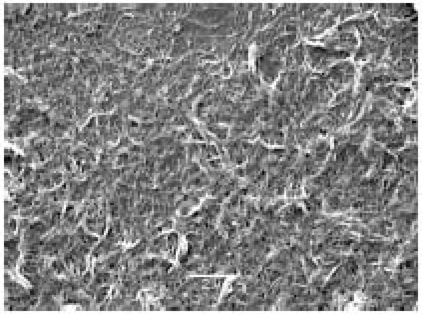
# SWCNT film fabrication



(a)



(b)



(c)

Material:

CNT: **ARC-discharge**

Semiconducting Single-Walled Carbon Nanotubes (SWNTs) 1 mg /100ml. Diameter Range: 1.2nm-1.7nm, Length Range 300nm to 5 μm.

Substrate:
75mm*25mm Glass slide

# Thin-Film Preparation

1. Dilute 1mL CNT solution in 9mL DI water. This will make about 10mL of 1ug/mL solution.

2. Pass diluted CNT solution through an MCE (Mixed Cellulose Esters) filter (pore size 50nm, 25mm diameter) using a vacuum filtration apparatus, A thin-film of nanotubes will accumulate on the filter's surface. (Surfactant and water will pass through the filter; nanotubes will not.)

3. Once the desired volume of CNT solution has been filtered, allow the resulting CNT film to set for approximately 15 minutes.

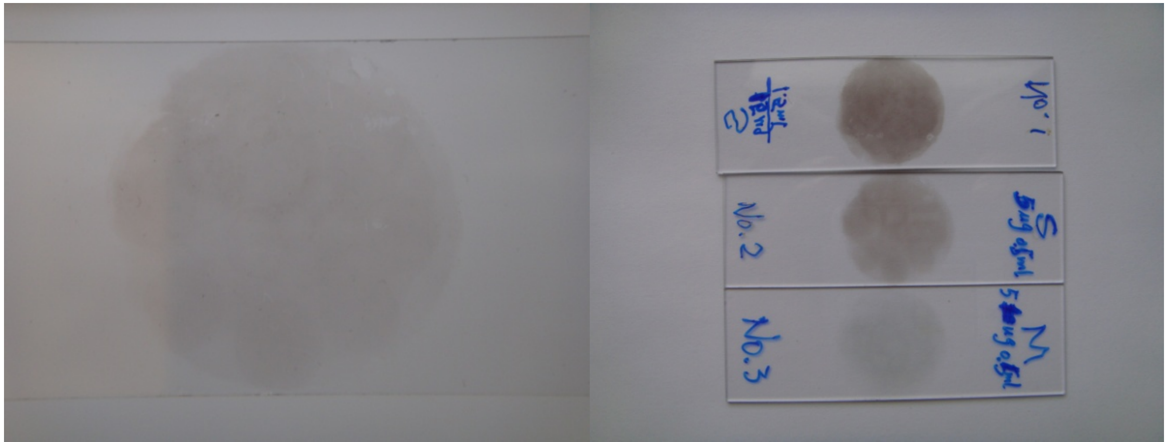
4. Gently rinse the film with about 1 mL of 2-propanol.

5. Gently rinse the film with ~30 mL of water.
Allow the film to set again for approximately 15 minutes.

6. Gently rinse the film with about 30 mL of DI water.
Allow the film to set again for approximately 15 minutes.

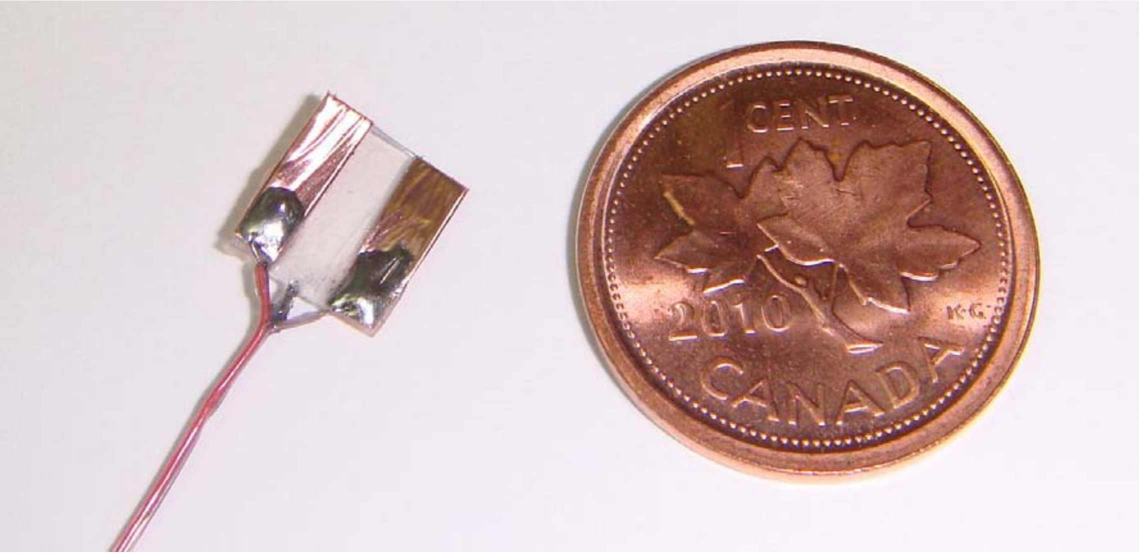
# Thin-Film Transfer to Substrate

1. Briefly dip the nanotube-coated MCE filter in ethanol, then press the filter film-side-down against the glass substrate at center using gentle pressure.
2. Immediately suspend the substrate filter-side up horizontally over a bath of boiling acetone . The acetone vapors will gradually dissolve the MCE filter. Wait for about 1 hour until the MCE filter is no longer visible.
3. Place the substrate in a stirred bath of liquid acetone for 15 minutes to remove the remaining MCE residue.
4. Immediately transfer the substrate to a stirred bath of methanol for an additional 15 minutes.
5. Dry the CNT film in air for 10 minutes.
6. Bake for 1-2 hours at 250$^{o}$C in air.

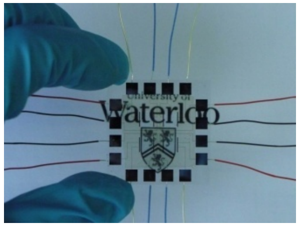


The finished transparent CNT film should have thickness of less than 10nm depending on how much volum of diluted CNT solution is filtered.

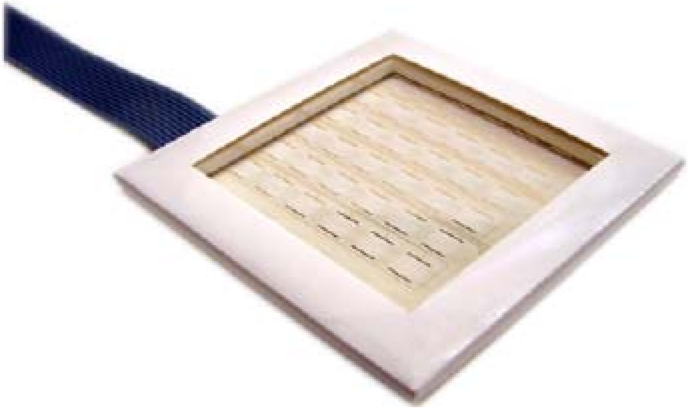
# Radiation Dosimeter

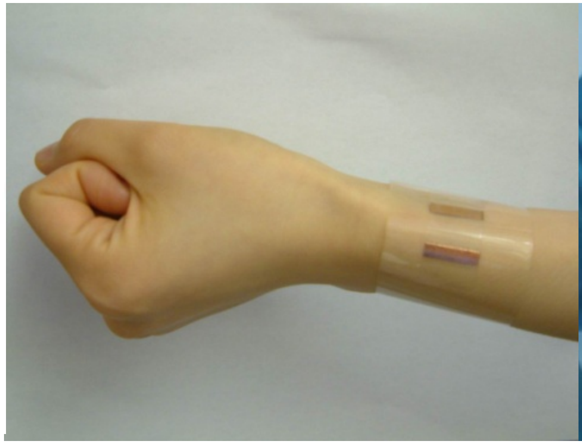


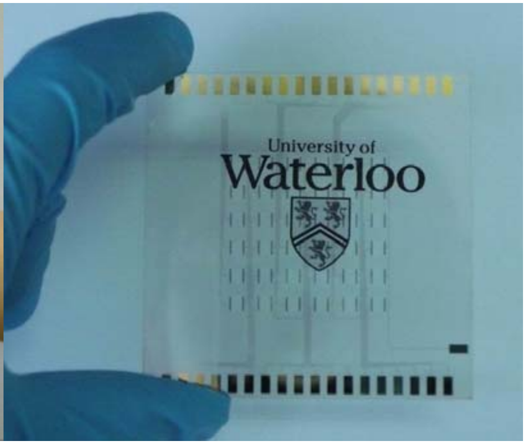
Flexible



Transparent







# System Test

| | Dose rate measurements | Dose measurements | Field size measurements |
|---|---|---|---|
| X-ray beam energies (MV) | 6, 15 | 6 | 6, 15 |
| SSD (cm) | 100 | 100 | 100 |
| Doses (MU) | 100 | Vary from 100 to 600 | 100 |
| Dose rates (MU/min) | Vary from 100 to 600 | 600 | 600 |
| Field sizes (cm$^2$) | 1 × 1, 1.8 × 1.8 | 1.8 × 1.8 | Vary from 0.5 × 0.5 to 1.8 × 1.8 |
| Bias voltage (V) | 10 | 10 | 10 |

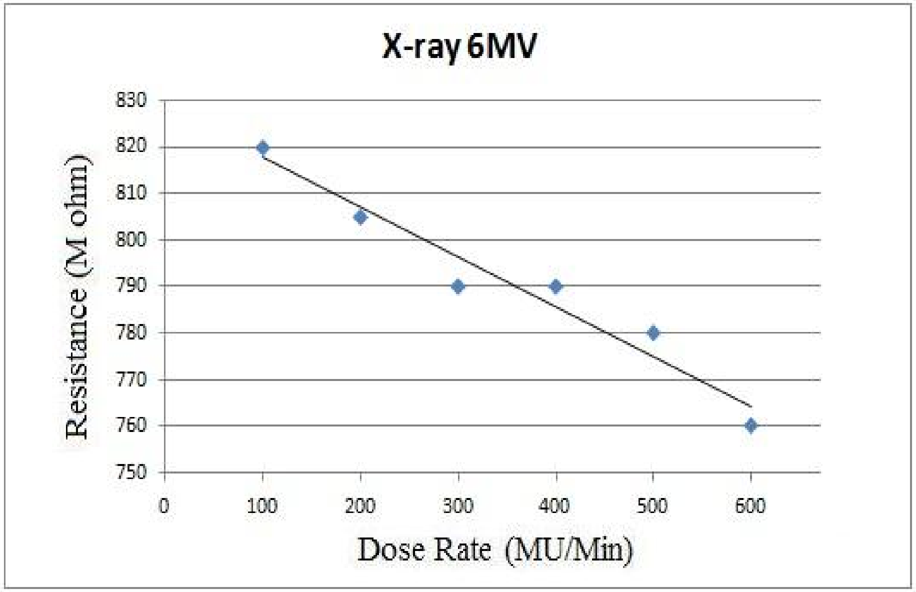
Varian Clinac 21 EX medical linear accelerator

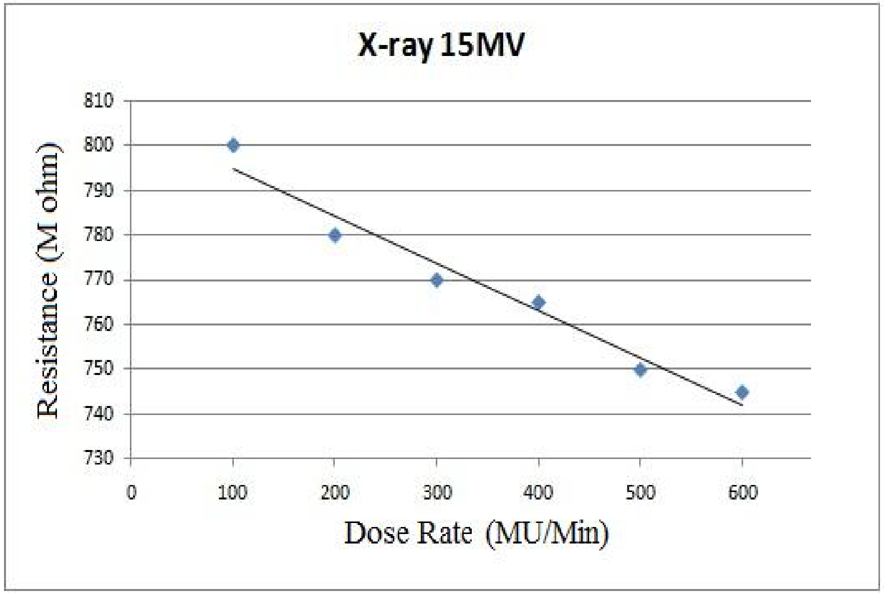
# System Test

Sample was put on a 10cm solid water and data from the electrometer is recorded by a laptop computer

Experiments are monitored through video camera

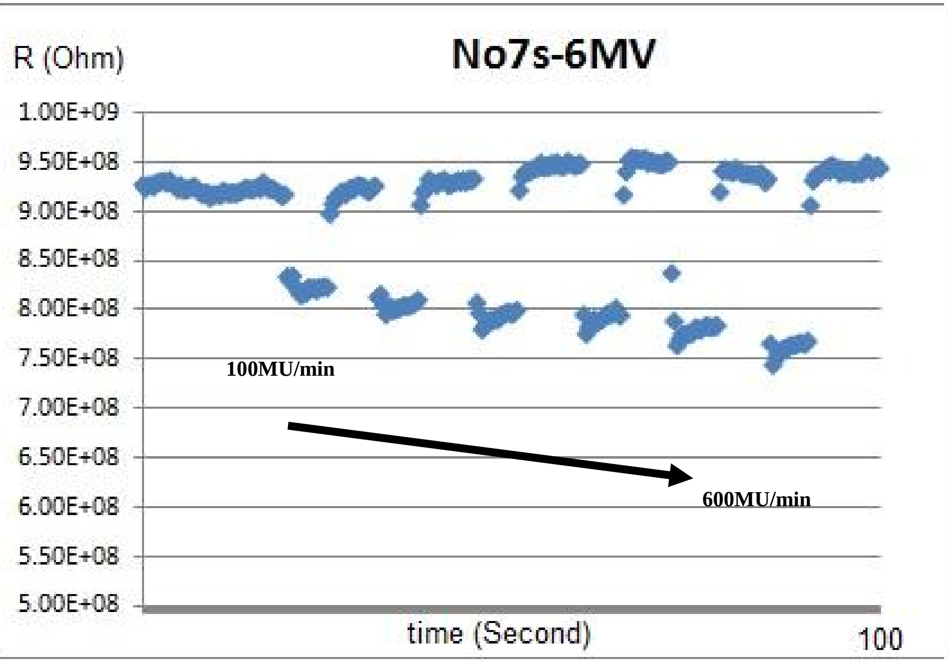
# System Test





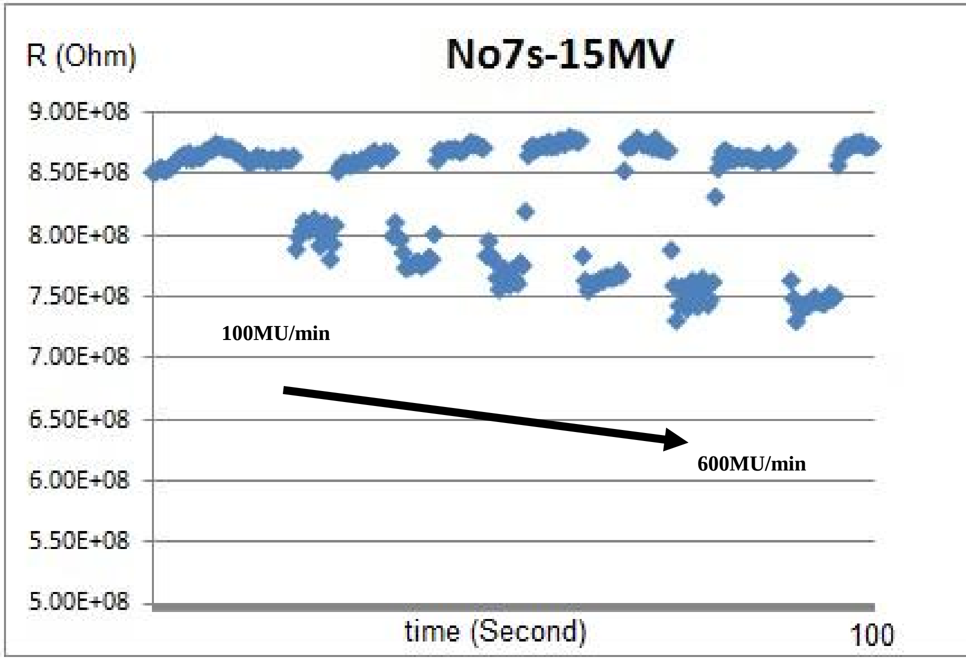
A **monitor unit** (**MU**) is a measure of machine output of a linear accelerator in radiation therapy.
Linear accelerators are calibrated for a specific energy such that 1 MU gives an absorbed dose of 1 cGy (or rad) at a depth of $D_{max}$ (or maximum dose) for a field size of 10x10 cm for a source-to-axis distance (SAD) of 100 cm. Some linear accelerators are calibrated using source-to-skin distance (SSD) instead of SAD. Monitor unit can be different for different sites.

# System Test


No7s-6MV

100MU/min

600MU/min


No7s-15MV

100MU/min

600MU/min

J. Ma, J.T.W. Yeow, J.C.L. Chow, R.B. Barnett, *Carbon*, vol. 46, no. 14, pp. 1869-1873, 2008
X. Gao, Q.S. Kang, J.T.W. Yeow, R.B. Barnett, *Nanotechnology,* 21, 285502, 2010
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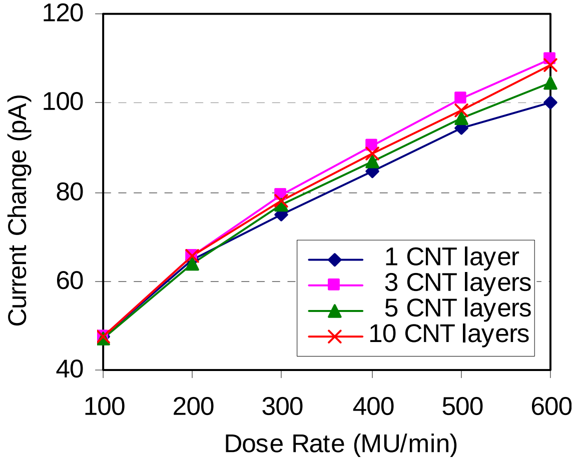
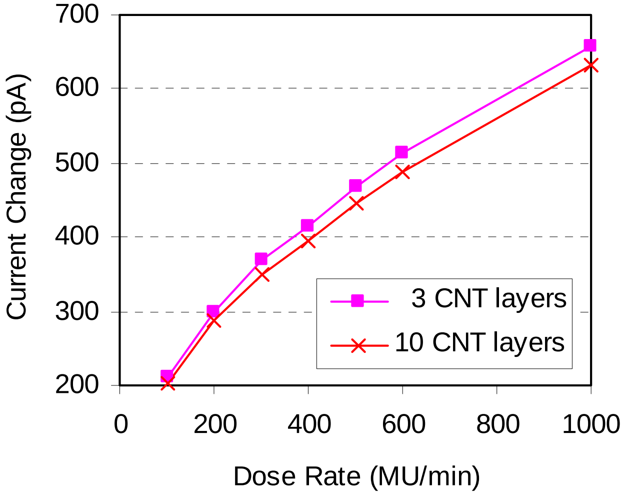
J. Ma, J.T.W. Yeow, J.C.L. Chow, R.B. Barnett, *7th IEEE Conference on Sensors*, Lecce, Italy, October 26-29, 2008.
J. Ma, J.T.W. Yeow, J.C.L. Chow, R.B. Barnett, *50th AAPM Annual Meeting*, Houston, Texas, USA, 2008.
J. Ma, J.T.W. Yeow, J.C.L. Chow, R.B. Barnett, *Proc. 8th IEEE Conference on Nanotechnology*, Arlington, Texas, USA, 2008.

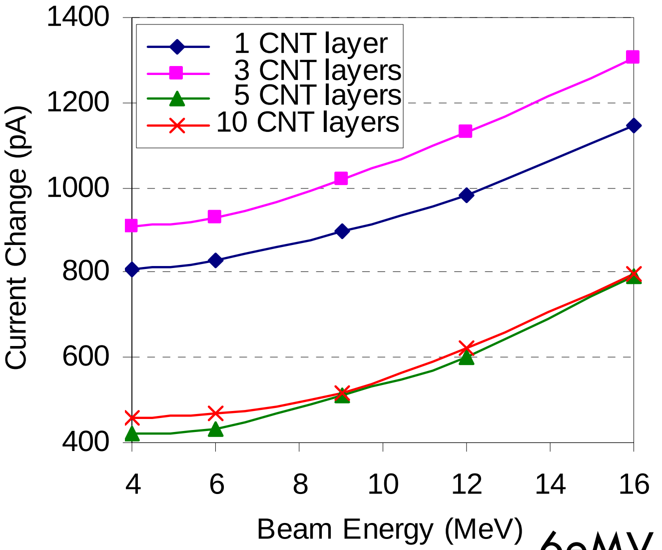
# System Test

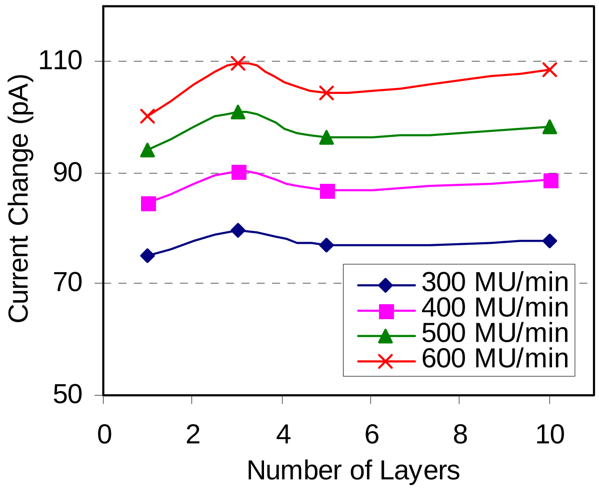
6MV

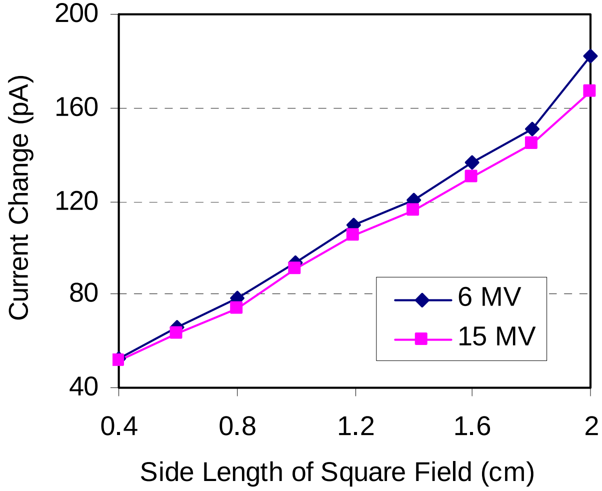


4eMV

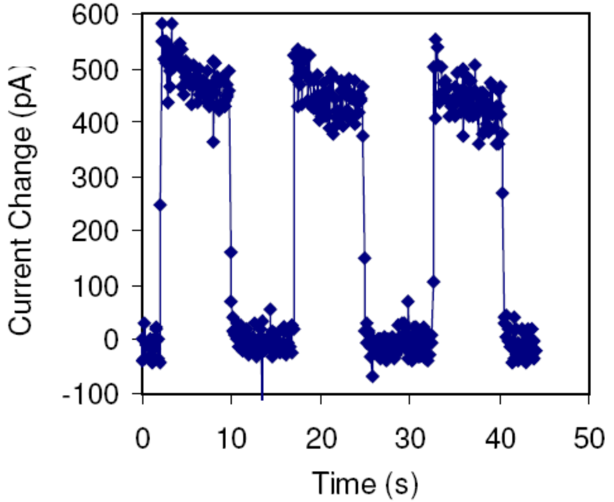






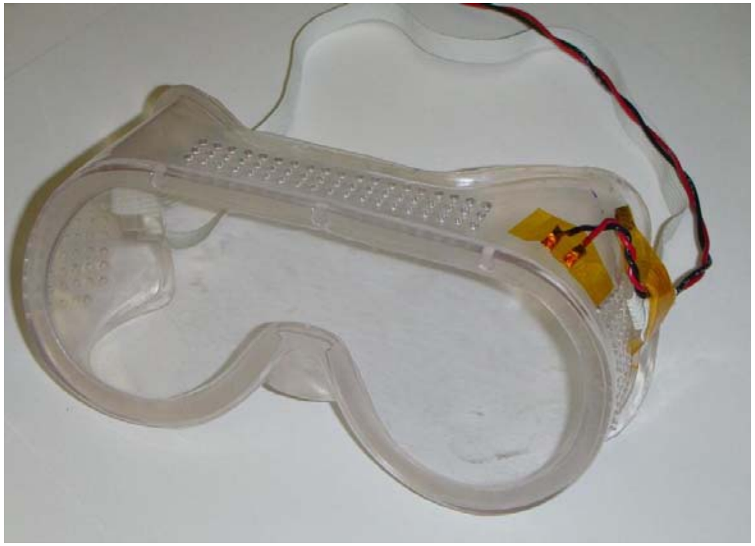


6eMV



# Wearable Sensors

Radiation sensors are integrated onto a space glove



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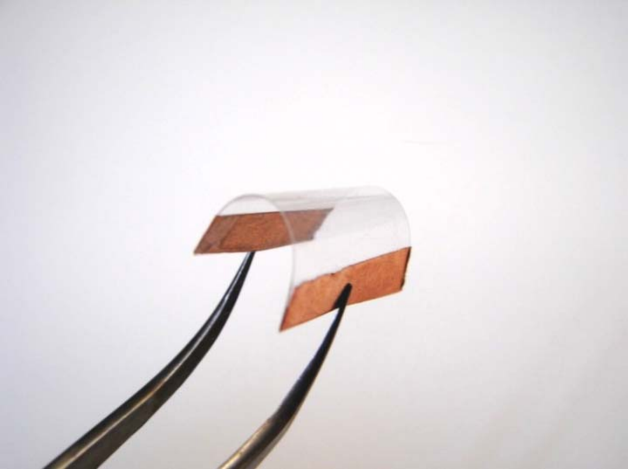

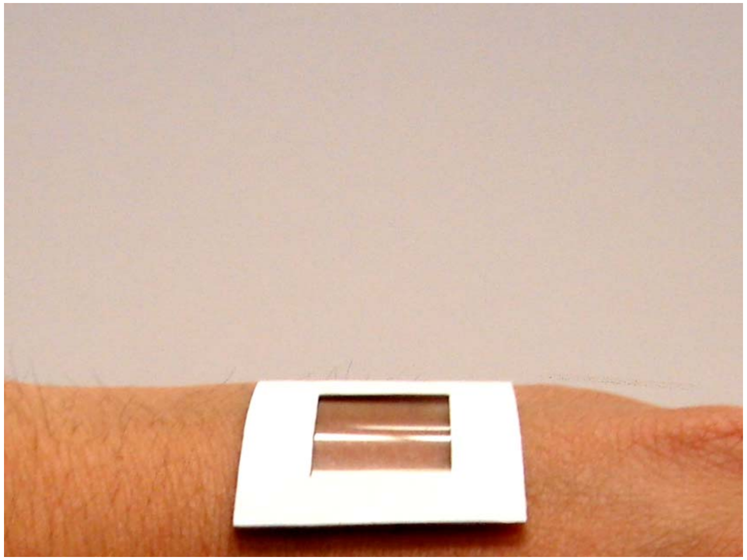

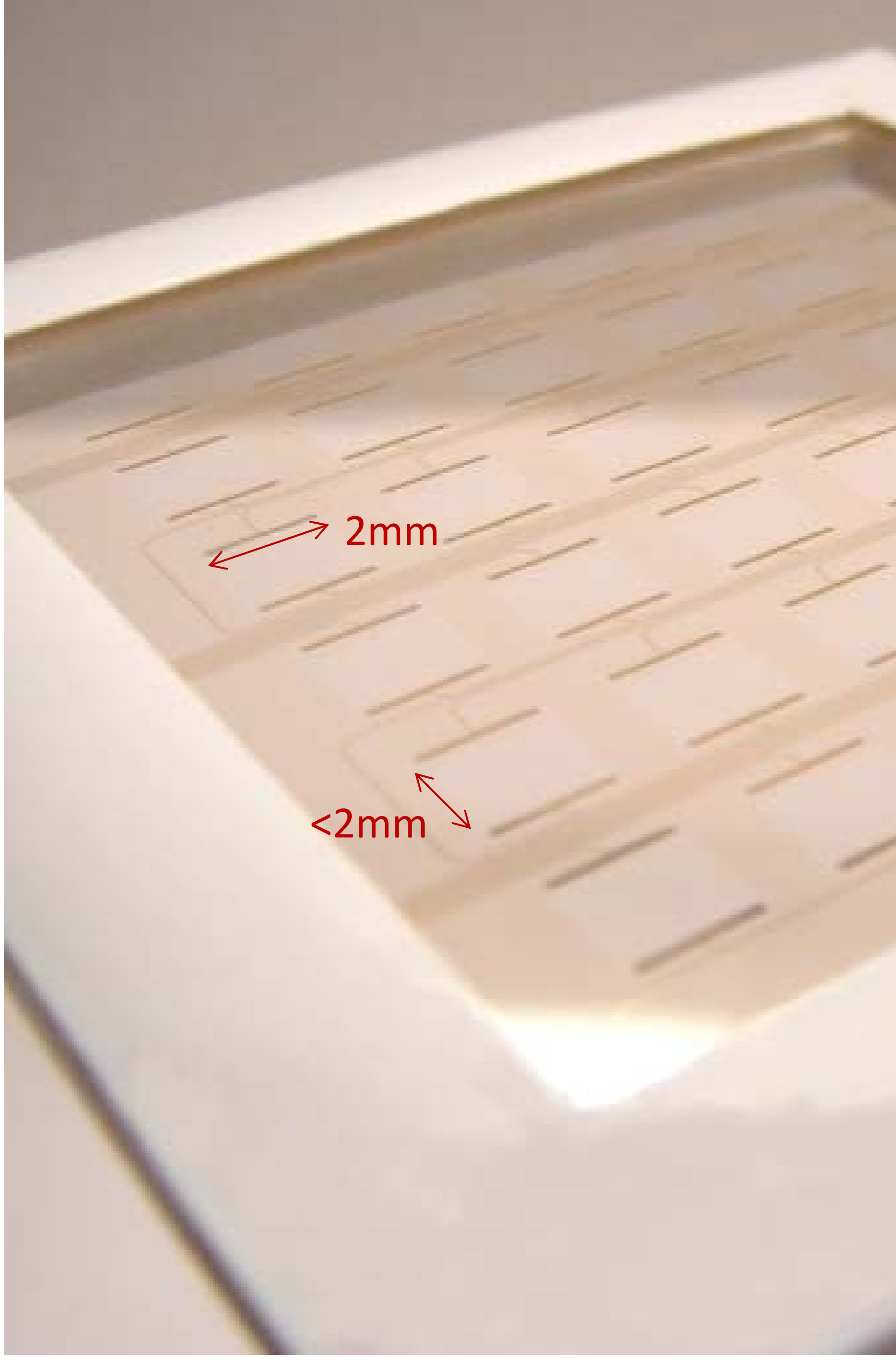

ARTsensing are the pioneers in radiation detection technology

# Conclusion

- Ultra Light Weight Radiation Dosimeter is demonstrate
- Real-Time and Long Lifetime
- Able to be integrated onto Space Garment to Monitor Radiation Exposure in Real-Time
- Able to Conformal to Electronic Packaging to Monitor Single-Event Upset