Stanford Cancer Imaging Training Program

Technology development for a 100 picosecond coincidence time resolution time-of-flight positron emission tomography system

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Stanford Cancer Imaging Training (SCIT) Seminar / RSL Weekly Seminars

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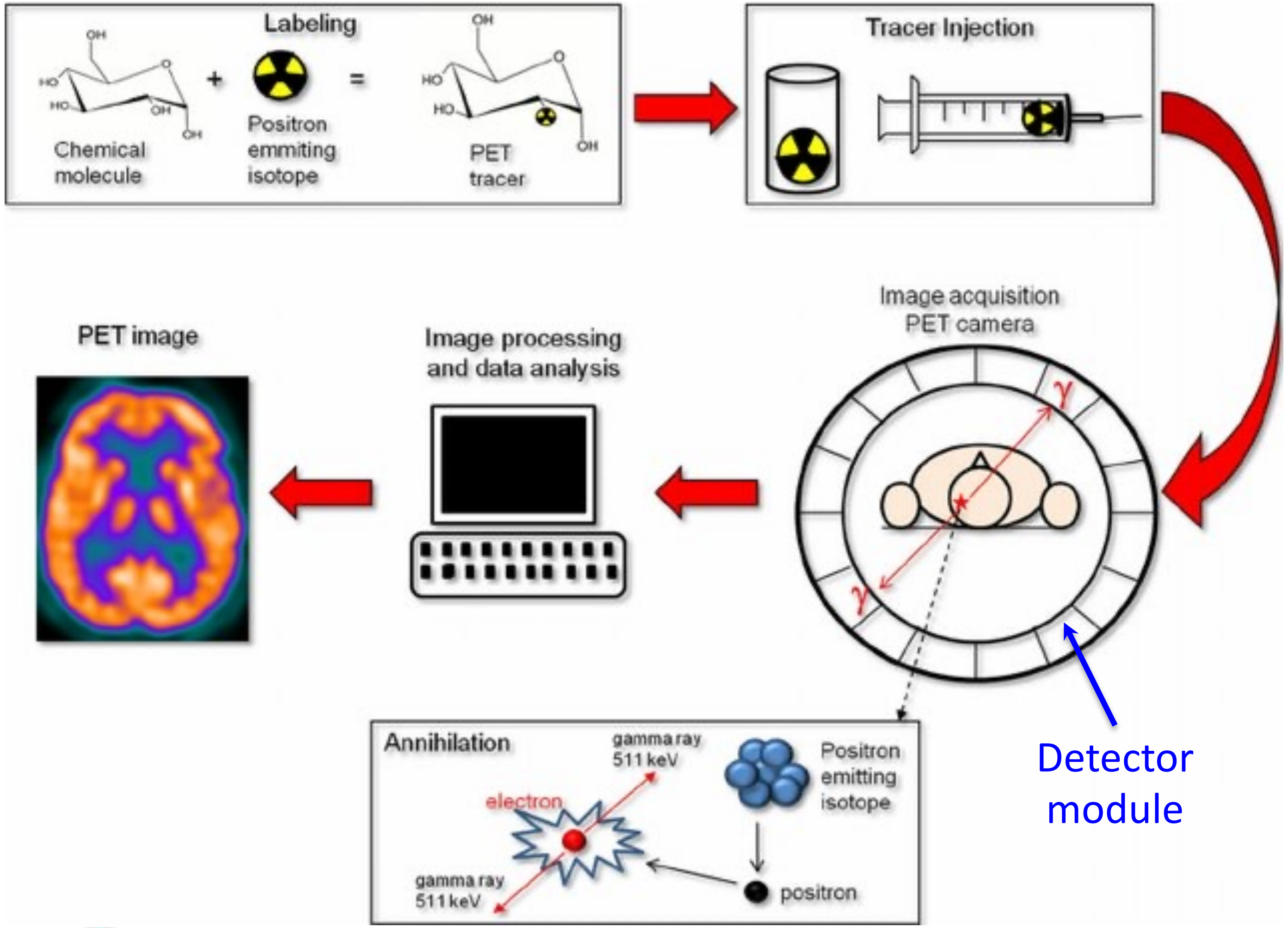
Positron Emission Tomography (PET) System

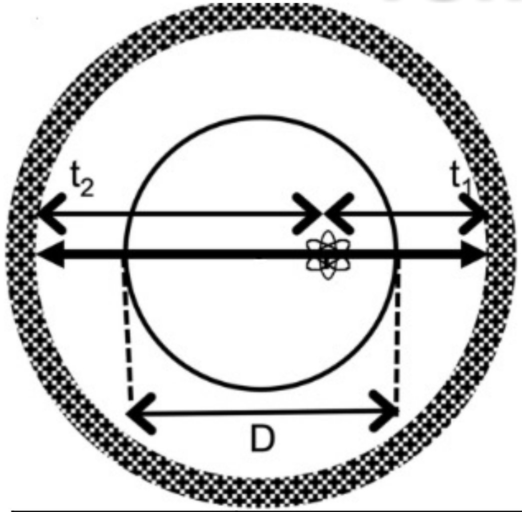
- **%80 of PET usage in Cancer:**
  - Detecting and staging specific types of cancer and/or assessing response to treatment
- **Cardovascular and/or Neurollgical Disease**
  - Evaluating the function of organs, such as the heart and/or brain

Concept Behind PET



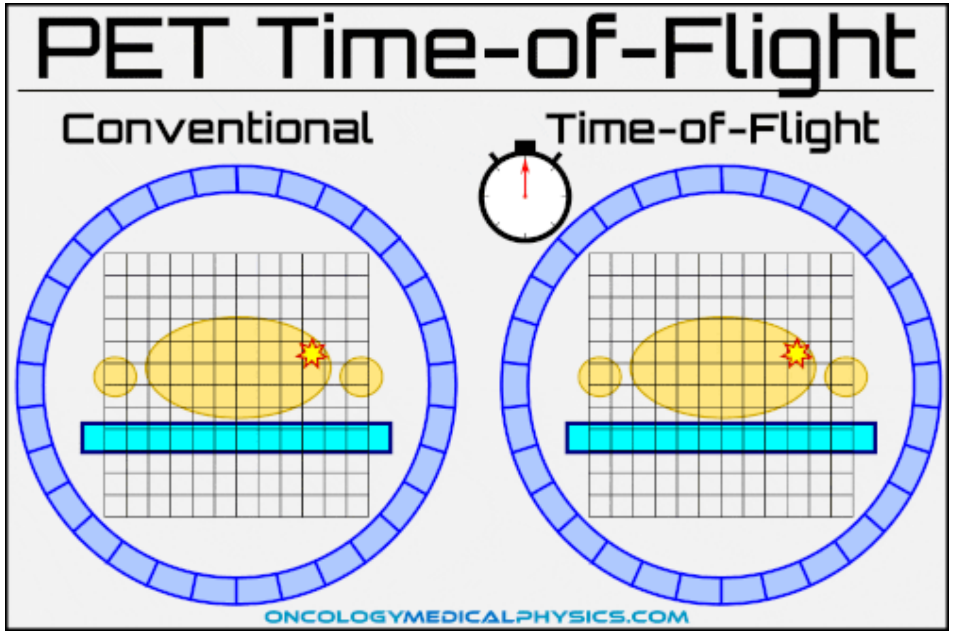
- Positron emitter radionuclides
  - e.g ^{11}C, ^{13}N, ^{15}O, & ^{18}F
- Ring of Detector modules
  - Scintillation crystals + photosensor + electronic readout
- Event localization along lines of response (LOR)
  - Arrival time difference of coincident events

Time of Flight Positron Emission Tomography (TOF-PET)



- **Δt = t_2-t_1:** Arrival time difference between photons in coincident events
- **CTR (Coincidence Time Resolution):** FWHM of Δt distribution
- **D:** Patient diameter (e.g. 40 cm)
- **c = 3×10^10 cm/s:** speed of light
- **Δx = c × CTR/2:** Localization error

https://oncologymedicalphysics.com/nuclear-tomographic-imaging/



CTR (ps)	$\Delta x = c \times \frac{CTR}{2}$	$Gain = \frac{SNR_{TOF}}{SNR_{Non-TOF}} \approx \sqrt{\frac{D}{c \times \frac{CTR}{2}}}$
1000	15 cm	1.6
500	7.5 cm	3.1
400	6 cm	2.6
214	3.7 cm	3.5
100	**1.5 cm**	**5.2**

Δx>D

Equal probability in all voxels along the LOR ☹

Δx<D

Confined probability to a small segment on the LOR ☺

State-of-the-Art: 214 ps CTR TOF-PET/CT

https://www.siemens-healthineers.com/en-us/molecular-imaging/pet-ct/biograph-vision-quadra

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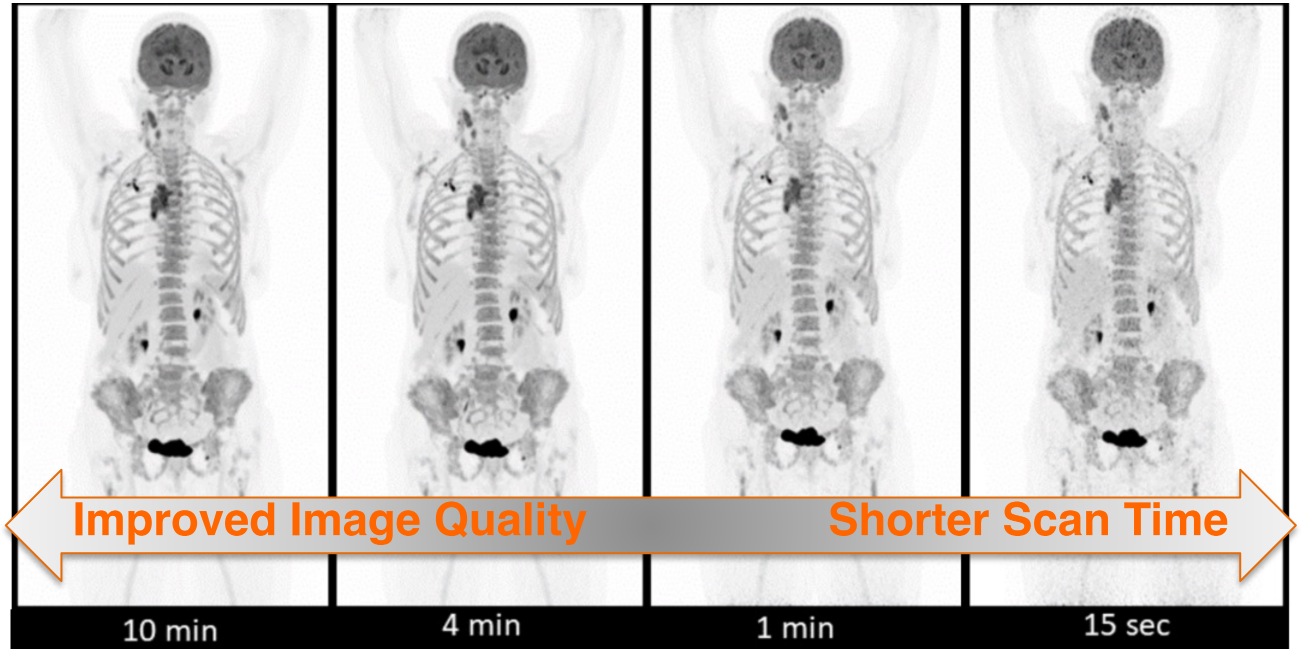
Single Bed Position Images



- **Improved CTR (214 ps) and localization along LOR (3.7 cm)**
  - Improved reconstructed image SNR, signal-to-background ratio, image quality, accuracy, and lesion detectability
- **or getting the same image quality as Conventional PET**
  - Lower injected dose to patients or shorter scan time
  - Wider category of patients can be served

System Level Electronic Readout for TOF-PET

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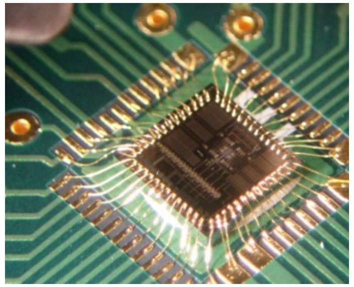
- **At system level, 214 ps is the best commercially-available CTR (Biograph TOF-PET/CT)**

- **Currently several benchtop experiments with CTR ≤100 ps using single-pixel detectors**
  - Challenging to scale results up to full system

System Design Approaches:

- **One-to-one coupling of scintillation crystals to compact sized SiPMs:**
  - × Large number of electronic readout channels needed
  - × Costly, not power efficient, and heat generated degrading SiPM performance, especially CTR

- **Designing ASICs**
  - × Long design time
  - × Also costly



Multiplexing:

- **Simply hardwiring SiPMs signals together**
  - × Parasitic capacitance >>> CTR degradation
- **Resistive charge division**
  - × High RC constant >>> CTR degradation
- **Delay-line method**
  - × Lower SNR, especially for longer delays
  - × Requiring more resources from FPGA

Scale-Up Scheme of 100 ps TOF-PET

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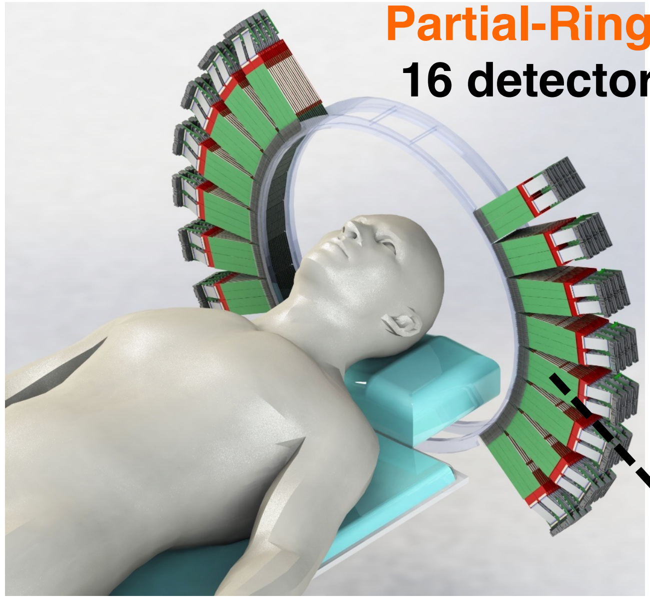
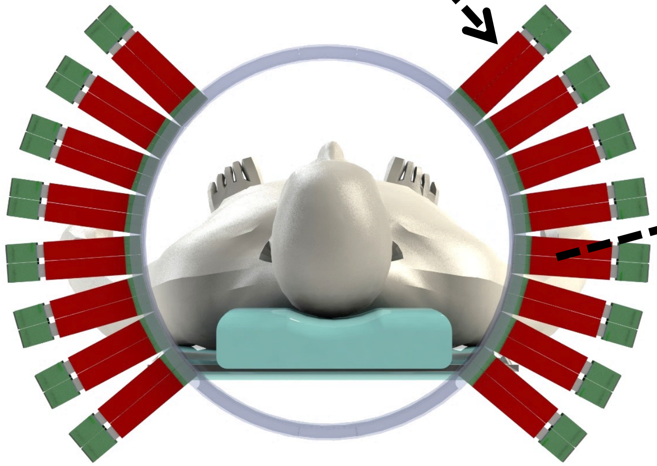
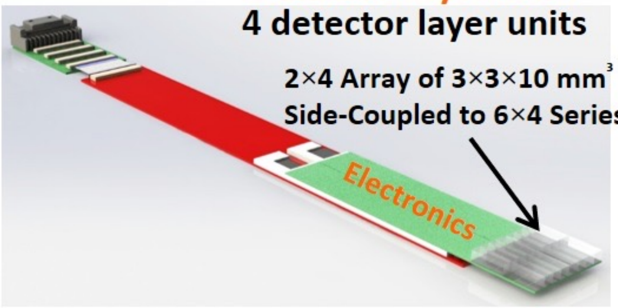
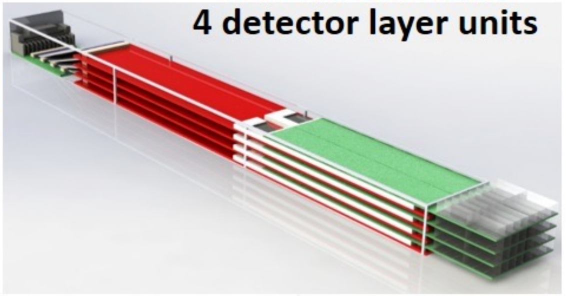
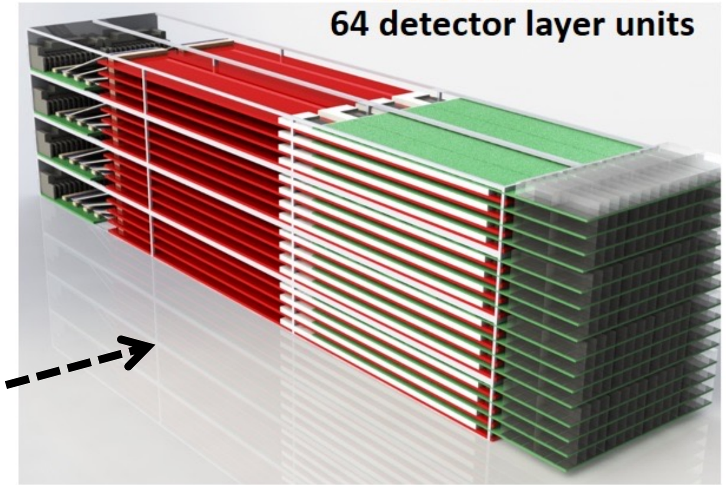
- J. W. Cates, C. S. Levin, Physics in Medicine and Biology, 2018
- S. Pourashraf, et al, Physics in Medicine and Biology, 2021
- S. Pourashraf, et al, IEEE TRPMS, 2022











64 Timing

32 Energy

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Electronic Read-out of Detector Layer Unit

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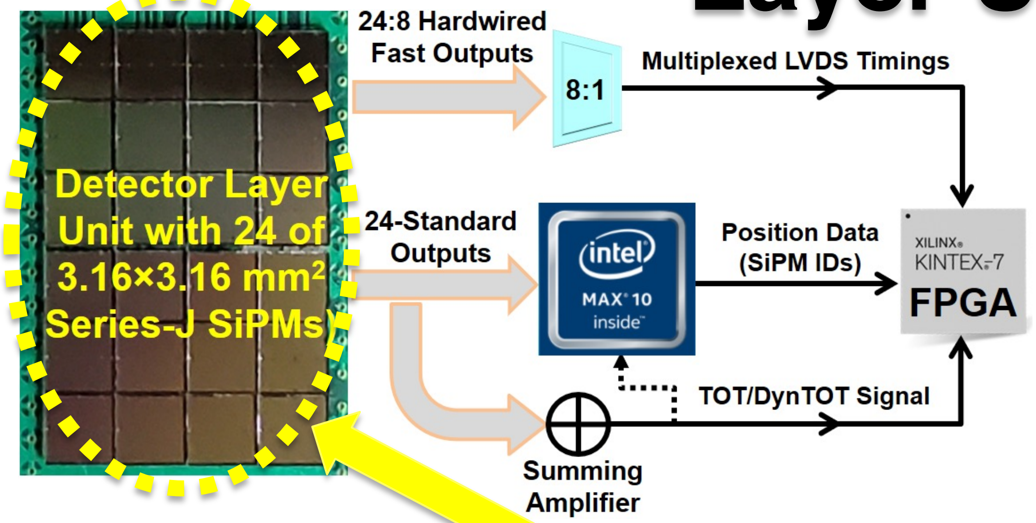
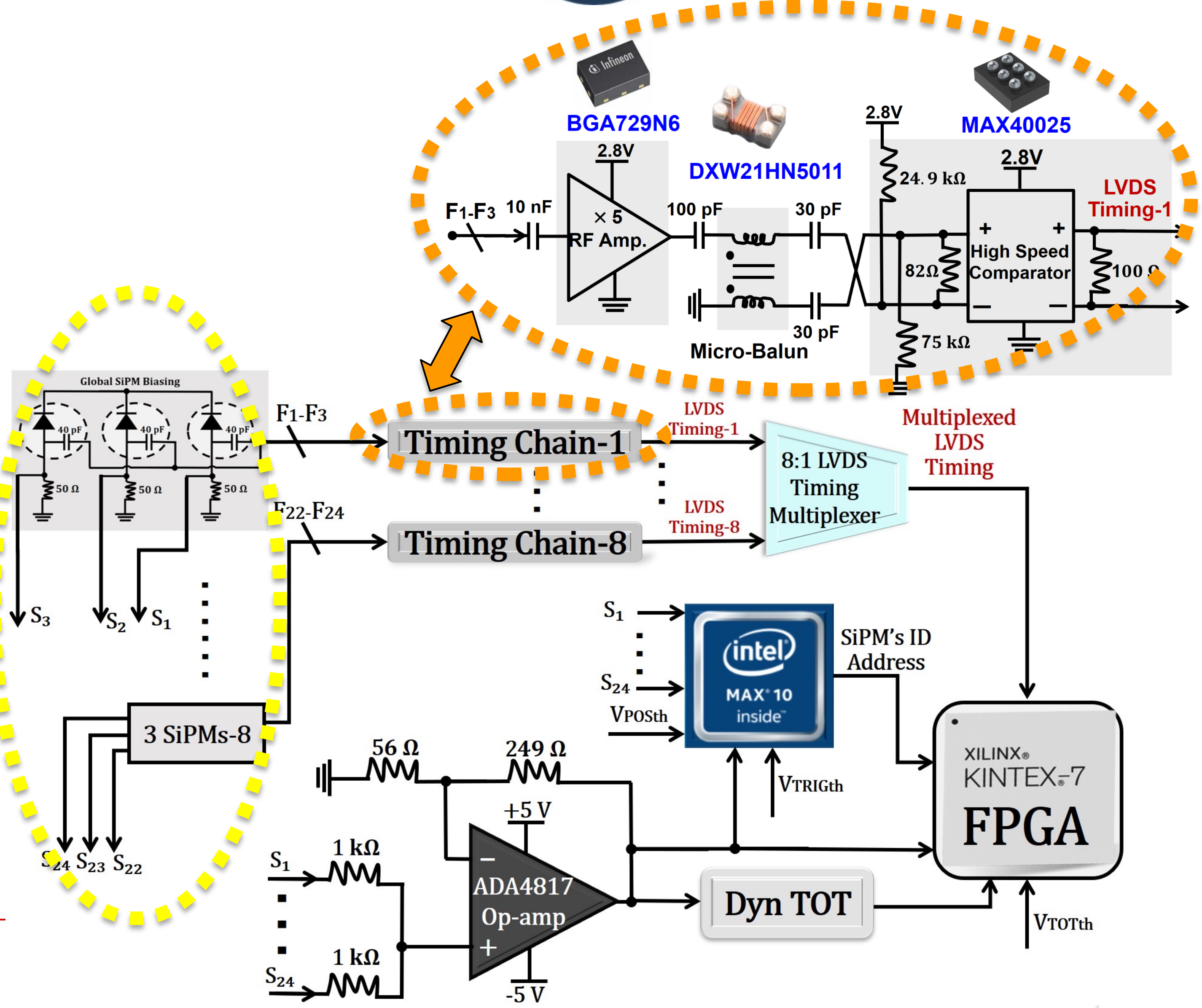


- **Hardwired each 3 SiPM fast outputs**
  - **Creating a 24:8 multiplexing ratio**

- J. W. Cates, C. S. Levin, Physics in Medicine and Biology, 2018
- S. Pourashraf, et al, Physics in Medicine and Biology, 2021
- S. Pourashraf, et al, IEEE TRPMS, 2022



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Multiplexing of Timing Channels

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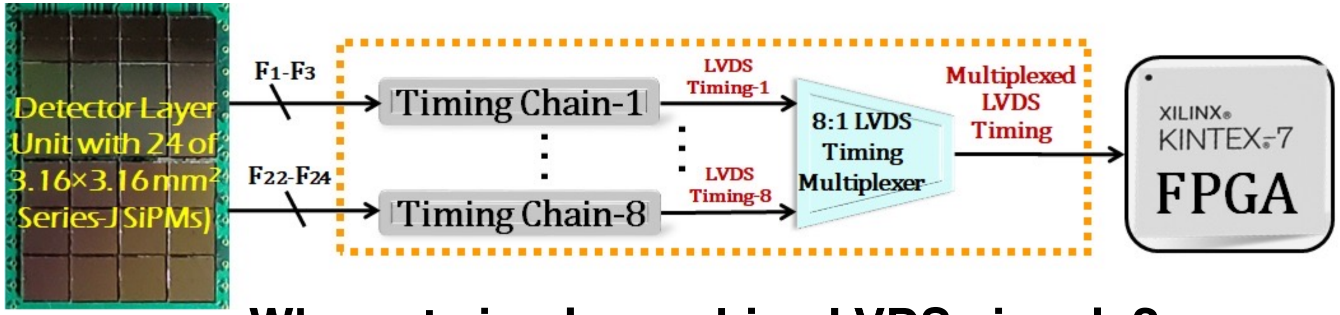
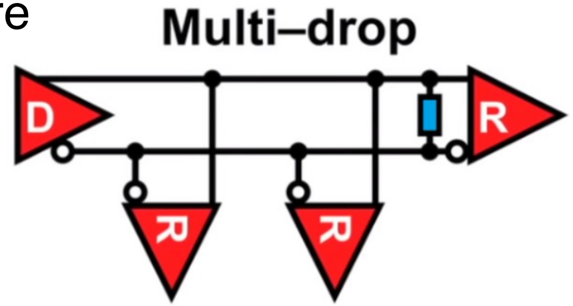


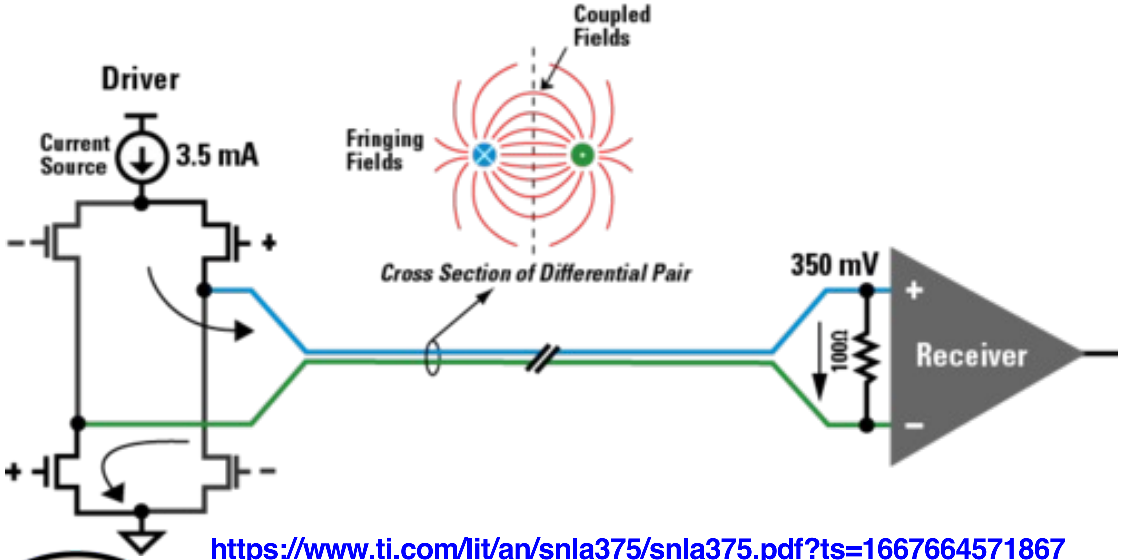
- Not aware of an electronic component to efficiently combine our sharp edge LVDS timings!

Why not simply combine LVDS signals?

- Standard LVDS has several advantages, but are current mode drivers not voltage!



- But our case, several drivers (D) hanging off a main bus line with one receiver (R) at the end!



https://www.ti.com/lit/an/snla375/snla375.pdf?ts=1667664571867

- Impedance mismatch and reflection due to stubs (unterminated length of drivers to the main bus)
- Needs careful considerations
  - Otherwise signal integrity issue, increased jitter, and loss of information

Our 24:1 Timing Multiplexing Approach

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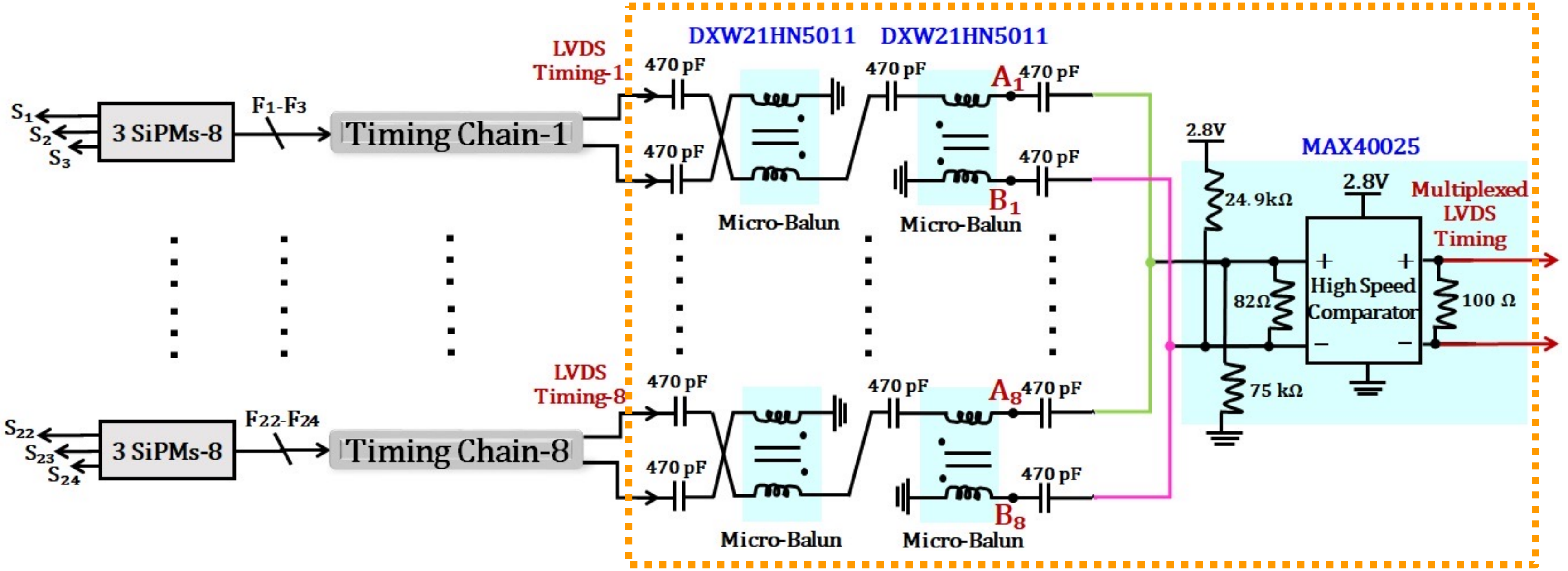
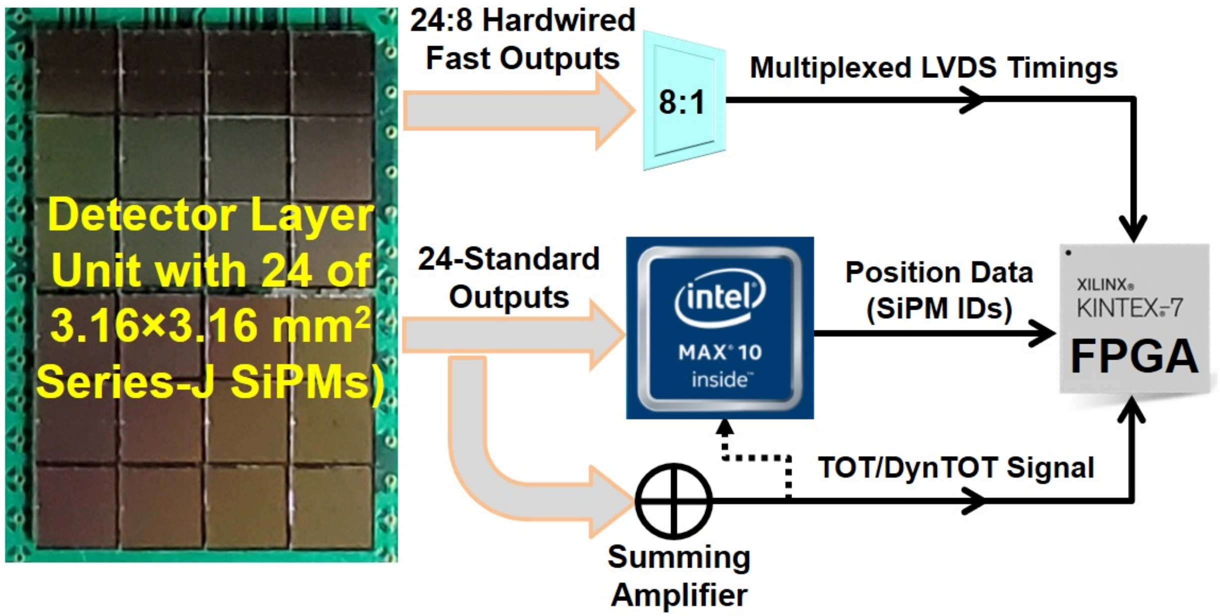


- **Only passive micro-baluns and one extra comparator used**
  - Saving footprint
  - Cost effective
  - Power efficient

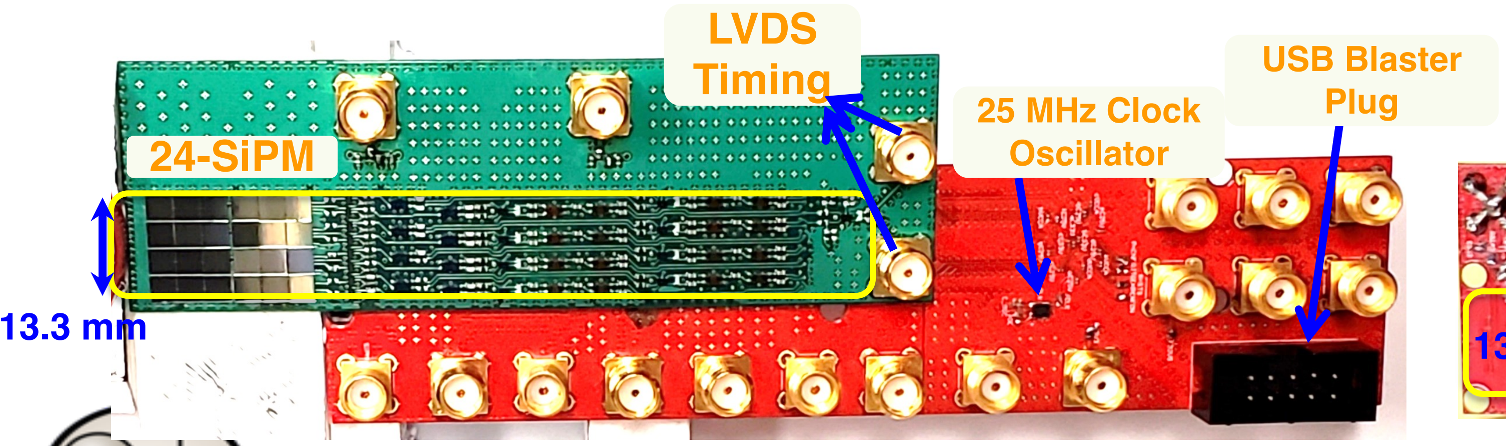
Just 4.5 mW/Channel extra power dissipation!

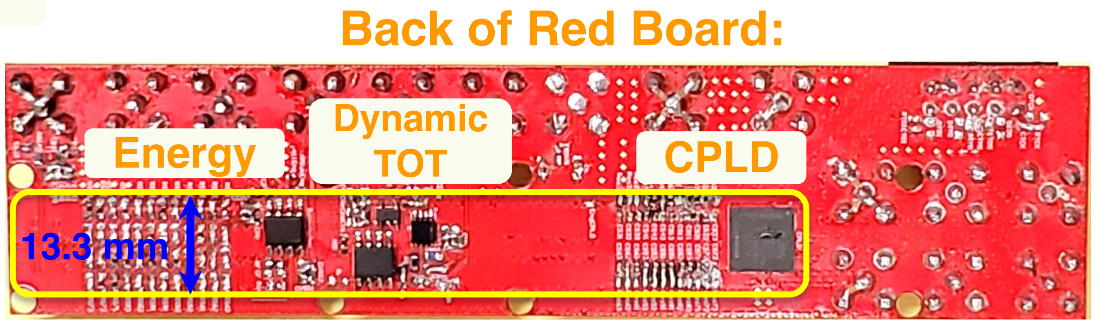
- Converting 8-LVDS timing signals to single-ended outputs using passive micro-baluns
- Then again converting these single-ended outputs to differential signals using micro-baluns
- Finally, **hardwiring these 8 differential timing outputs at nodes $A_{1...8}$ & $B_{1...8}$** inputting the differential pins of the last MAX40025 comparator to produce the final LVDS timing channel

PCBs for System Development



- **Compact and scalable**
  - Timing chain implemented in 13.3 mm width of a 4-layer FR4 PCB (green board)
  - 4x6 array of 3x3 mm² SiPMs on timing board
  - Energy chain implemented in 13.3 mm width of a 6-layer FR4 PCB board (red board)





PCB and Physical Implementation

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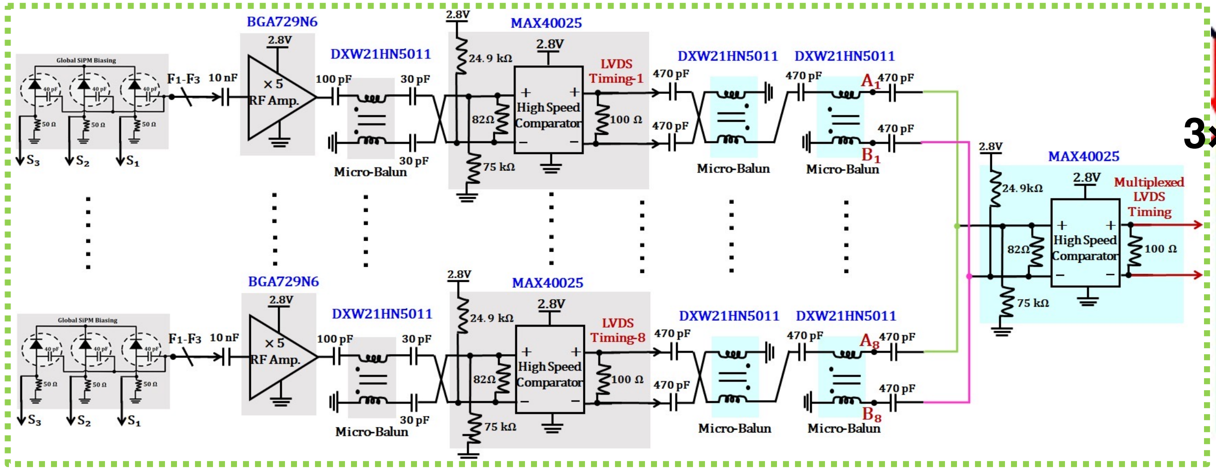
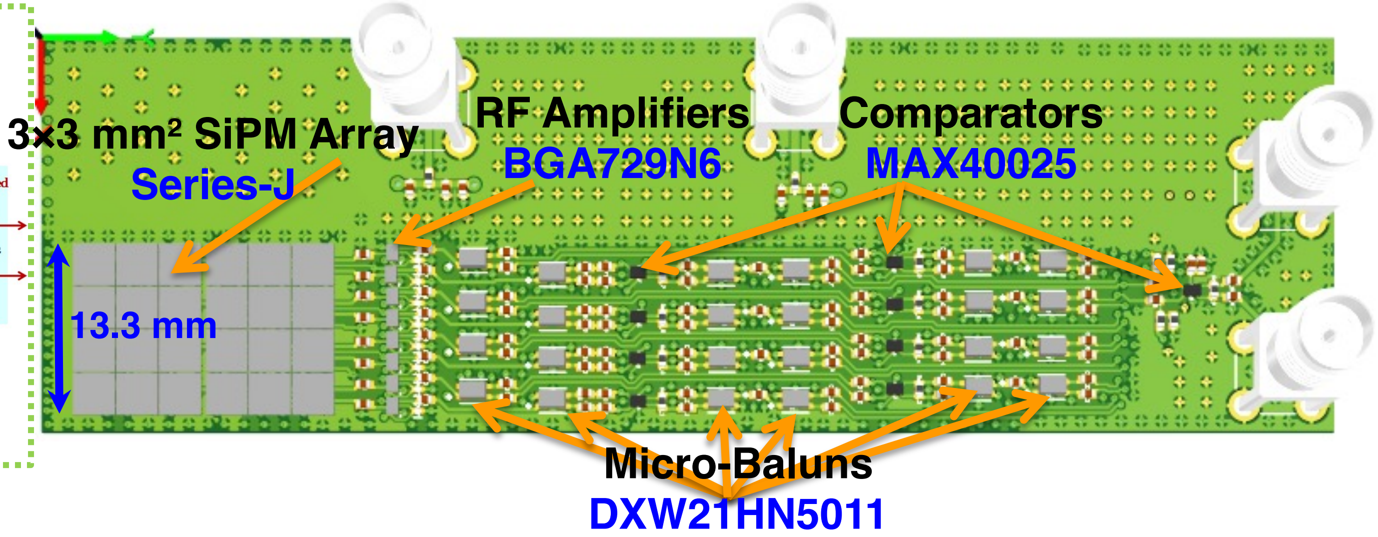
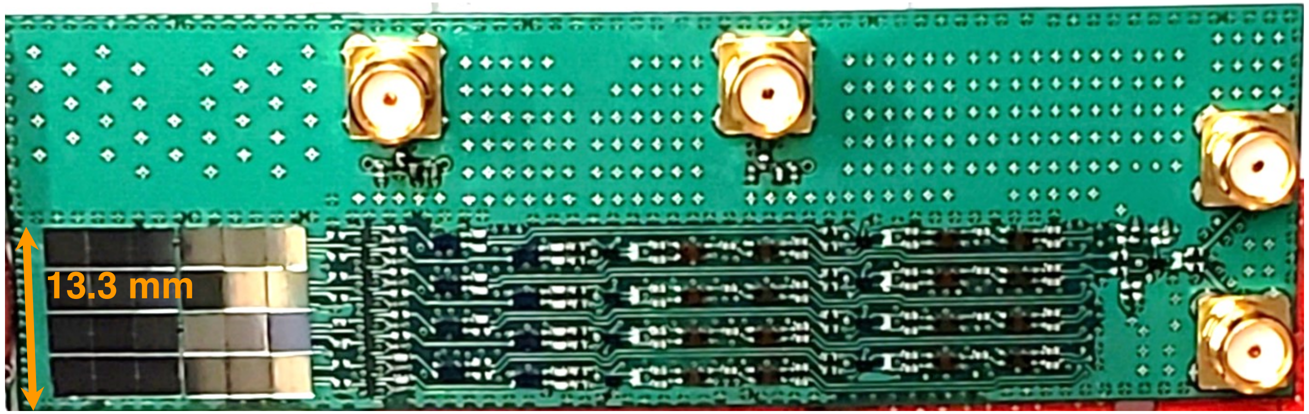


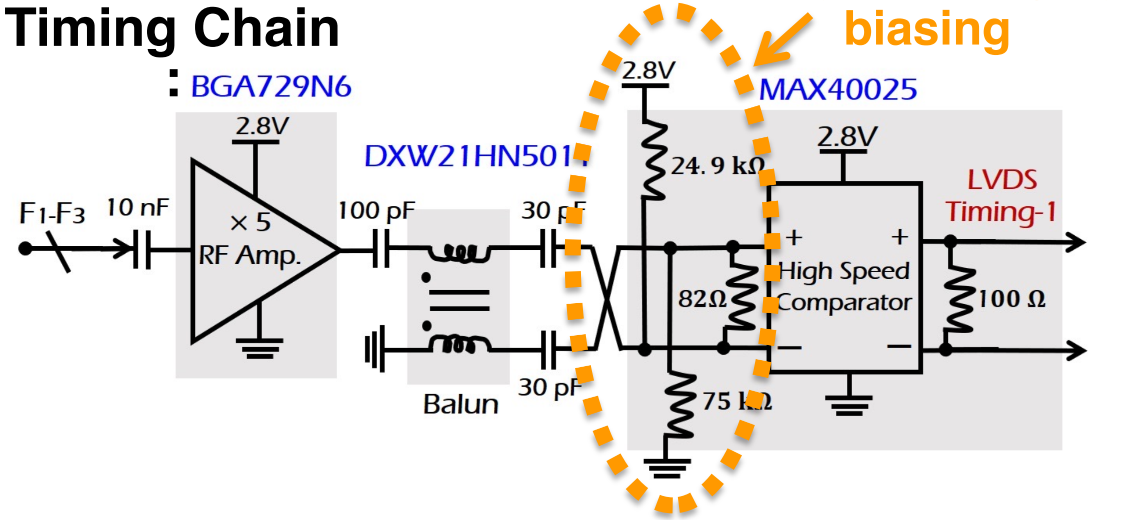




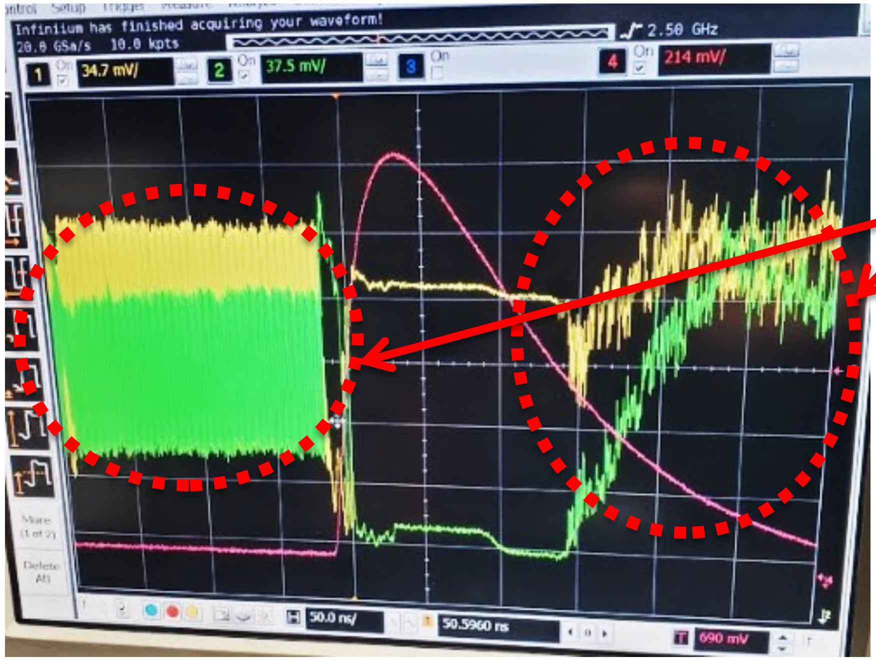
- **Multiplexing chain:**
  - **Didn't increase the 13.3 mm width of our PCB ☺**
    - ✓ **High sensitivity remains**
  - **Increased the length of PCB only ~27 mm**
    - ✓ **Should not have effect on increasing jitter as the timing signals are already digitized! ☺**

Fail-Safe Biasing for Comparators

One channel Timing Chain



- **External fail-safe resistive biasing at the differential inputs of all MAX40025 comparators**
  - It provided 2.1 V common mode voltages for comparator's positive and negative inputs
  - It also provided V_{id}= - 2.5 mV dropped on 82 Ω line termination resistors of comparator to clean up the LVDS timing signals at idle line states



- Careful selection of resistive network is needed as it can introduce more jitter
- **In our system, V_{id} can be <2.5 mV as the noise level is very low (~1 mV)**

Experiments with 24:1 Timing Multiplexing Readout

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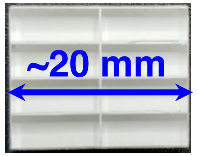
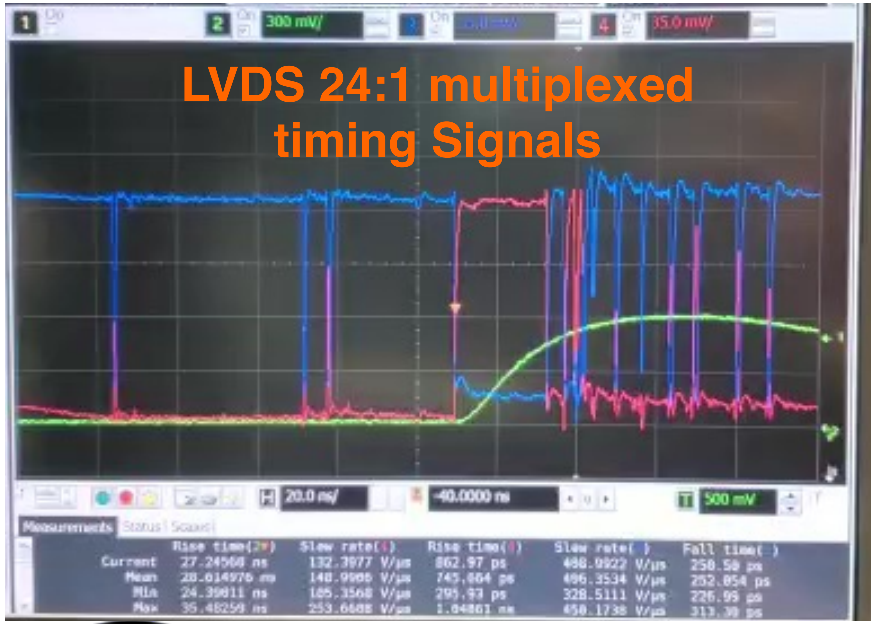
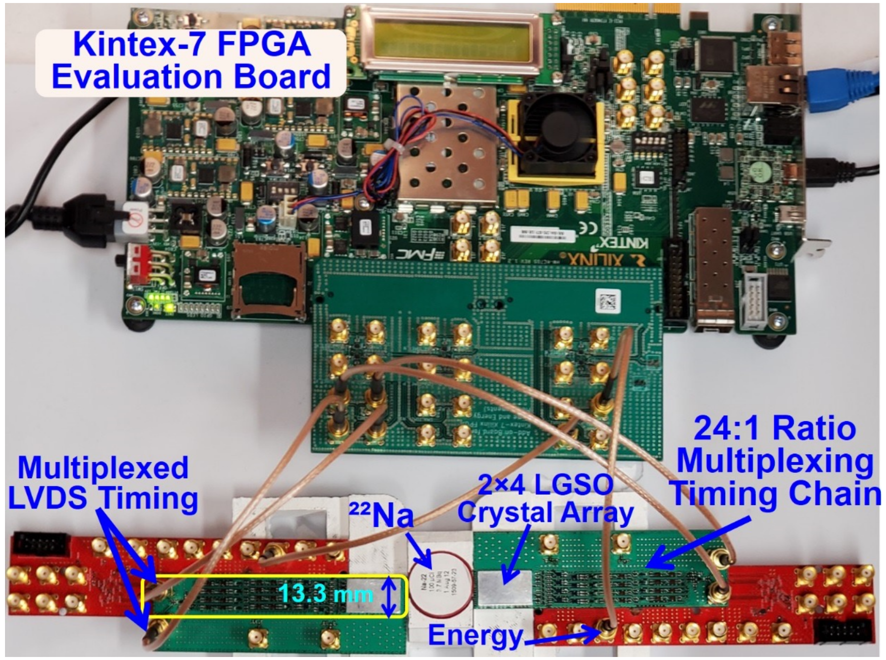
- LVDS 24:1 multiplexed timing signals of one detector unit (**Positive** & **Negative**)
  - **Using 2x4 array of 3x3x10 mm³ fast LGSO crystal coated with $BaSO_4$ reflector**
  - **Triggered with Energy Signal**

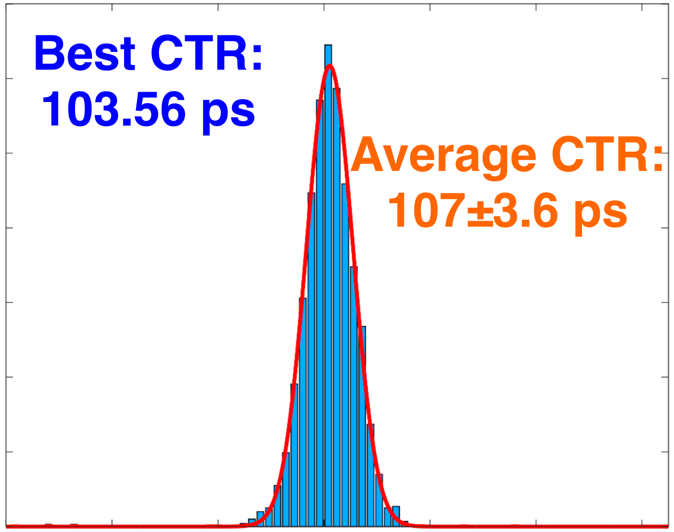




- Combined 24 SiPMs' fast output
  - 24:1 SiPM-to-channel multiplexing
- Average CTR of **107±3.6 ps** over multiple measurements @optimum 31 V SiPM biasing
  - **Near to 100 ps CTR as single 10 mm crystal detector ☺**

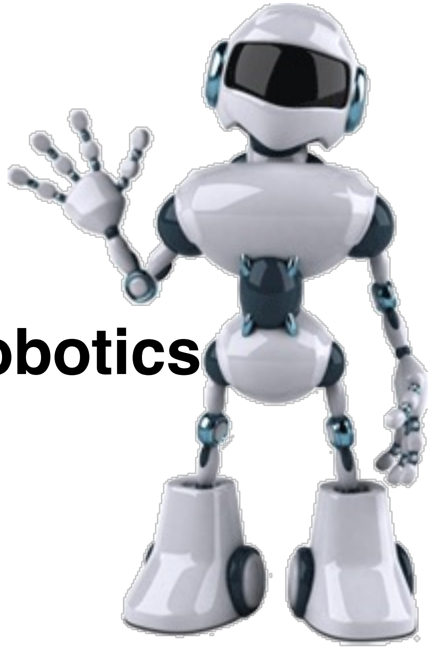


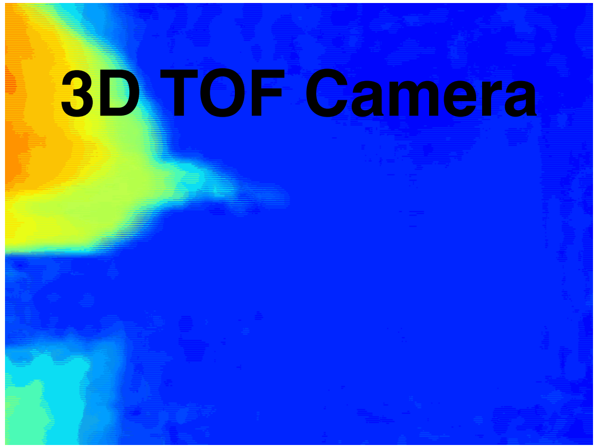
CTR of 24:1 Multiplexed Timing



Some Other Time of Flight Applications

Robotics





- **This 24:1 timing multiplexing method also has the potential to be used in other TOF applications due to:**
  - Simplicity and Scalability
  - Cost/Area/Power Efficiency
  - **Most importantly, its “Ease of Implementation” & “Robustness”**

Discussion

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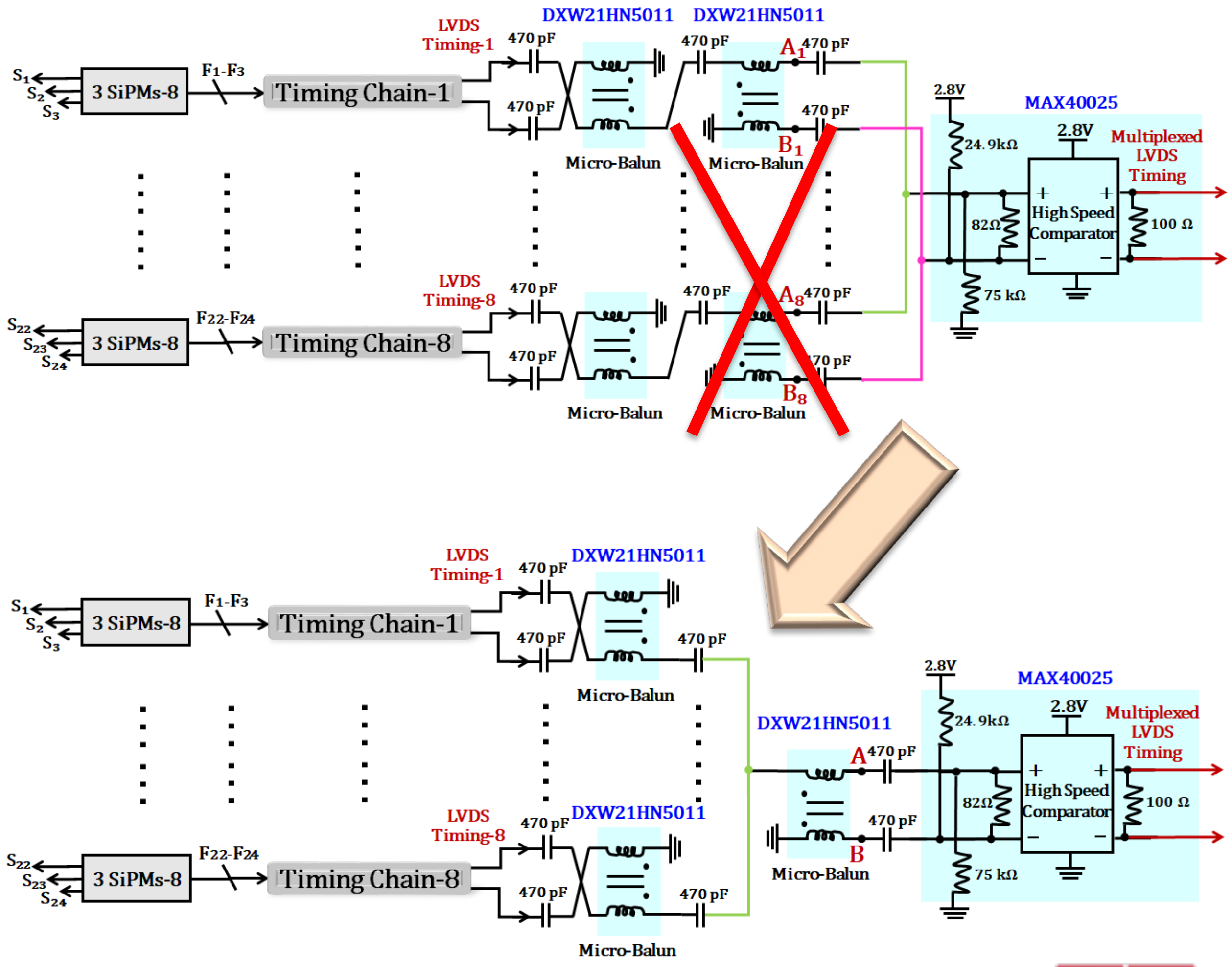
- **Effective implementation of compact TOF-PET detector layer**
  - Combined 8-timing channels (24 SiPM's fast outputs)
  - **107 ps FWHM CTR** for 20 mm long crystal elements
  - 1.1 W power dissipation per detector unit layer
- **Simpler possible version of the multiplexing scheme**
  - Should mostly perform the same
  - Saving 7 micro-baluns
- **There is a high potential this multiplexing scheme can serve more than 24 SiPMs (e.g. 48)**



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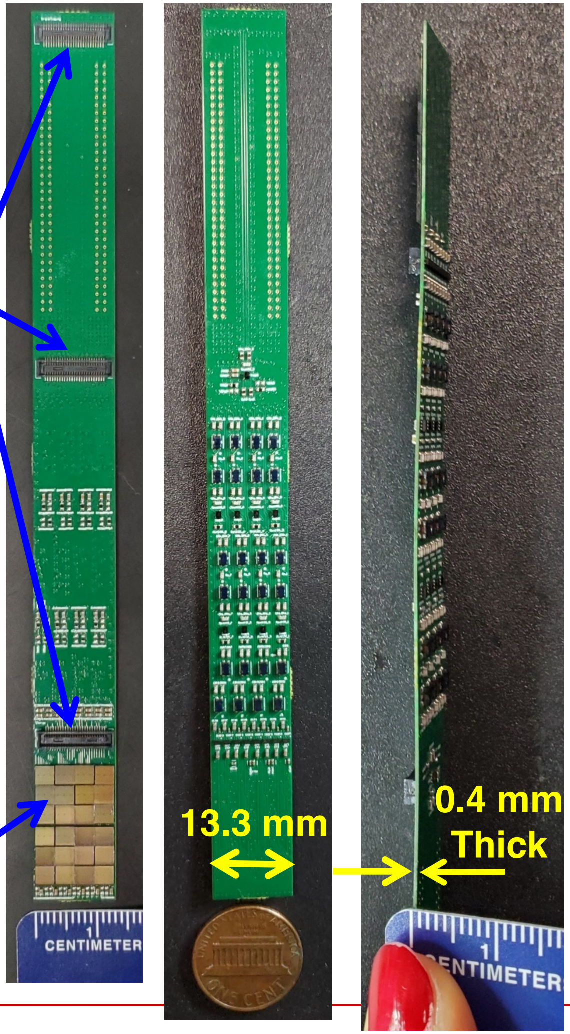
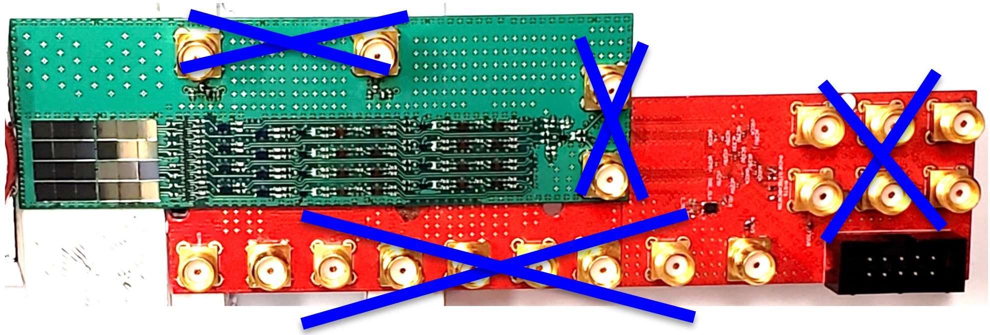
Next Steps:

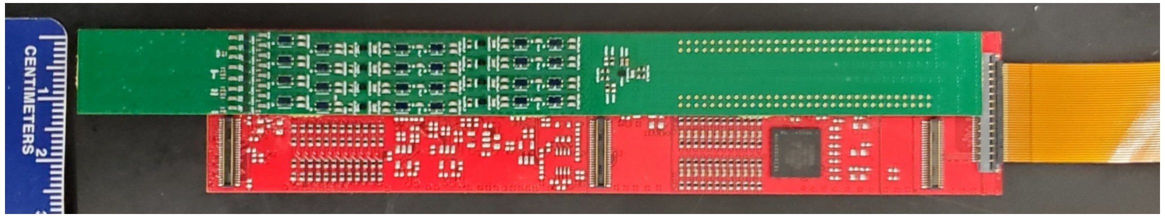
- **Currently** testing SMA-less Detector Layer Units (highly compact)
- **Timing** measurements with **green 4-layer FR4 PCBs** of **13.3 mm width** & **0.4 mm thickness**
- 4x6 array of 3x3 mm² SiPMs (photo-sensors) on back of green timing board



Previous Readout with SMA Connectors



Under Test SMA-less Readout
(Challenging to test)



- Each two timing boards will be mounted on a **10-layer FR4 red board** assigned for energy and positioning assessment

Getting Closer to Final Goal:
Partial-Ring TOF-PET (16 Detector Modules)

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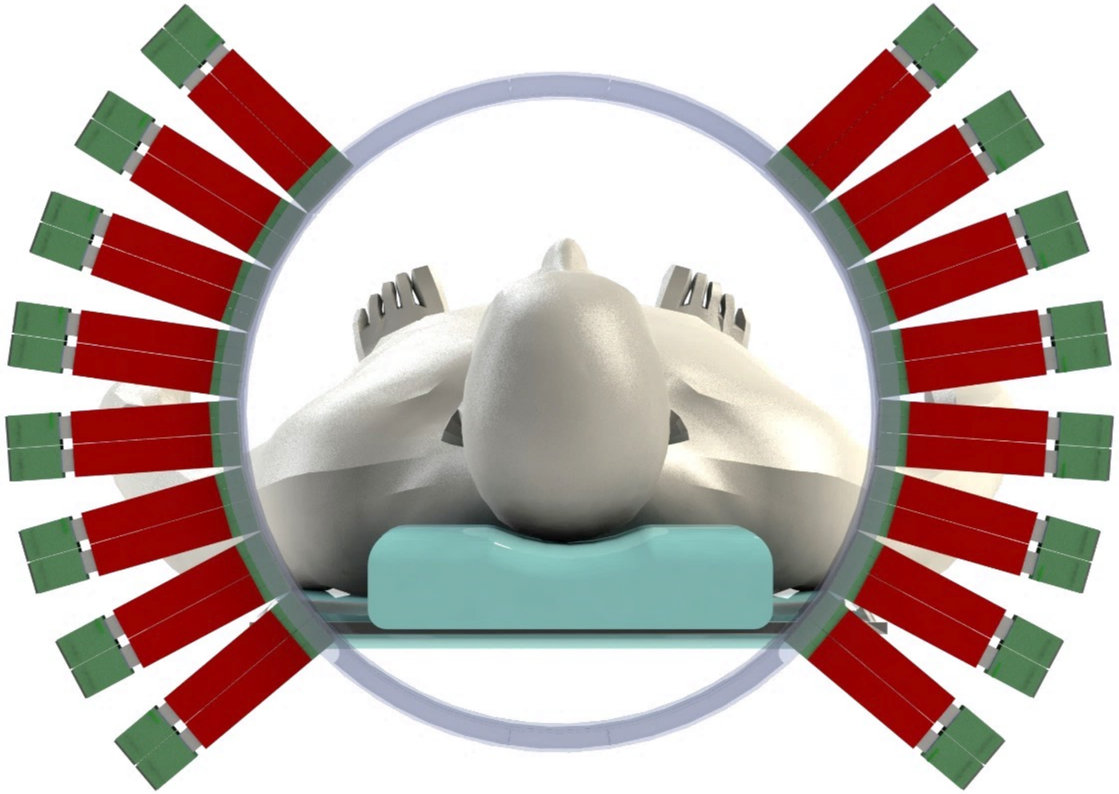

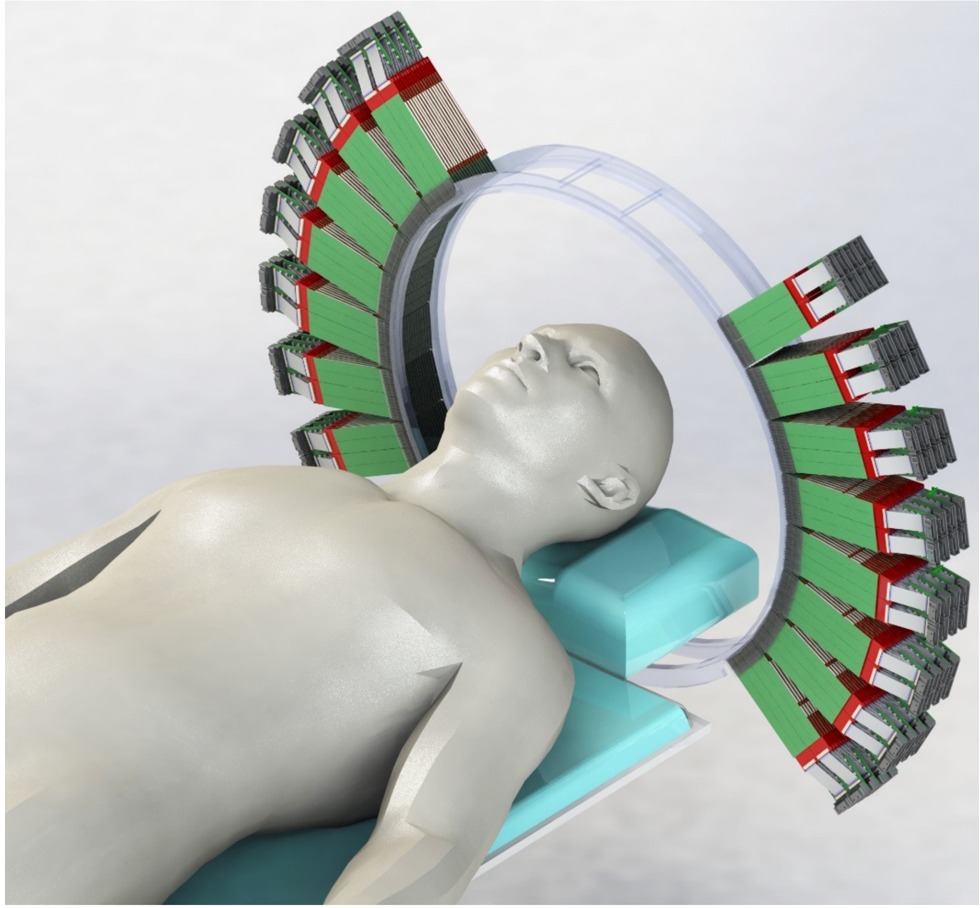

Thank You!

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and

Mentors:

Drs. Andrei Iagaru & Craig Levin

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