High-Flux CdZnTe detectors: Spectral Computed Tomography and Beyond

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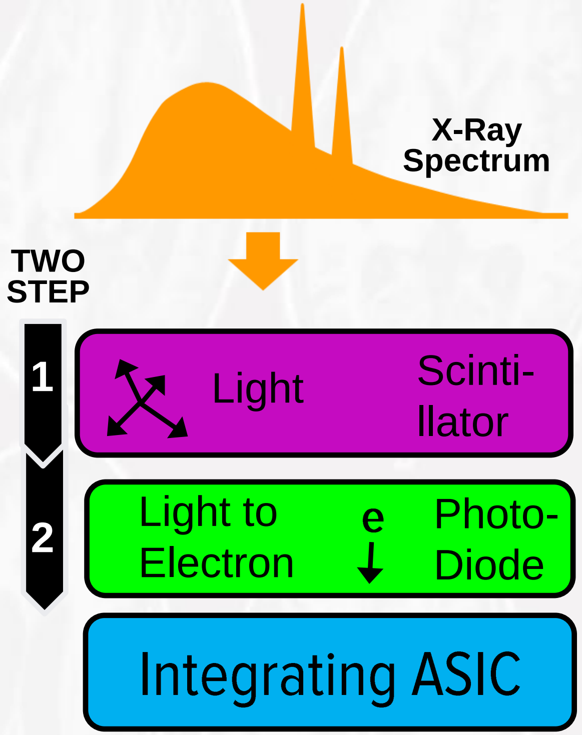
Outline

- CdZnTe Technology
- CdZnTe vs CdTe
- Redlen Company
- Detector Module Implementation
- Spectral CT Clinical Applications
- Spectral CT Research at UViC
- Beyond Spectral CT
- Summary and Outlook

CdZnTe Technology

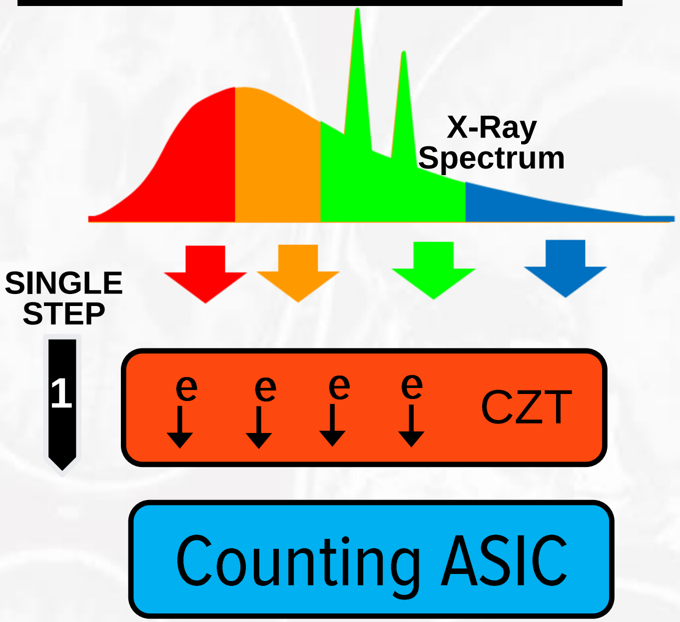
CZT’s Value Proposition for X-Ray Imaging

Scintillator



Scintillator Integrating Detector

CZT



Photon Counting Direct Conversion Detector

CZT Benefits

1. Small Pixels = Better Image Resolution
2. Better Efficiency = Up to 80% Less radiation
3. Energy Bins = Materials Identification
4. Energy Bins = More Data / Photon! (10x)
5. More Data = Better AI performance

CZT Semiconductor Sensors

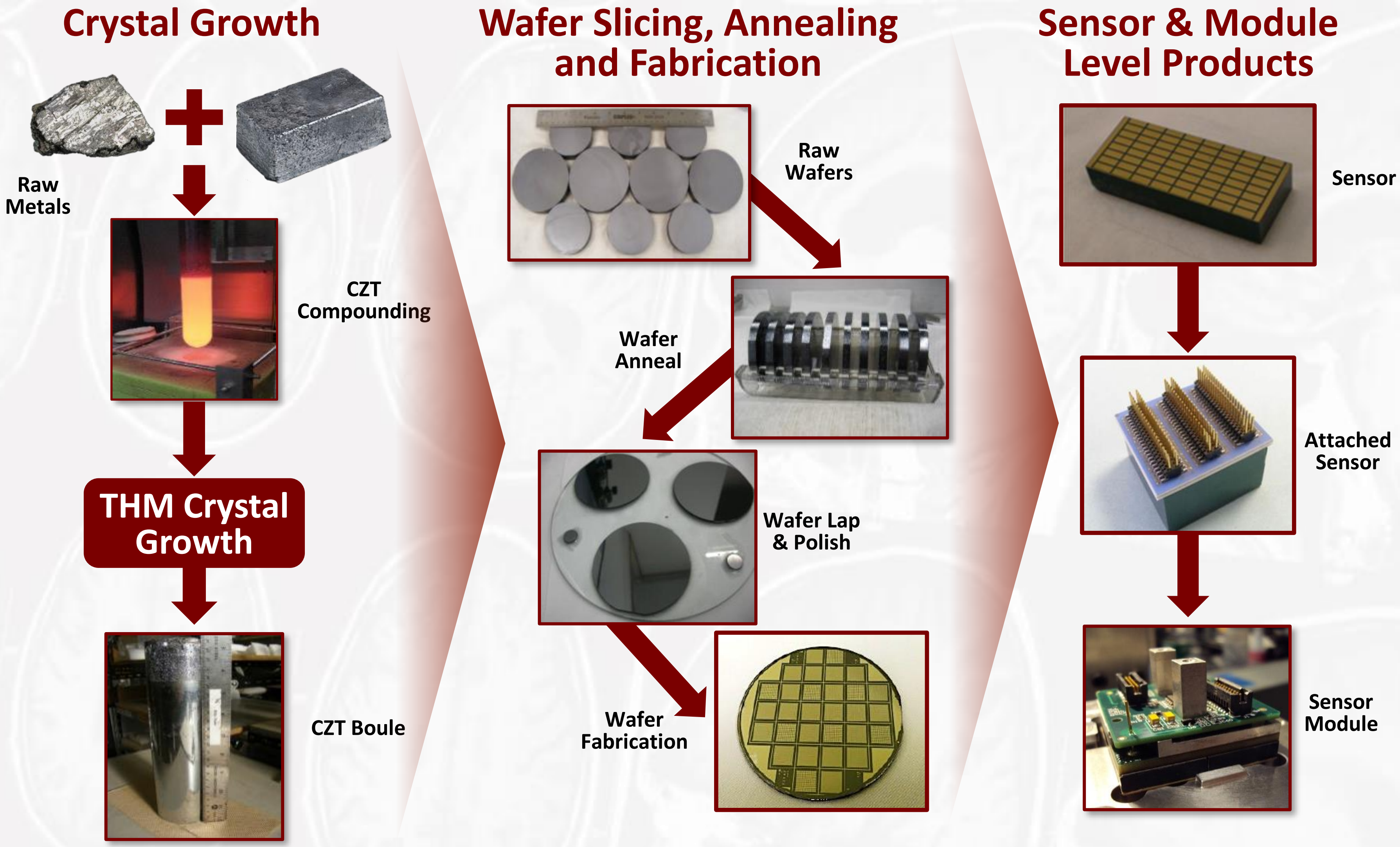
- Cadmium Zinc Telluride (CZT)
  - Optimal X-ray and Gamma ray detection material
  - High resolution / High sensitivity / Low radiation dose
- Historical CZT production used “off the shelf” solutions
  - Poor yields/inconsistent quality
- Only Redlen solves the CZT high-flux problem
  - 20 years of R&D, proprietary CZT “Traveling Heater Method “ (THM) growth process
  - High yields, consistent quality, volume production
- Two process recipes
  - Low-flux process (5 to 15 mm thickness, spectroscopic applications) optimized for electron transport
  - High-flux process (2 to 2.5 mm thickness, photon counting applications), optimized for balanced electron and hole transport

CZT Boule

CZT Sensor Wafer

CZT Sensor Module

CZT Manufacturing Process



CdZnTe Applications

Photon Counting CT

NM Cardio

SPECT / CT

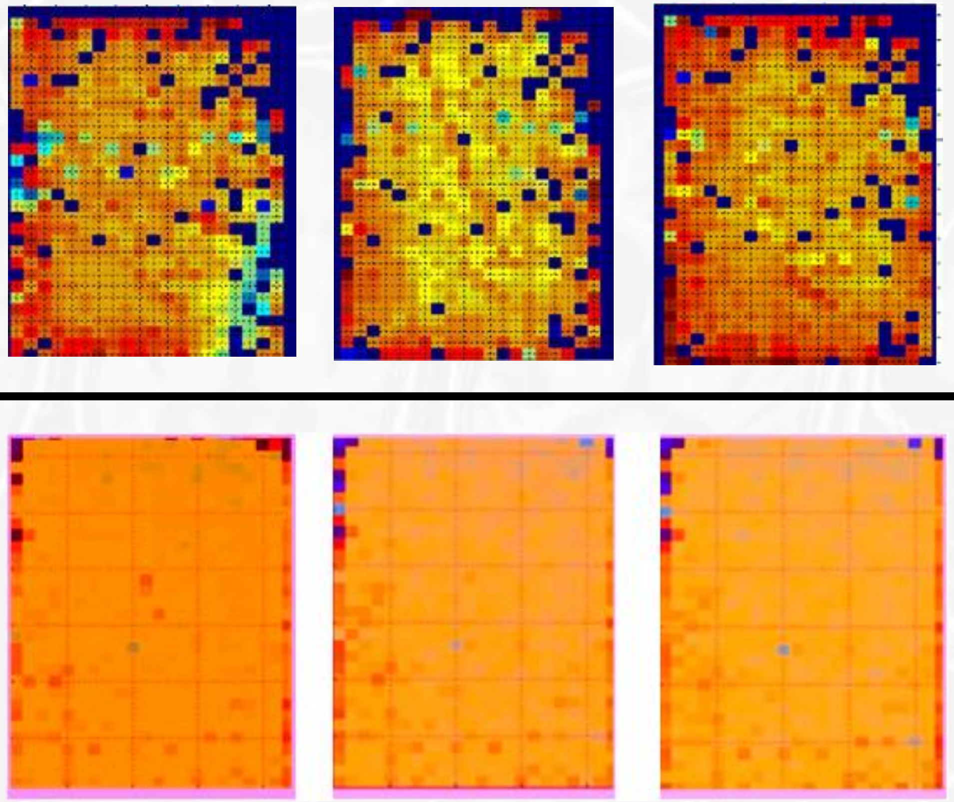
Baggage Scanner

Radiation ID

Infra-Red

CdZnTe High Flux Performance

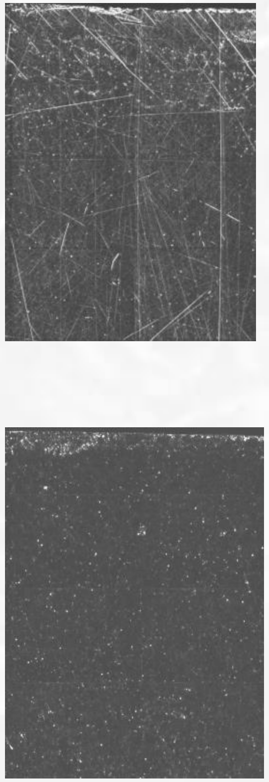
X-ray Count Maps



Using previous processes

Using new processes

Surface microscopic images

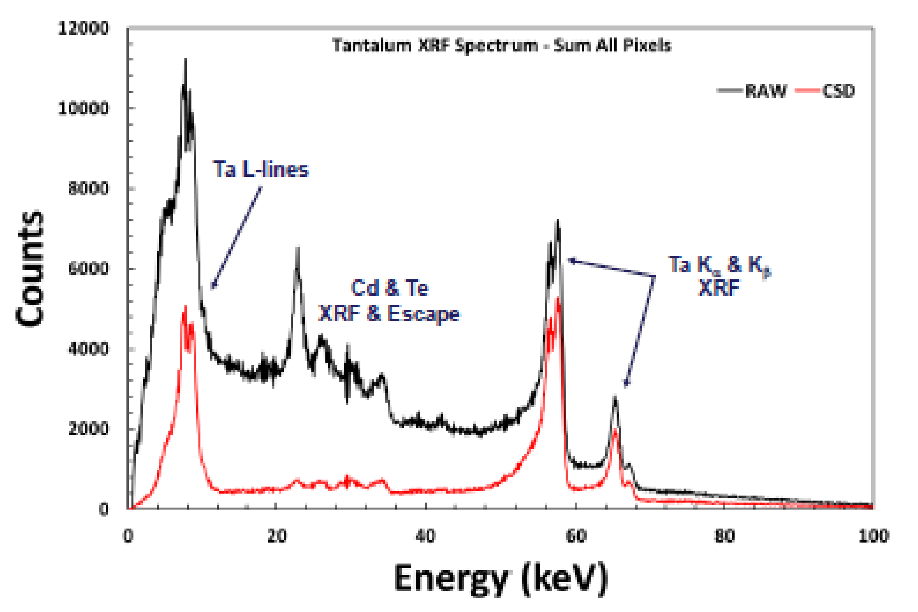


- Over **600 Mcps/mm^2** performance achieved
- New processes reduce stress during growth and significantly **improve count uniformity**.
- Edge pixel problems largely solved
- Achieved **2-3 x higher yields** – resulting in lower costs

CdZnTe Characterization at 1MHz

- Check out this poster at the conference

Property	HEXITEC	$HEXITEC_{MHz}$
Array Size	80×80	80×80
Pixel Pitch (µm)	250	250
Frame Rate (kHz)	10	1000
Max Flux (ph s^{-1} mm^{-2})	10^4	10^6 (Spectroscopic) 10^7 (Imaging)
Architecture	Peak-track-and-hold	Integrating
Output	Analogue	Digital
Data Rates (GB s^{-1})	0.1	10



UKRI Science and Technology Facilities Council

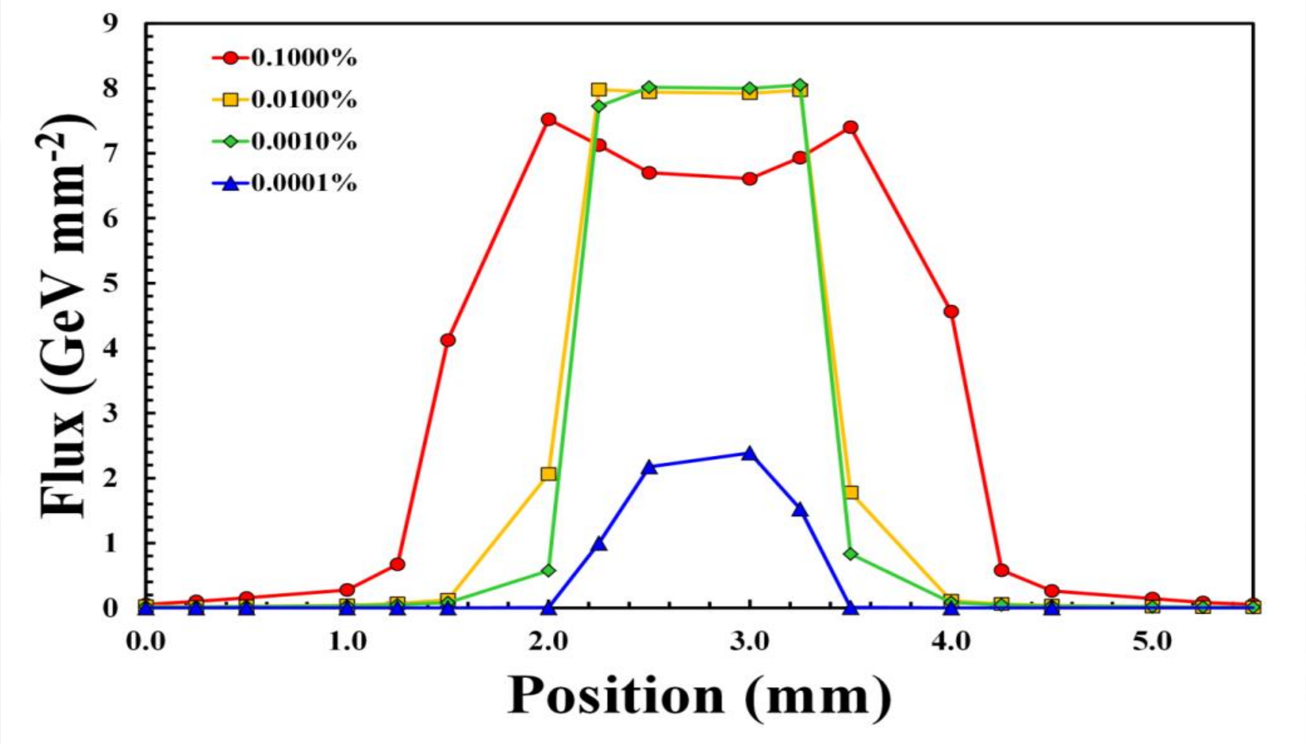
Technology

technologysi.stfc.ac.uk

Spectroscopic Imaging of Hard X-rays for Material Science Applications

M. C. Veale[1*], B. D. Cline[1], I. Church[1], S. Cross[1], C. Day[1], M. French[1], T. Gardiner[1], J. Holden[1], L. L. Jones[1], J. Lipp[1], T. Nicholls[1], M. Prydderch[1], J. Nobes[1], M. Roberts[1], A. Schneider[1], P.Seller[1], D. Sole[1], R. M. Wheater[1], M. D. Wilson[1], F. Van Assche[2], M. N. Boone[2], S. Collins[3], T. Connoley[3], O. Magdysyuk[3], C. Huang[4], E. Liotti[5], A. Lui[5], K. Suzuki[6] & H. Sakurai[6]

CdZnTe detectors at a Free Electron Laser



- Measurements successfully demonstrated the linear response of the CdZnTe detectors to increasing numbers of X-rays up to a flux of 8 GeV mm-2 per 120fF pulse, the limit of the dynamic range of the LPD ASIC
  - instantaneous flux it would be 10^13 Gcps/mm2

M C Veale https://orcid.org/0000-0001-5457-4884

- M. C. Veale et al, “Cadmium Zinc Telluride Pixel Detectors for High-Intensity X-Ray Imaging at Free Electron Lasers”`

CZT vs CdTe Comparison

CdZnTe vs CdTe Summary

- High stopping power of CdTe/CdZnTe has been known for over 50 years
  - But commercial applications have only emerged over last several years
- CdTe was first material to be used as it is simpler to grow
  - BUT CdZnTe followed few years later and the overall CdZnTe market size is now significantly larger
- CdTe is produced by Acrorad (Japan)
  - acquired by Siemens (Germany) in 2011
- CdZnTe is produced by multiple companies:
  - Redlen Technologies (Canada), acquired by Canon (Japan) in 2021
  - eV Products/Kromek (US/UK), OMS/GE (Israel/US), Imdetek (China)
- Major material differences:
  - CdTe sensors easier to fabricate (less brittle, better edge pixels) but inferior to CdZnTe in high count performance
  - CdTe polarizes more quickly, limitation in high-flux performance, reliability and stability, needs to pulse HV bias
  - CdZnTe achieves 10x higher count rates and is thicker leading to higher DQE

CZT vs CdTe Material Properties (1)

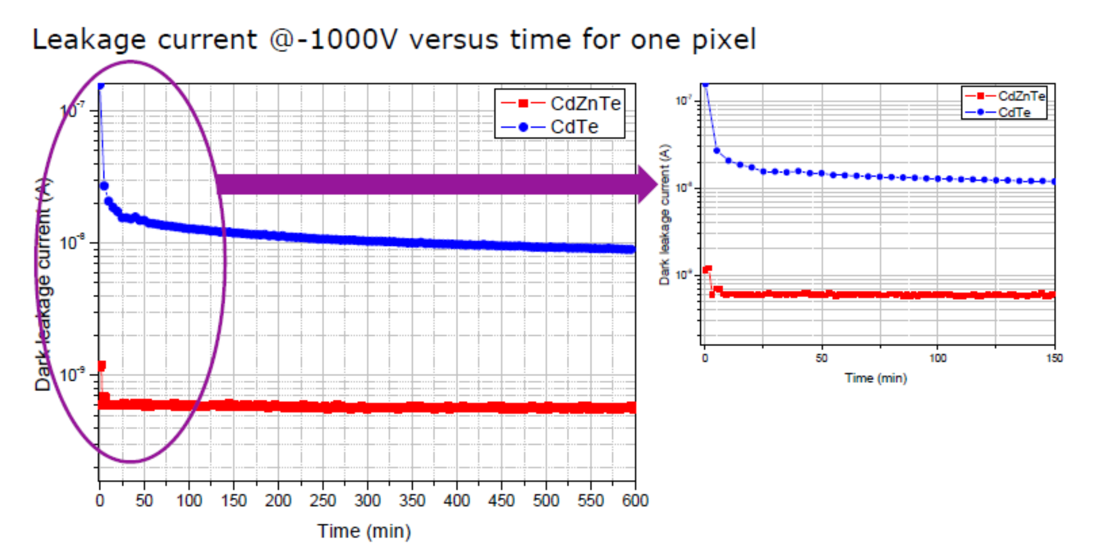
- History
  - CdTe was developed first, CZT followed once advantages of adding Zn became apparent. Currently 5 companies are providing or developing CZT (but only 1 high-flux CZT) and only 1 company provides CdTe. Most CT OEMs use CZT, but 1 uses CdTe (Siemens) and 1 uses silicon (GE)
- CZT has larger energy bandgap
  - Band gap increases from 1.5 eV (CdTe) to 1.6 eV (CZT). The wider band gap enables a higher maximum resistivity from 2×10^{10} Ω-cm to 5×10^{10} Ω-cm. Maximum resistivity is not always achieved in practice because of incomplete electrical compensation (Acrorad operates at 10^8 Ω-cm to 10^9 Ω-cm range)
- CZT has lower leakage (dark) currents
  - Leakage current of CZT sensors is typically an order of magnitude lower than that of CdTe due to resistivity difference. Lower leakage ultimately improves SNR.
- CZT has less polarization, and performs at higher flux levels
  - CdTe material polarizes more quickly and requires frequent refreshing (HV reversal). Schottky contacts limit hole transport out of sensors.
- CZT has better radiation hardness and soft-error rates
  - 2x improvement over CdTe

CZT vs CdTe Material Properties (2)

- CZT less dislocations but more brittle
  - ZnTe has a higher binding energy than CdTe. Thus, the CdTe lattice is strengthened by the incorporation of Zn, leading to an increase of the shear modulus and solution hardening of the ternary compound
  - Alloying CdTe with Zn reduces the dislocation multiplication during post growth cooling, reduces the propensity for plastic deformation and the formation of dislocations; however, it also reduces dislocation motion and makes the ternary compound more brittle than CdTe.
- CZT thicker sensors
  - In high-flux applications (spectral CT) CZT uses 2mm thickness (typ) and CdTe uses 1.6mm (maximum)
  - In low-flux applications (security, Nuclear Medicine) CZT thickness is in 5-15mm range; CdTe is not used
- CZT better long-term stability
  - The higher binding energy and shorter bond length between Zn and Te atoms also induces a local strain into the host CdTe lattice and a relaxation of the Te atoms around the Zn atom. The local lattice distortions increase the migration barrier of interstitial atoms in the proximity of Zn atoms. As a result, diffusion and ionic migration rates are reduced in CZT compared to CdTe.

Stability assessment by DeeTee (1)

- Leakage current stability
  - CZT leakage 100x smaller
  - CZT leakage much more stable. CdTe current drops by 10x after HV on, continues to drift for 10 hours
- Detection Technology Plc (DeeTee) Press Release 19 December 2018
  - Detection Technology Plc acquires the business of the French technology company MultiX S.A.



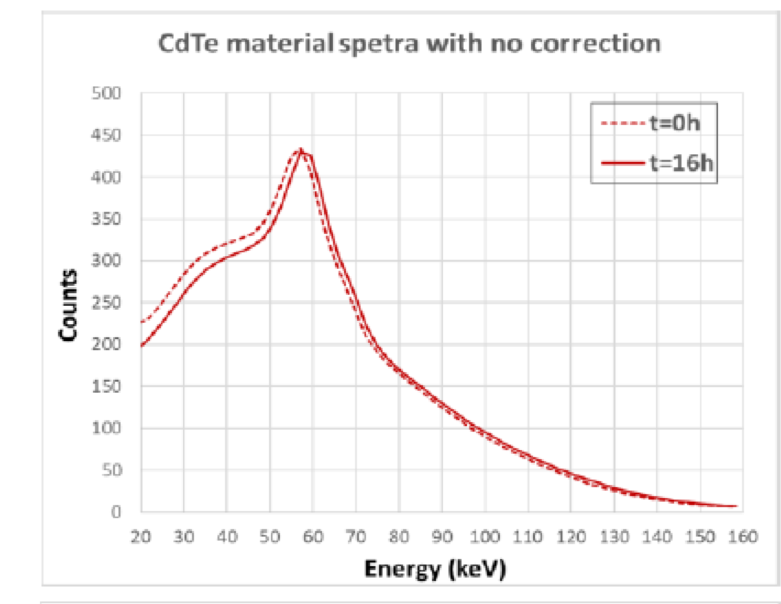
For five CdTe & CdZnTe tested sensors with 128 pixels each the :

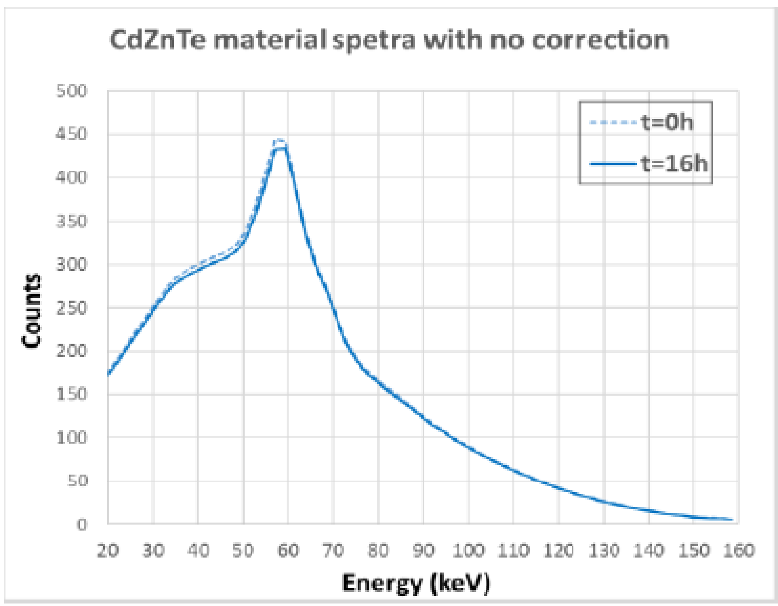
- CdTe : One decade decrease of the dark leakage current was observed after switching ON the bias voltage, followed by a continuous slow slope over 10 hours.
- CdZnTe a small decrease is observed, within 5 minutes, followed by almost stable leakage current
- ~2 decades of difference between CdTe and CdZnTe

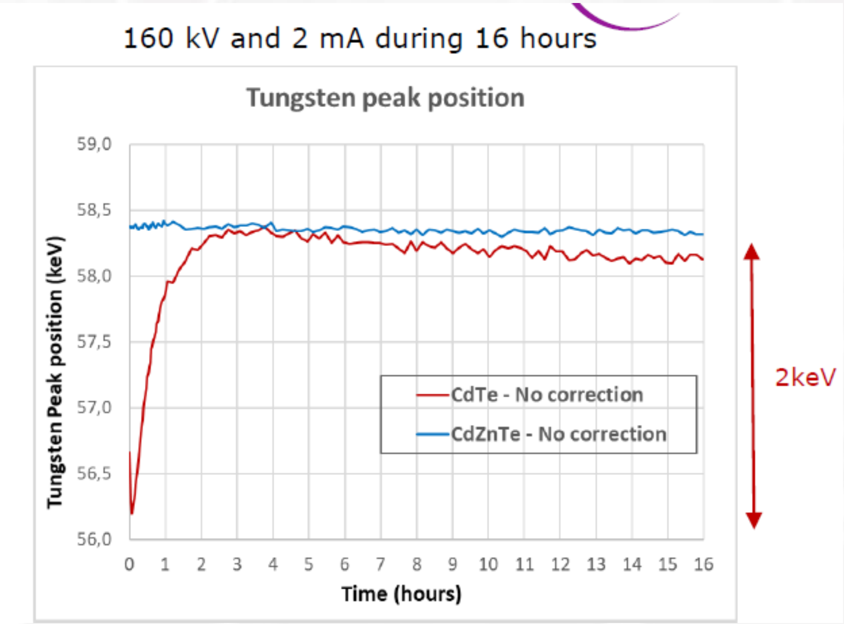
- Mohamed Ayoub, Éric Marché, Bruno Favrel, Patrick Radisson, Alexander Winkler, **Study of the performance stability of CdTe and CdZnTe materials at various fluence rates**, IEEE-RTSD 2020 | October 31th, 2020

Stability assessment by DeeTee (2)

- Spectral stability
  - CdTe peak shift by 2keV at the start and then long-term drift
  - CZT peak very stable with very small drift







- Mohamed Ayoub, Éric Marché, Bruno Favrel, Patrick Radisson, Alexander Winkler, **Study of the performance stability of CdTe and CdZnTe materials at various fluence rates, IEEE-RTSD 2020** | October 31th, 2020

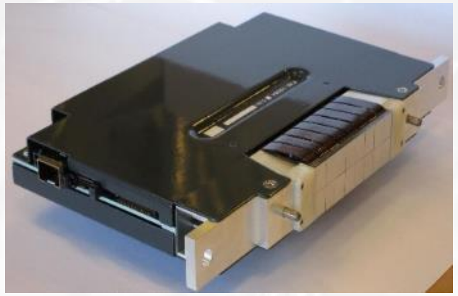
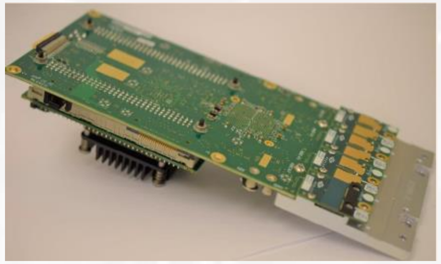
Company

Who is Redlen?

- Founded – 2000, Victoria BC
- Delivering a Quantum Leap in Radiation Imaging Capability
  - Core competency: high-flux CZT imaging sensors
- Targeting US $2B/Year of Medical, Security, NDT Detectors
  - Strong customer base of leading OEM's
- 40,000 Sq-Ft Production Facility in Victoria, BC
  - 200+ staff, 15+ PhD, 40+ with advanced degree, many job openings
- Acquired in 2021 by Canon Inc. to continue to serve WW market
  - https://biv.com/article/2021/09/canon-taking-control-bc-chipmaker-redlen-345m-deal

2000	2011	2016	2025
SCIENTIFIC DISCOVERY	EARLY ADOPTER	EARLY MAJORITY	MASS PRODUCTION

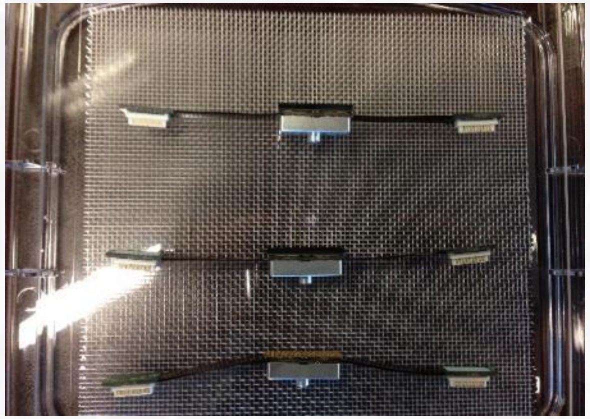
Redlen Applications

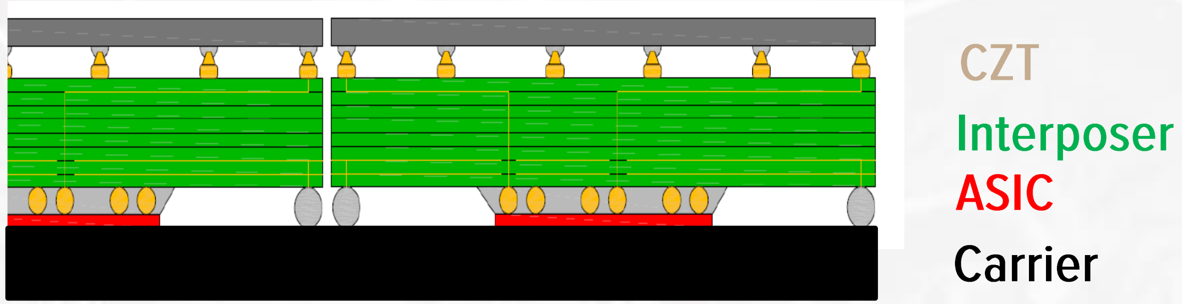
	Redlen Inside	Application
Medical		
Security		
NDT		

REDLEN TECHNOLOGIES

Detector Module (DM) for PCCT

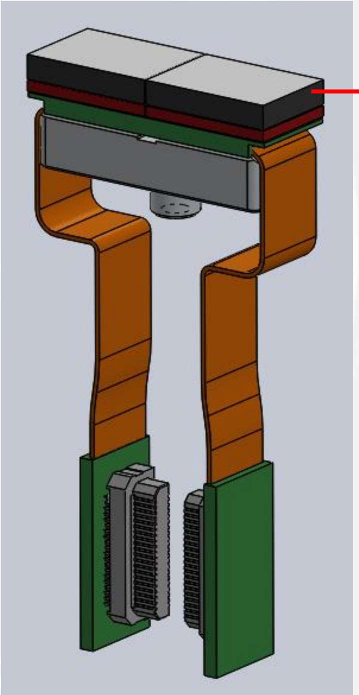
4-side Buttable Configuration

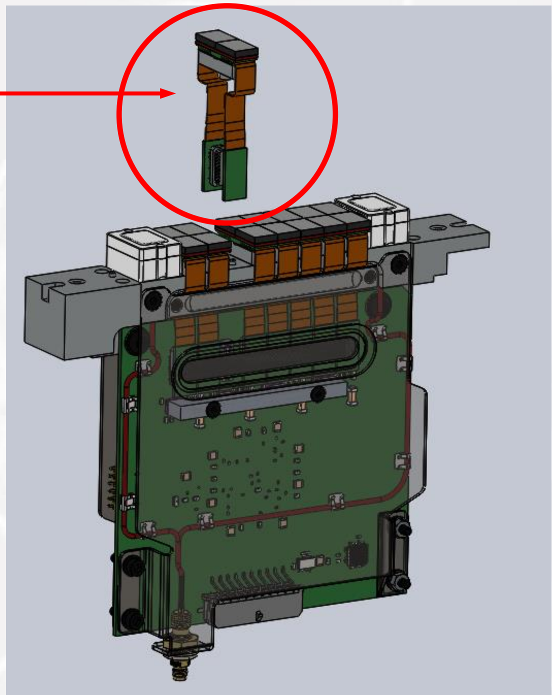




- Dual sensor configuration in 4-side buttable sub-module that is fully testable
- Unlimited (in theory) Field of View (FOV)
- Different CZT pixel pitches can be accommodated with customization of the interposer (250um-500um range)
- Flip-chip attach of ASIC to organic laminate interposer to minimize capacitive loading
- Sensor significantly larger than silicon die => complete shielding for radiation hardness

Detector Module (DM) Design





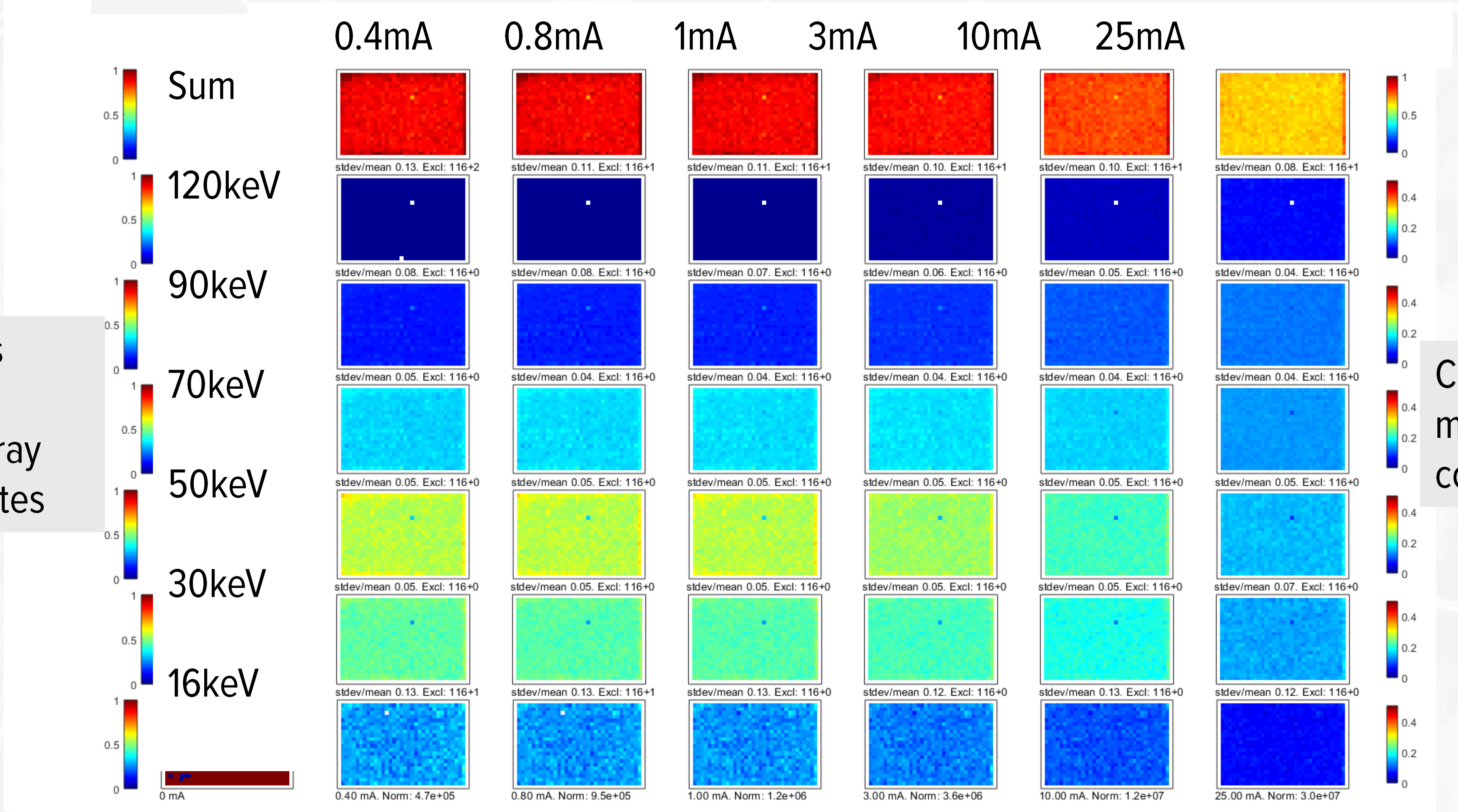
Mini Module (MM) is the core Sensor + ASIC unit in the Detector Module (DM)

- Sensor, ASIC, Interposer, Carrier, and MM sub-components support 4-way buttable array construction
- DM supports 2-way buttable array construction to form DMS

DM X-ray Testing

- COMET X-ray Tube, 25mA
- Selectable radiation sources
- Adjustable distance
- Various filter and collimation options
- 120keV-160keV
- Data I/O format is 10 GbE

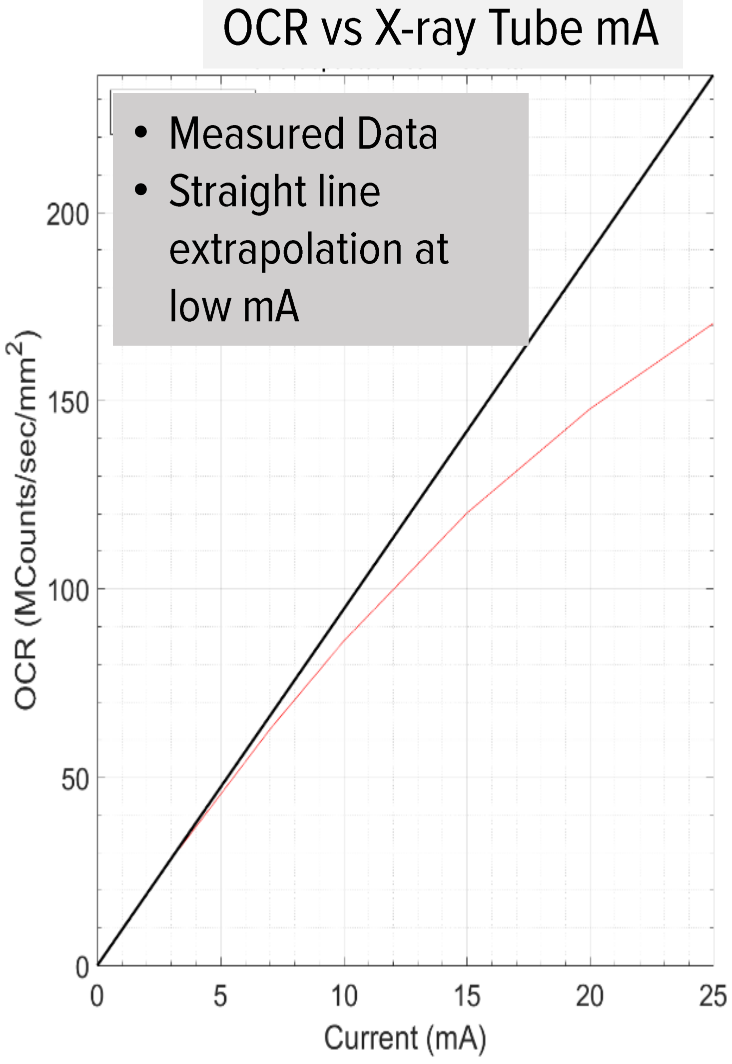
Bin Count Uniformity

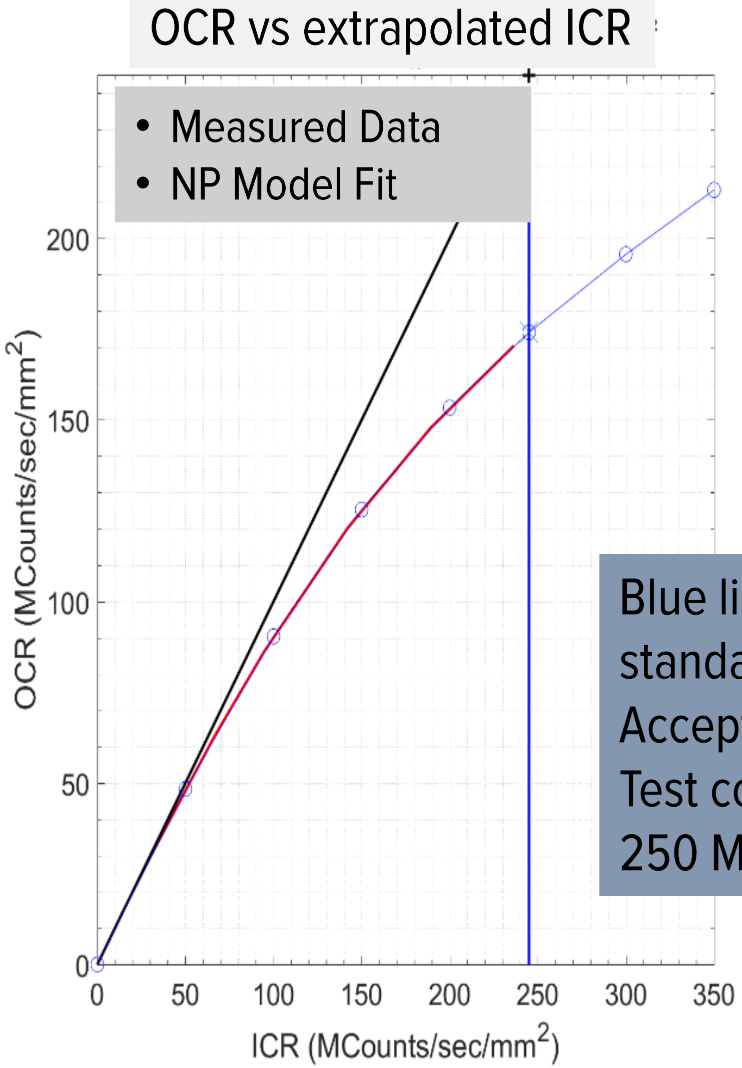


6 Energy bins measured at increasing X-ray tube count rates

Colors indicate measured counts

OCR-ICR Characteristics



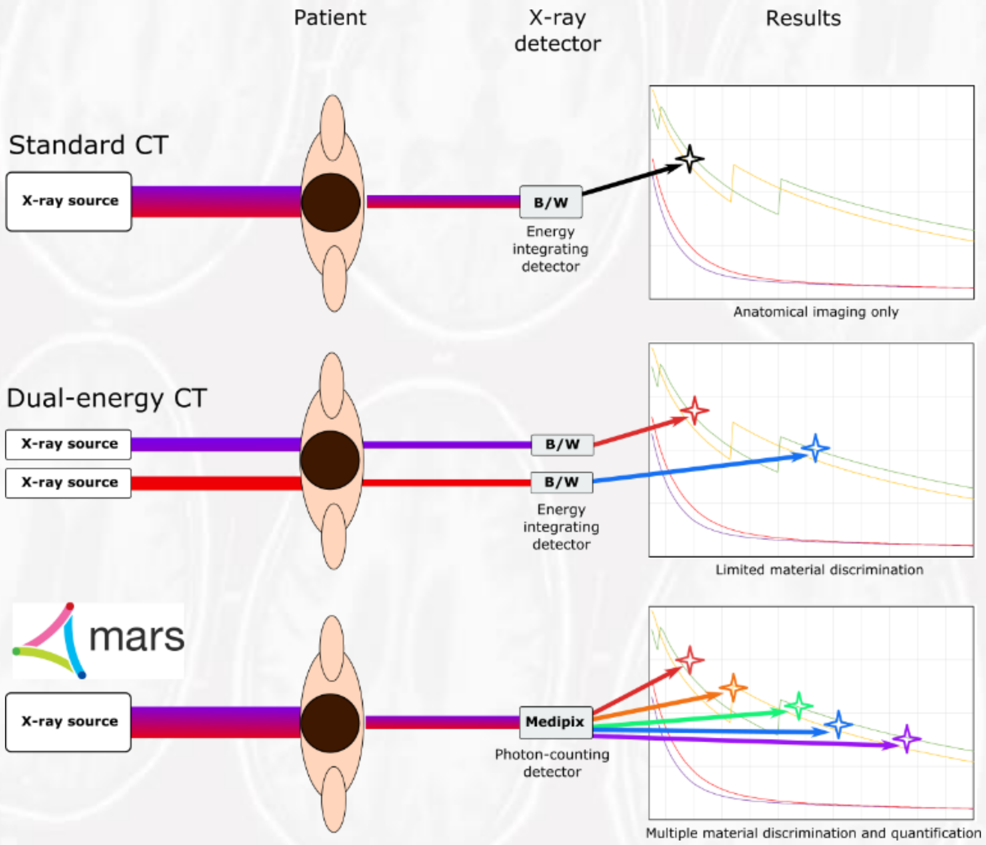


Blue line indicates standard Factory Acceptance (FAT) Test conditions at 250 Mcps/mm2

Spectral Computed Tomography

Spectral Computed Tomography

- Transition X-ray Spectral Photon Counting is similar to B/W to color transition
  - Some resemblance from high-definition TV to 4k transition



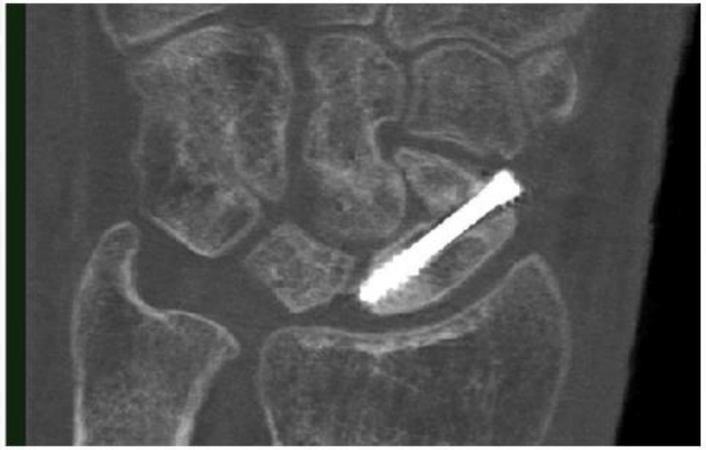
Main characteristics:

- Material Detection:
  - plaque, calcification, blooming artefacts
- Spatial Resolution: 300 um vs 1,000 um
- Dose: Up to 80% Lower
- Data: 100x More Data
  - Enables Machine Learning AI
- Flux rate up to 600 Mcps/mm^2

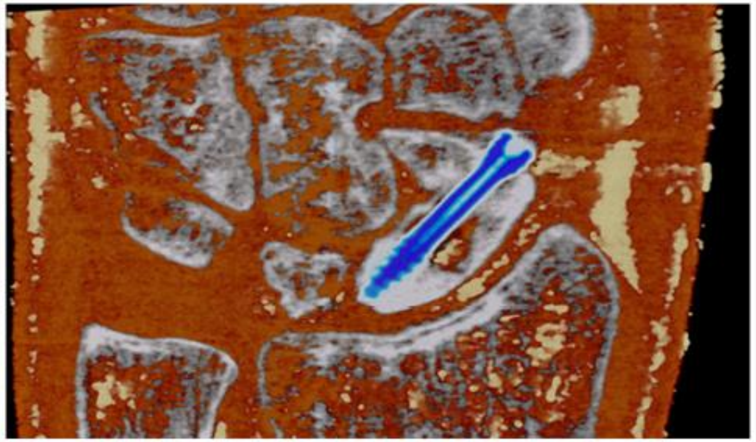
MARS Spectral Computed Tomography (1)

- Commercialized system : MARS Microlab 5X120
- First installation: June 2021 - CHUV Lausanne, Switzerland
- Small field-of-view for extremity CT scans
- 110/220 µm pixel pitch – uses MEDIPIX-3 ASIC and 2mm CdZnTe
- Material discrimination (soft tissue, lipid, water and metal)
- Application to scaphoid fracture post surgery

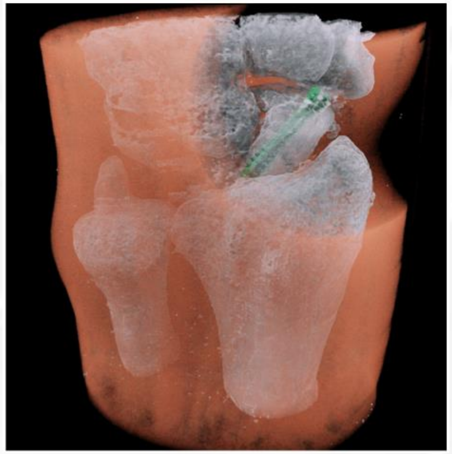
Conventional Image



Material Identification



3D Rendering



Source: https://www.marsbioimaging.com/media/

MARS Spectral Computed Tomography (2)

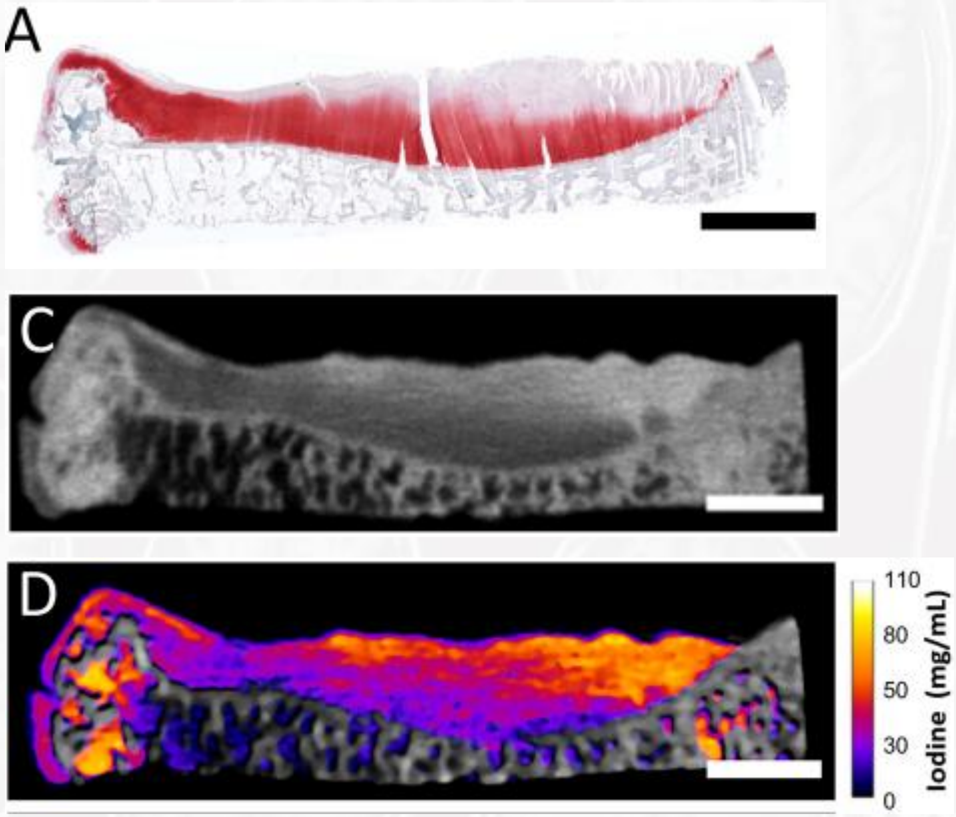
- Application to human osteoarthritic cartilage analysis:

Human tibial plateau

Histology

Conventional

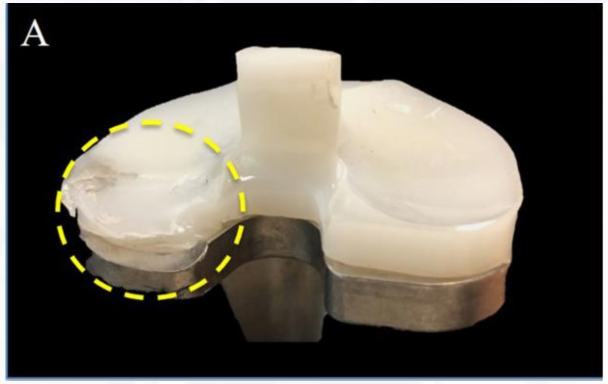
PCCT with Iodine Overlay



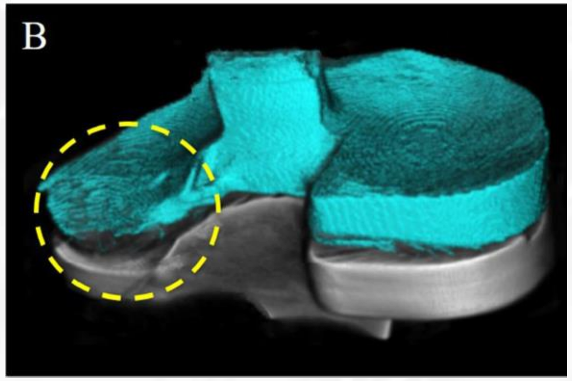
Source: Baer et al., APL Bioeng. 5, 026101 (2021)

Arthroplasty implant failure

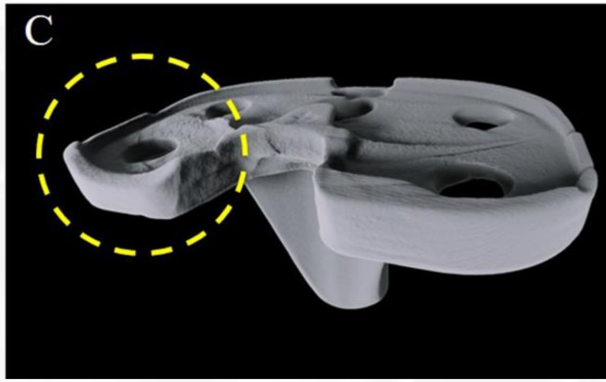
Photo



MARS Image



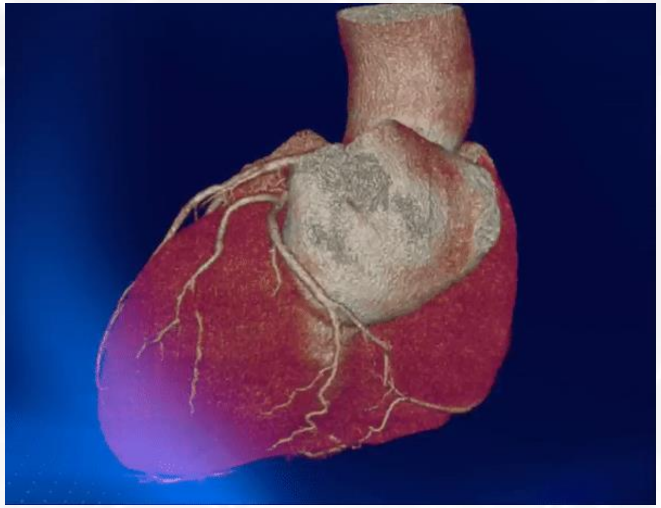
With Polyethene removal algorithm



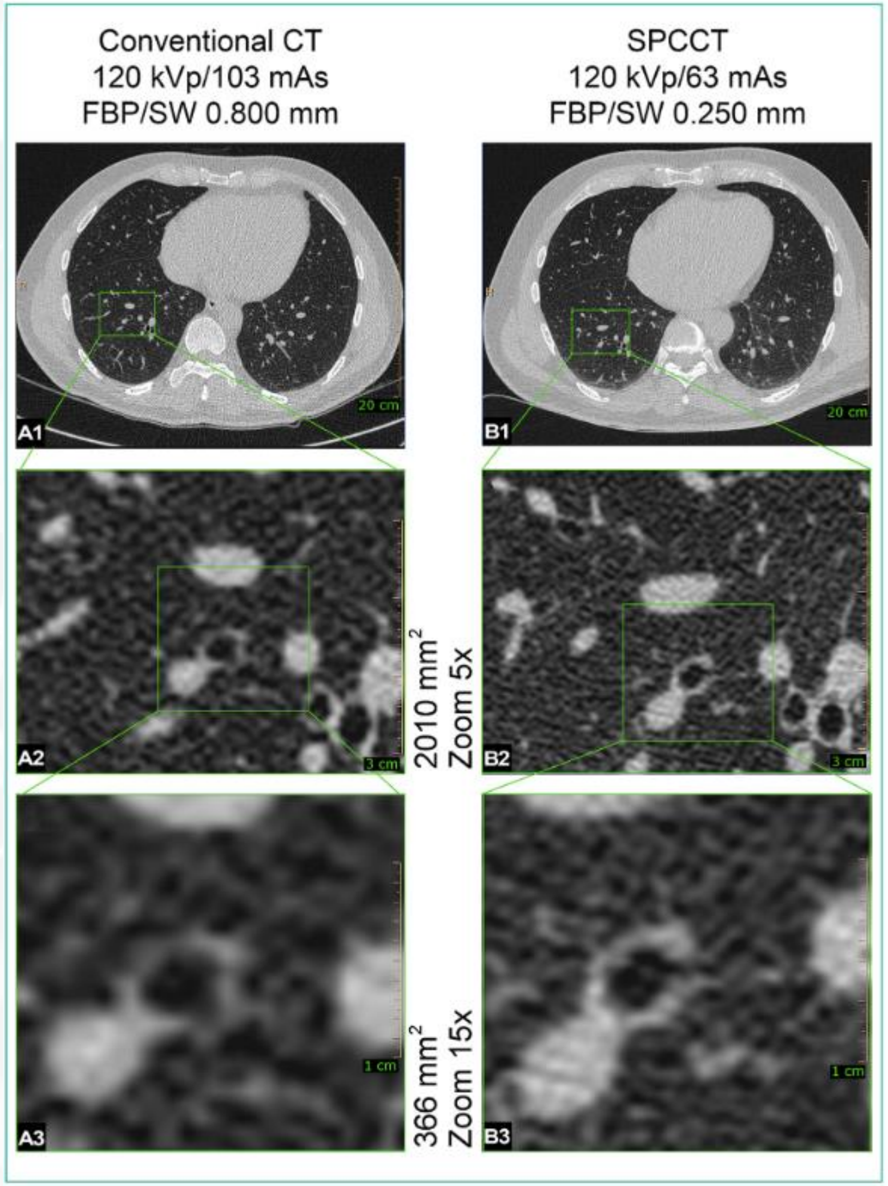
Source: Chun Man Lau et al., Scientific Reports | (2021) 11:1554

Philips Spectral CT

- Philips SPCCT large field of view (500 mm) prototype
- First installation: April 2019 – Lyon Cardiology hospital, France
- 270 µm pixel pitch at iso-center
- Enhanced resolution in patient scan compared to the state-of-the-art dual-energy CT (IQON)
- 90% demonstrated dose reduction



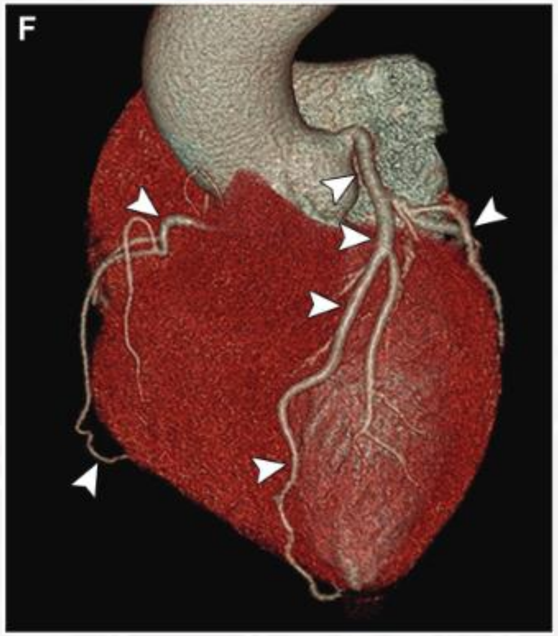
Lung imaging



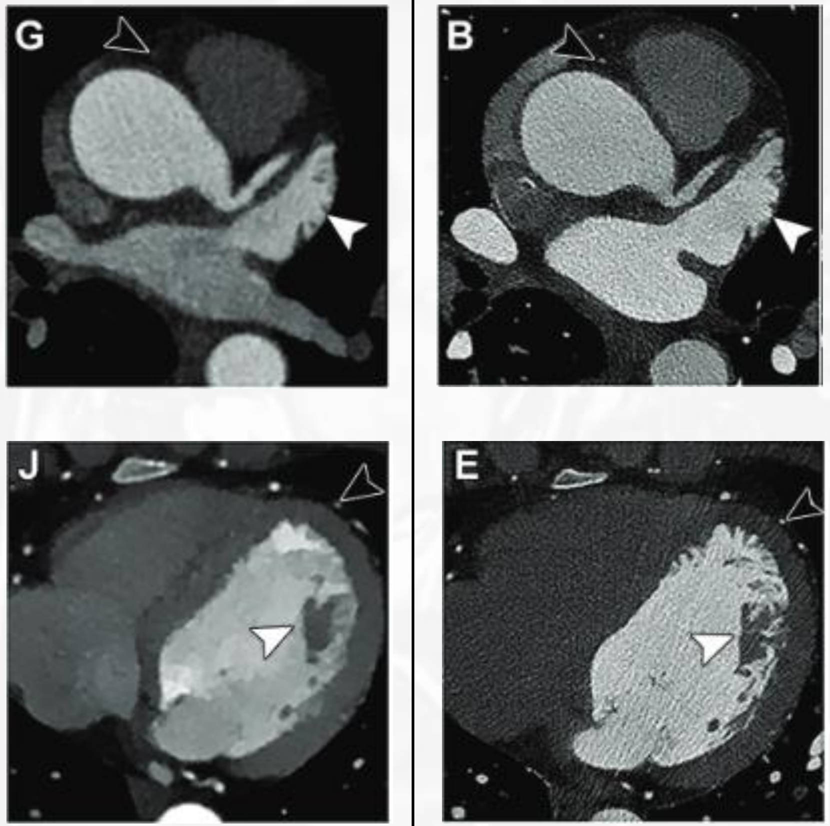
Source: Si-Mohamed et al., Diagnostic and Interventional Imaging (2021)

Coronary CT Angiography (IQON vs SPCCT)

- IQON is dual CT scanner that uses dual-sandwich scintillator structure
- SPCCT is spectral CT scanner that uses CdZnTe



Philips IQON EID CT | Philips SPCCT

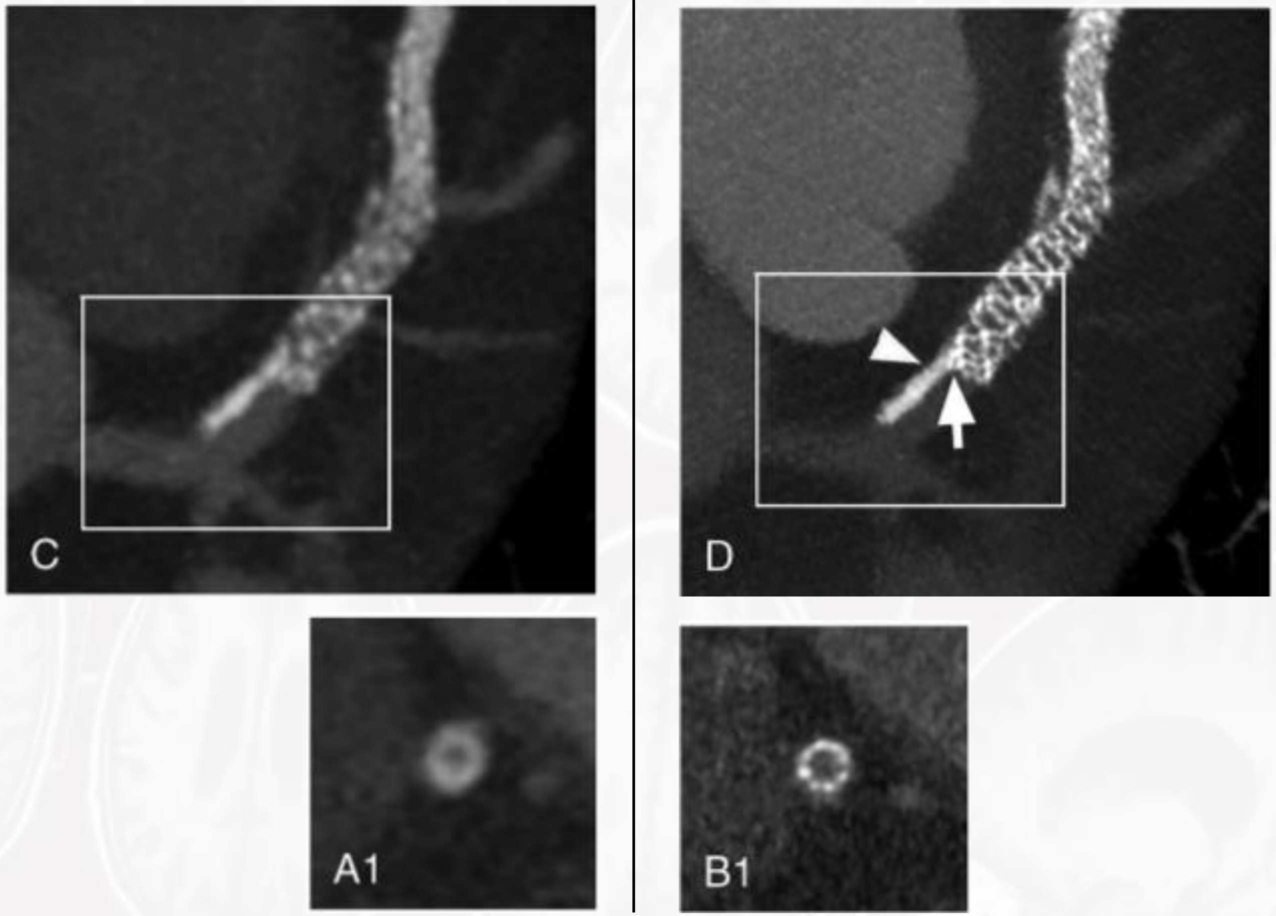


From *Si-Mohamed et al., 2022,* Coronary CT Angiography with Photon-counting CT: First-In-Human Results, https://pubs.rsna.org/doi/10.1148/radiol.211780

Coronary Stent Assessment (IQON vs SPCCT)

- With Photon Counting coronary stents are visible

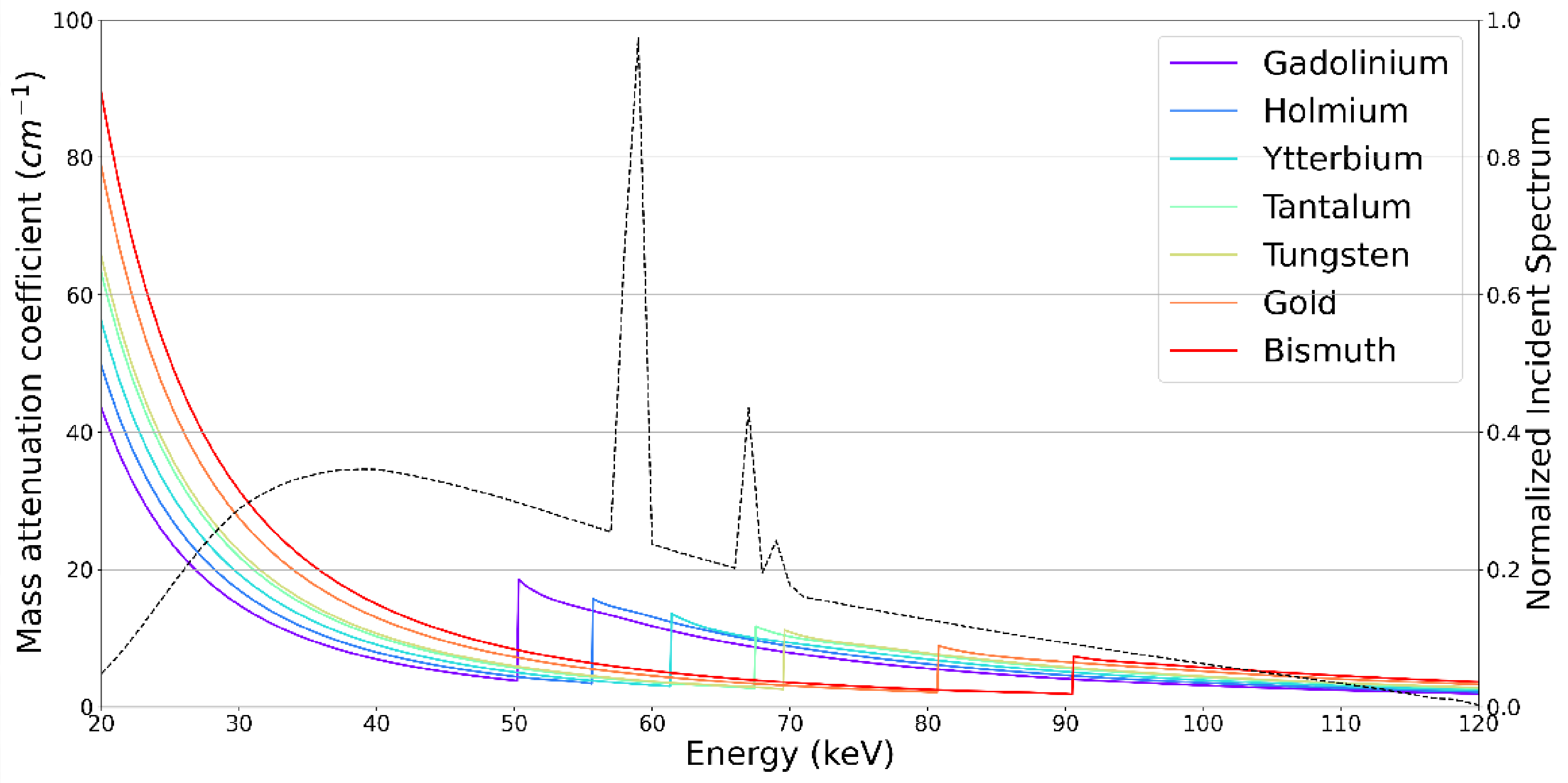
Philips IQON EID CT | Philips SPCCT



- From Boccalini et al., *2022, First In-Human Results of Computed Tomography Angiography for Coronary Stent Assessment With a Spectral Photon Counting Computed Tomography*
- https://journals.lww.com/investigativeradiology/Fulltext/2022/04000/First_In_Human_Results_of_Computed_Tomography.2.aspx

K-edge Imaging

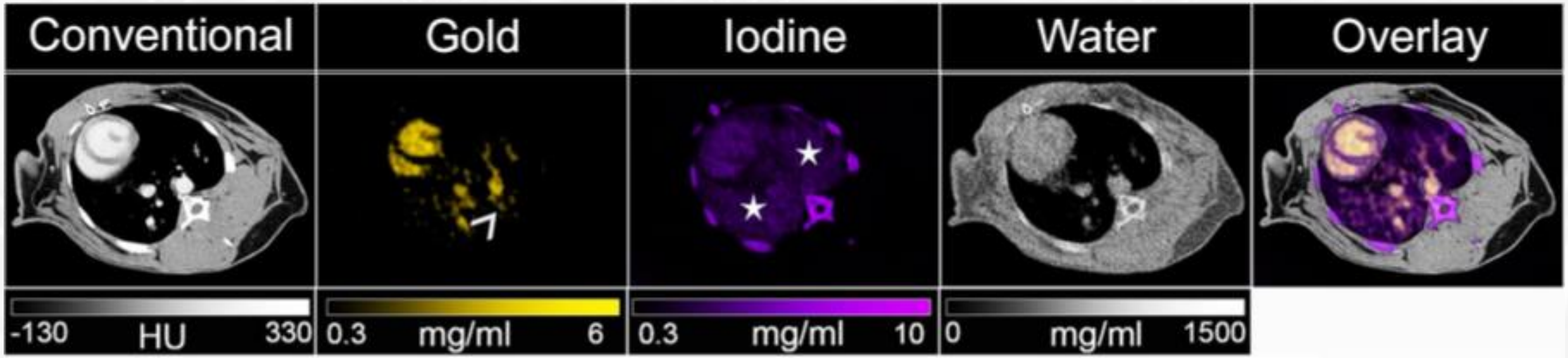
- K-edge materials in the medical CT range:



- Only Iodine is used as a contrast agent for CT today but Gadolinium is also used for MRI
- Research in other material of interest: gold nanoparticles (AuNPs), Holmium, Ytterbium, Tantalum, etc
- Study in small animals, human clinical trials require FDA approvals

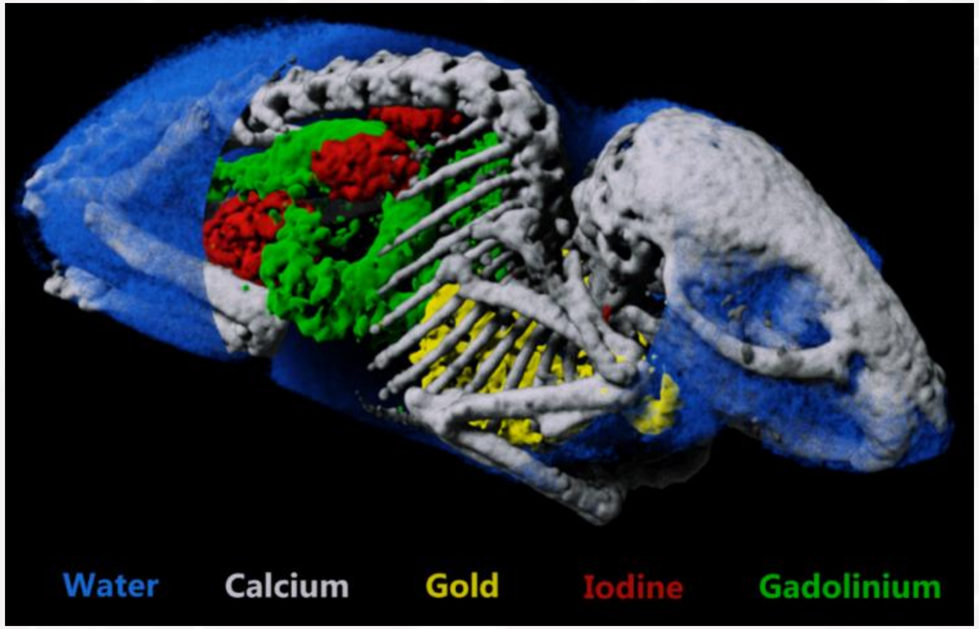
In-Vivo Dual Contrast Study

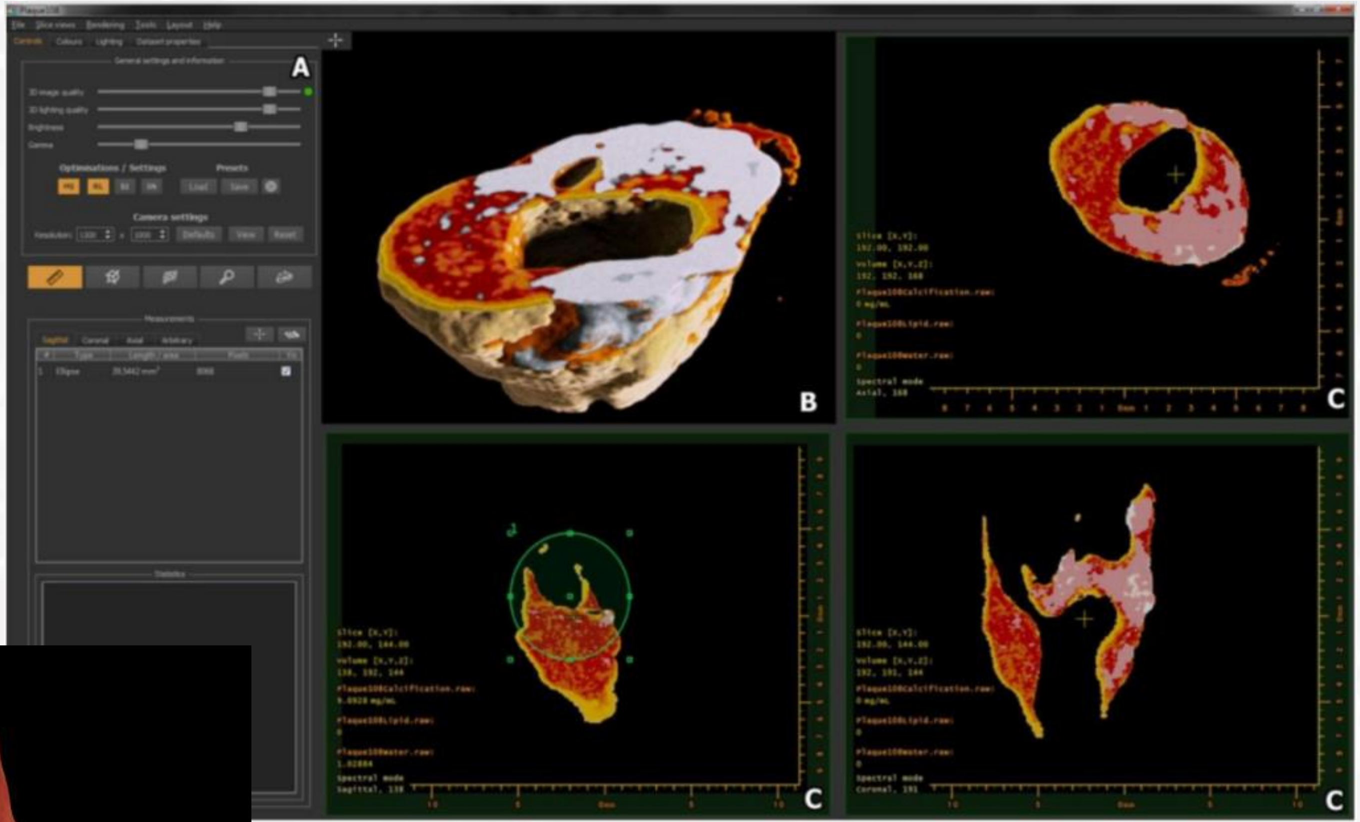
- With Photon Counting Multiple Contrast Agents could be used simultaneously exploiting K-edge properties

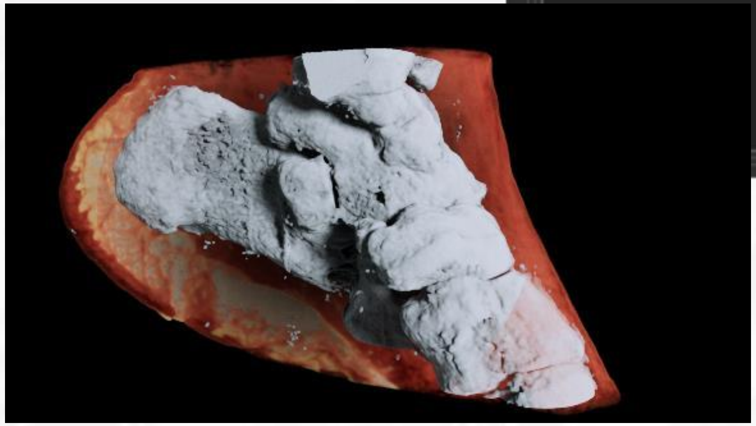


From Cormode et al., 2017, Multicolor spectral photon-counting computed tomography: in vivo dual contrast imaging with a high-count rate scanner, www.nature.com/articles/s41598-017-04659-9

MARS K-edge Imaging



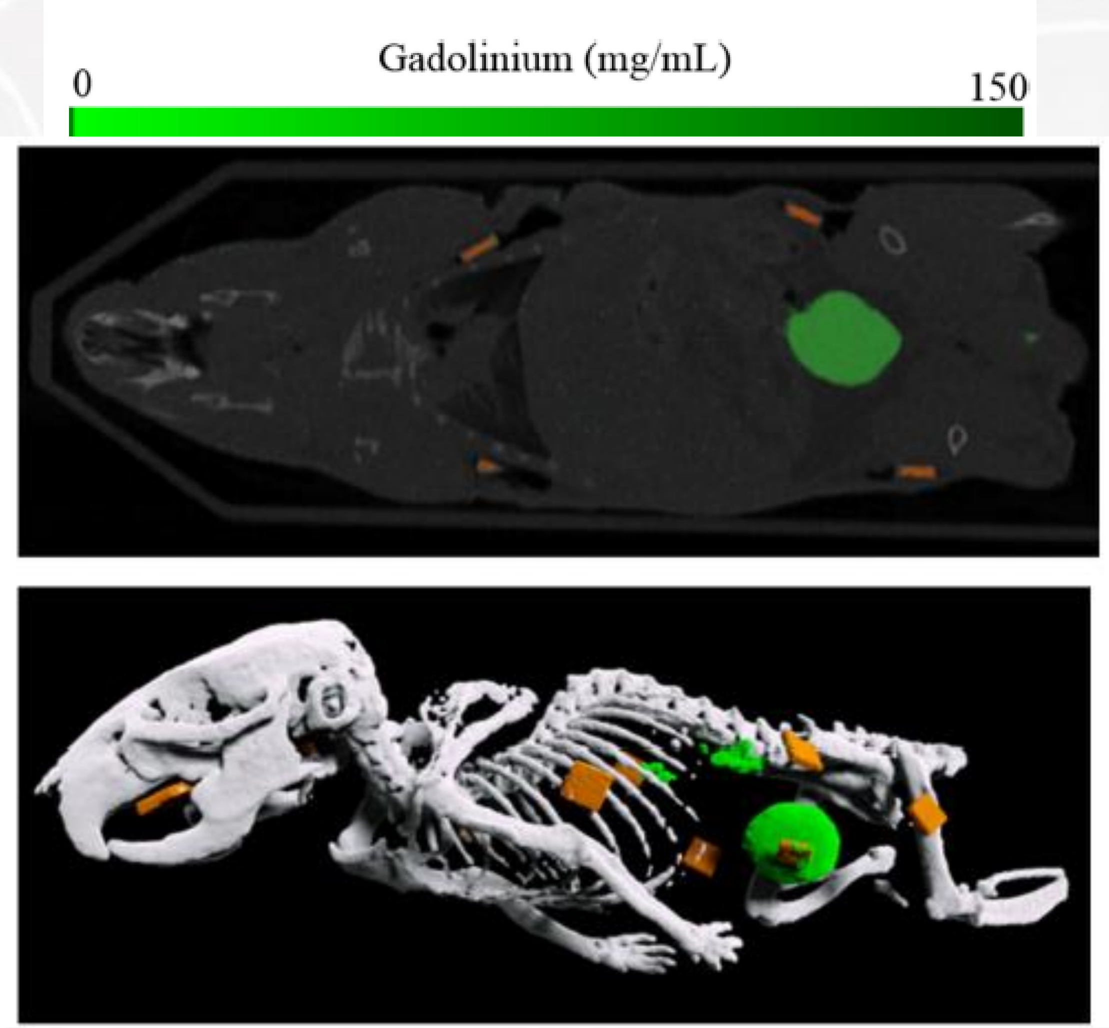




- Can image 3 K-edge contrast agents simultaneously: Gold, Iodine, Gadolinium

Gadolinium Imaging – Mars Imaging

- Gd déposition in the bladder and the kidneys in a mouse
- From Marfo et al, 2020, *Assessment of Material Identification Errors, Image Quality, and Radiation Doses Using Small Animal Spectral Photon-Counting CT*



Spectral CT at UViC

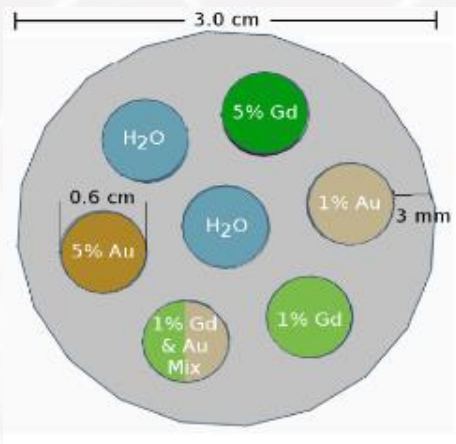
CdZnTe UViC Scanner

- Bench-Top Scanner installed at XCite Lab, University of Victoria, BC, Canada
- 24x576 pixels panel with 330µm pixel pitch, 100 mm field of view
- Gen1 Detector Module (DM) from Redlen Technologies

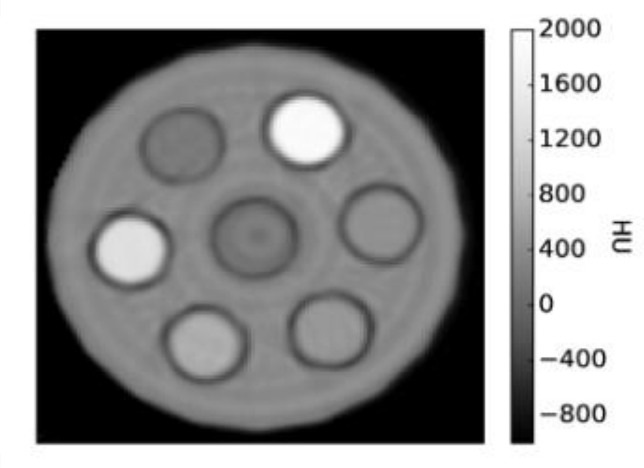
CAS Dunning *et al.* J. of Medical Imaging 7*(3),* 033502 (2020), CAS Dunning, UVic PhD dissertation, 2020.

UVIC K-edge Study (Gd and Au contrasts)

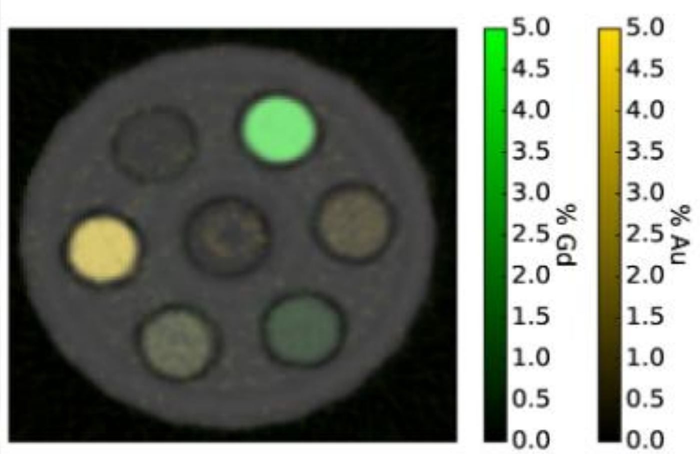
Phantom

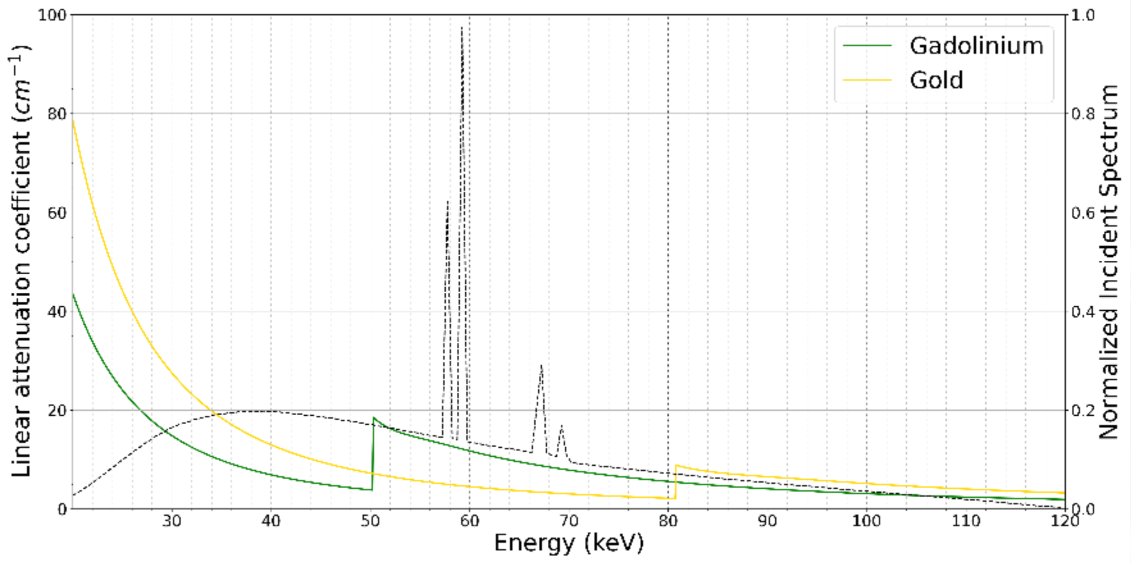


Conventional Image



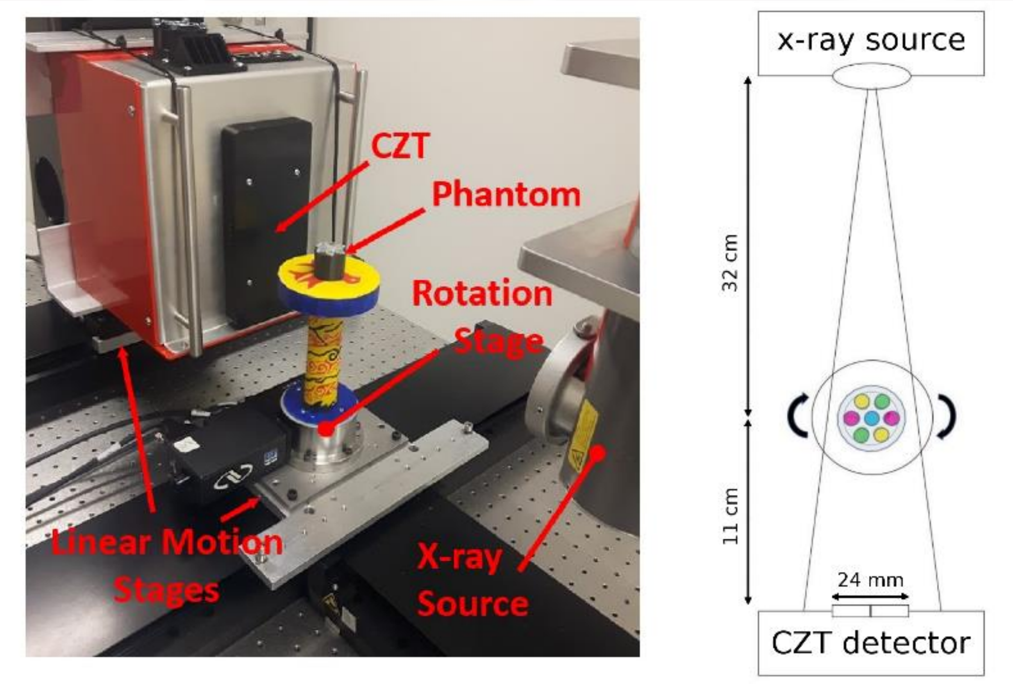
Gadolinium and Gold Overlay:

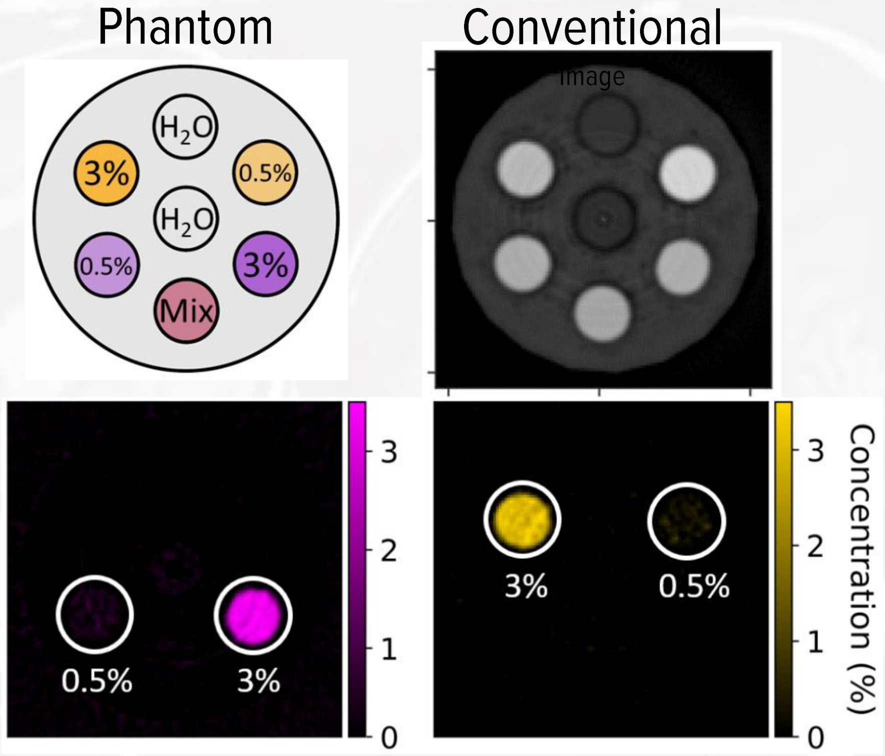




- From *Dunning and Bazalova-Carter, 2020: Design of a combined X-ray fluorescence Computed Tomography (CT) and photon-counting CT table-top imaging system, JINST 2020*

UViC K-edge Study (Gd and Au contrasts)





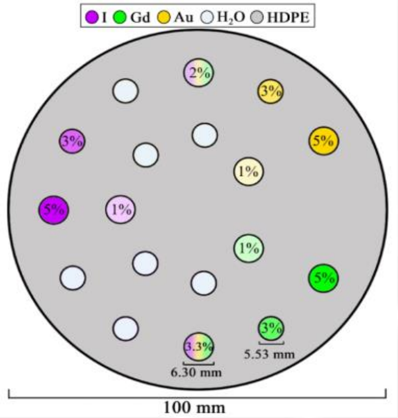
Gadolinium Image

Gold Image

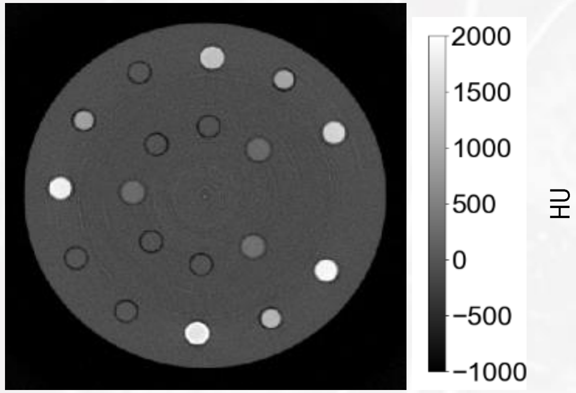
- From Richtsmeier et al., 2021: *Multi-contrast K-edge imaging on a bench-top photon-counting CT system: Acquisition parameter study, JINST 2020*
- *The* study was mainly to look at the parameters that would give us the best visualization and separation of multiple contrast agents.

UViC: K-edge Study (I, Gd and Au contrasts)

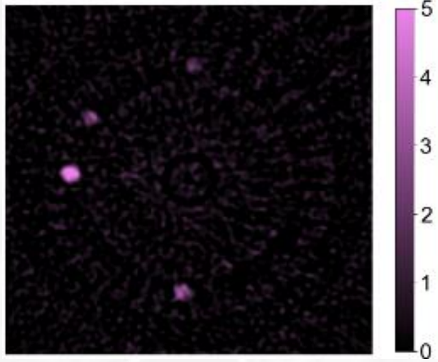
Phantom



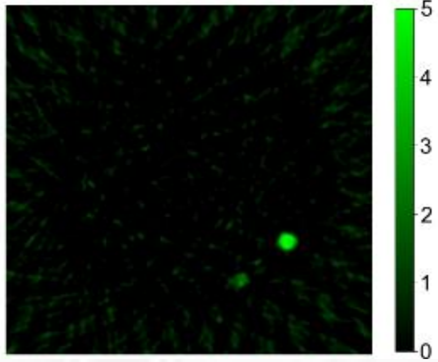
Conventional Image



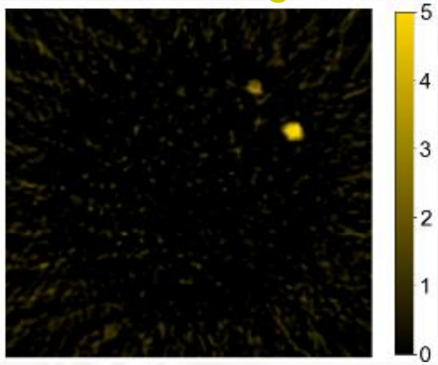
Iodine Image



Gadolinium Image



Gold Image



- From Clements et al., 2022: *Multi-contrast CT imaging using a high energy resolution CdTe detector and a CZT photon-counting detector, 2022 JINST 17 P01004*
- Triple contrast, larger FOV and improved image reconstruction algorithms

Beyond Spectral CT

Higher Flux Levels Possible

- Current high-flux CdZnTe has been developed for spectral CT applications
  - Detector modules are routinely FAT (Factory Acceptance Testing) at 250 $Mcps/mm^2$ using production X-ray chambers
  - Sustained operation at 600 $Mcps/mm^2$ in laboratory tests, still properly counting photons
    - ASIC limitation is 62.5 Mcps/pixel which provide basis for 600 $Mcps/mm^2$ operation
- Higher flux rates seem possible
  - Pulse operation at 10,000 $Mcps/mm^2$ in scientific experiments have been demonstrated for very short pulses
  - Is science interested in doing more? How far do we need to go?
  - How high can we go? (CdZnTe, ASIC, FPGA and readout signal processing limitations)
- Smaller pixels possible
  - 250 um-500 um is routine for Redlen, but can do down to 50 um
  - How small pixels are needed?

Conclusions and Outlook

Conclusions

- CdZnTe is becoming mature technology
  - Material yield and quality sufficient for volume applications in Spectral Computed Tomography
  - Several SPCCT scanners being build by multiple OEMs
  - Wafer scale sensor fabrication, automation in progress
  - Full recycling of off-cuts, crystal growth solvent and non-spec detectors
  - Research focus changing from material science to imaging application domain
- High-Flux CdZnTe Performance
  - Major improvements in sensor performance achieved in the last 5-years
  - Many high-flux CdZnTe modules available for customer sampling that utilize various ASIC solutions
  - Routinely FAT (Factory Acceptance Testing) tested in the factory at 250 Mcps/mm^2 using production X-ray chambers
  - Sustained operation at 600 Mcps/mm^2 in laboratory tests
  - Pulse operation at 10,000 Mcps/mm^2 in scientific experiments, interested in doing more!

Outlook for CZT at Redlen

- To remain world's largest supplier of CdZnTe products
  - Expanding purpose-built, state-of-the-art production capacity
  - Full ISO 9001 certification
  - Focus now on scale up / quality /cost reduction
- Range of commercial/research engagement options – COTS to research development partnership
  - Open for engagement!
- Delivery of high-flux CdZnTe sensor up 10 Gcps/mm^2 (pulse) and 600 Mcps/mm^2 (sustained)
  - More scientific experiments needed!

Acknowledgements

- The presenting author acknowledges numerous colleagues from Redlen Technologies (too many to mention by name) that have developed high-flux CdZnTe technology and several research collaborators internationally that I had a privilege to work with over last several years

- Special thanks to Professor Magdalena Bazalova-Carter (UViC) and her students and post-docs (Dr. Pierre-Antoine Rodesch, Devon Richtsmeier, Dr. Laszlo Zalavári, Dr. Joanna Nguyen, now at GE, Dr. Chelsea Dunning, now at Mayo, Jericho O’Connell and many others) that set-up bench-top spectral CT scanner at UViC, Victoria, Canada using Redlen CdZnTe technology and performed innovative experiments in spectral CT

- Tremendous gratitude to our research collaborators at STFC detector research group (Dr. Matt Wilson, Dr. Matthew Veale, Dr. Paul Seller, and many others) for several years of working together on CdZnTe material properties

Thank You! Let's work together

REDLEN TECHNOLOGIES

- If interested in high-flux CZT performance data and physics please contact **Dr. Matthew Veale** matthew.veale@stfc.ac.uk, STFC, UK
- If interested in collaborating on high-flux CZT systems please contact **Dr. Kris Iniewski** kris.iniewski@redlen.com, Redlen Technologies, Canada
- If interested in spectral CT applications please contact **Professor Magdalena Bazalova-Carter**, bazalova@uvic.ca, UVic, Canada

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