The EPID Strikes Back:
→ Future EPID Technology and Applications

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Acknowledgements:
• Youcef El-Mohri, Qihua Zhao (U. Michigan)

Some illustrations courtesy of:
• Gino Fallone – Cross Cancer Center
• Josh Star-Lack, Daniel Morf – Varian Medical Systems
• Larry Partain – TeleSecurity Sciences
• Joerg Rottmann, Ross Berbeco – Brigham and Women's Hospital

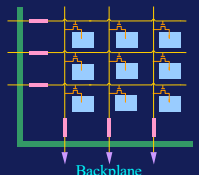
Outline

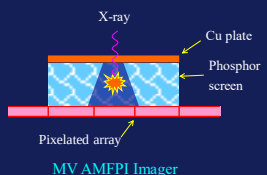
- Challenges in improving EPID performance
- Pathways for improvement:
  - → Fluence Imaging
    - Improve DQE of MV imagers
    - Introduce dual-energy BEV imagers
  - → Photon Counting
    - Prospects for large-area photon counting array (PCA) imagers
- Observations

Active Matrix Flat-Panel Imagers (AMFPIs)

- Based on 2D matrix of thin-film photodiodes and transistors + 1 mm Cu – GOS
- GOS ~61,000 photons/MeV; Optical efficiency of ~65%

However …
- DQE small, ~1% – low compared to modern diagnostic systems: ~40 to 70%
  - → Limits image quality at any dose
  - → Volumetric (CBCT) MV imaging requires doses >> 1cGy

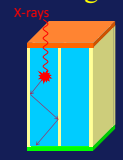


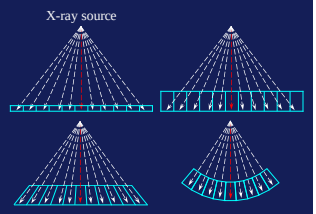


MV AMFPI Imager

Antonuk *et al.*, Med. Phys. 19(6), 1992

Segmented Crystalline Converters





$$DQE \propto QE \times \frac{MTF^2}{NPS}$$

→ Strategy: *Significantly* enhance QE while *limiting* MTF loss through use of matrices of optically isolated crystalline scintillator elements

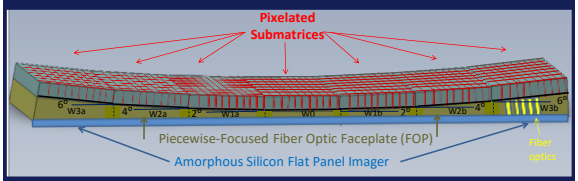
- ✓ Thicknesses up to 40 mm are practical (increasing QE up to ~80% at 6 MV)
- ✓ Very good element-to-element uniformity & good optical transport
- ✓ Design septal walls to minimize optical cross-talk and absorption
- ✓ Large area detectors are manufacturable

Desirable properties: high density + good light yield + high refractive index + rad-tolerant

Wang *et al.*, Med. Phys. 36(12), 2009; Liu *et al.*, Phys. Med. Biol. 57, 2012

Linear, Piecewise-Focused Strip Detector

Maximum remaining beam divergence = 1 degree
(SDD = 150 cm)



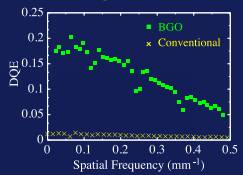
Six $CdWO_4$ (15k photons/MeV) subarrays with 0.784 mm pitch,
1 BGO subarray (8k photons/MeV), 1.17 mm pitch
Total: 28,072 elements.
DQE(0) ~22%

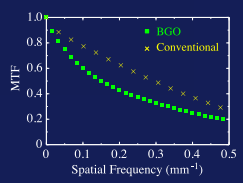
Slide courtesy of Josh Star-Lack & Daniel Morf; Med. Phys. 42(9), 2015

Performance Improvement with a 2D Segmented Scint.

BGO (8k photons/MeV) prototype:
11 mm thick; 1.016 mm pitch

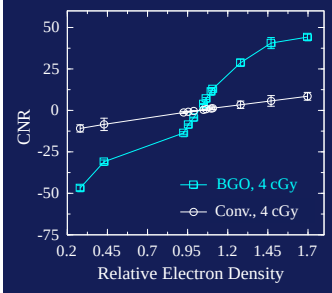
- Optical efficiency ~50%
- DQE(0) ~ 20%
- Quantum limited down to ~0.022 cGy

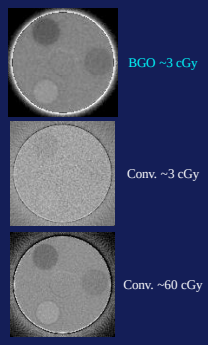




Wang et al. Med. Phys. 36, 2009

Empirical Demonstration of CBCT Improvement





BGO ~3 cGy

Conv. ~3 cGy

Conv. ~60 cGy

El-Mohri *et al* Phys. Med. Biol. **56,** 1509 (2011)

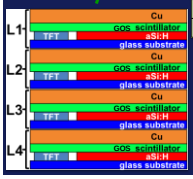
Multi-Layer Imager

1 control board

4 layer of readout modules

4 layer of gate driver modules

System	AS1200	MLI
Layers	1	4
Thickness	290 mm	430 mm
DQE (0)	~1.2%	~6.7%



Courtesy of Joerg Rottmann, Ross Berbeco, Josh Star-Lack

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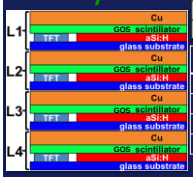


Scintillator	Density (g/cm^3)	Ref. Index	Light Yield Per MeV	Manuf.	Cost
LKH-5	3.8	1.6	4k	✔	$
BGO	7.2	2.1	8k	✔	$$$
$CdWO_4$	7.9	2.2	15k	✔	$$$
GOS	3.72	2.2	61k	✔	$

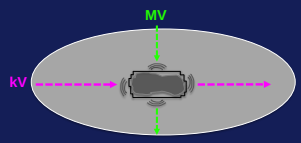
Courtesy of Joerg Rottmann, Ross Berbeco, Josh Star-Lack

kV Imagers in the Treatment Room

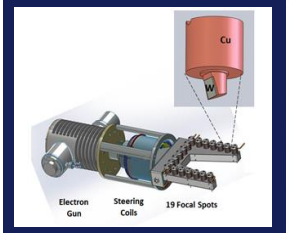
- X-ray attenuation dominated by photoelectric

  → High-contrast projection & volumetric images

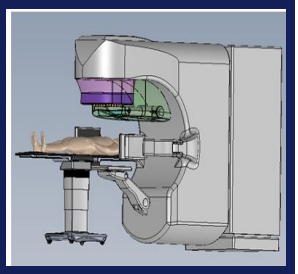
- Constraints:
  - kV beam direction not parallel to BEV
  - photon starvation from implants leads to artifacts



kV X-ray Sources Integrated into Treatment Head



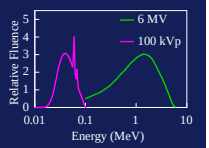
19 source TumoTrak ™ kV x-ray design



Partain et al., SPIE 9783, 2015

Improve Contrast – Dual-Energy Imagers

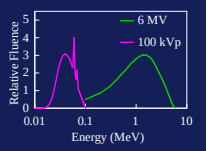
- Design segmented scintillator for multiple energies
  For example:
  → Provide high-DQE MV performance
  → Preserve performance of kV imaging systems



(Liu et al. Med. Phys. 42, 2015)

Improve Contrast – Dual-Energy Imagers

- Design segmented scintillator for multiple energies
  For example:
  → Provide high-DQE MV performance
  → Preserve performance of kV imaging systems
- Favorable design:
  2 cm BGO; 0.508 mm element pitch
  + rear illumination + black reflector
  + high-res & low-res operation for kV and MV



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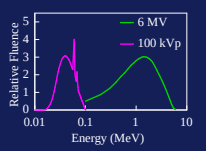
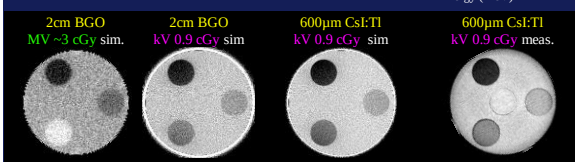


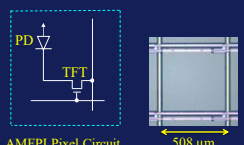


(Liu et al. Med. Phys. 42, 2015)

Improve Contrast – Photon Counting Array (PCA)

Conventional Imager

- Simple AMFPI backplane
- 1 TFT + storage capacitor
- Integrates deposited energy
- No energy resolution

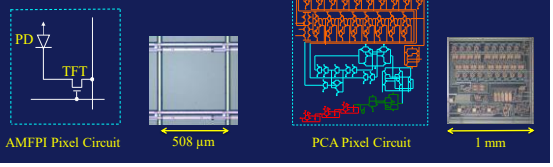


AMFPI Pixel Circuit

Improve Contrast – Photon Counting Array (PCA)

Conventional Imager
- Simple AMFPI backplane
- 1 TFT + storage capacitor
- Integrates deposited energy
- No energy resolution

PCA Imager
- 10^2 – 10^3 components
- Counts individual x-rays
- keV -level energy resolution



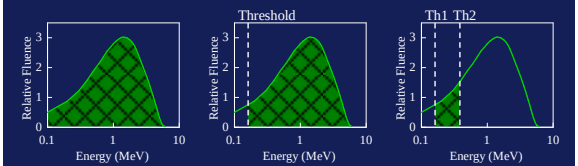
AMFPI Pixel Circuit | PCA Pixel Circuit

PCA: Energy Windowing

- Entails measuring & recording information from individual x-rays
- Increases signal-to-noise

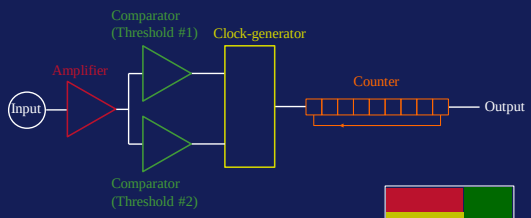
→ Potential for improvements in contrast & tumor identif. & tracking

- But requires complex detector backplane



Conventional | 1 Threshold – Scatter rejection | 2 Thresholds – Diagnostic component

2-Threshold / 1-Window PCA Pixel Circuit

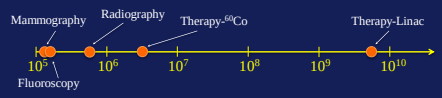


3 µm minimum feature size
8 metal layers

→ 355 µm pixel pitch

Count Rate Considerations

- Treatment machines provide radiation in form of trains of brief, high intensity pulses (e.g., ~36, ~5 μs pulses/MU)
- Results in high instantaneous fluence rates …
  ~6×10^9 x-rays / second / 0.5 mm pixel at 130 cm SDD
- … much higher than for other common x-ray procedures
- and cmpd to the count rate capabilities of 1st gen. poly-Si PCA
  ~6×10^5 counts / second for a 0.5 mm pixel



Instantaneous Incident X-ray Count Rate (counts/sec/pixel)

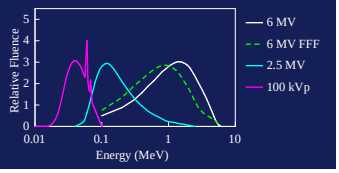
Summary

- Excellent prospects for significantly improved real-time tumor tracking

→ Near-term: Practical implementation of segmented scintillators gradually increasing MV EPID DQE eventually up to ~20%

→ Mid-term: Introduction of dual-energy imagers operated with with BEV kV, low-MV or flattening-filter-free beams

→ Long-term: Photon counting detectors with multi-energy-windowing offering new contrast capabilties with a MV or kV beam



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Linear Segmented Scintillator Array
Kirvan & Fallone – Cross Cancer Centre

Prototype benchtop MVCT system:

- 1 mm pitch
- 10 mm $CdWO_4$ crystals (15k/MeV) coupled to a photodiode array, ~19% DQE
- 16 × 16 element modules → detection area of 16 mm × 320 mm
- focused in an arc with radius of 92.5 cm

Picture courtesy of Gino Fallone; Med. Phys. 37(1), 2010