Modeling Data Management for a Next Generation Photon Counting CT Scanner

John Londt – GE HealthCare

Overview

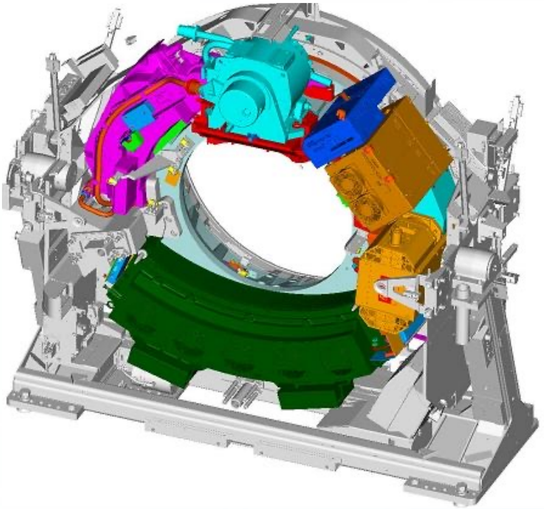
This presentation will describe using a SimEvents digital twin model of a novel photon counting CT scanner.

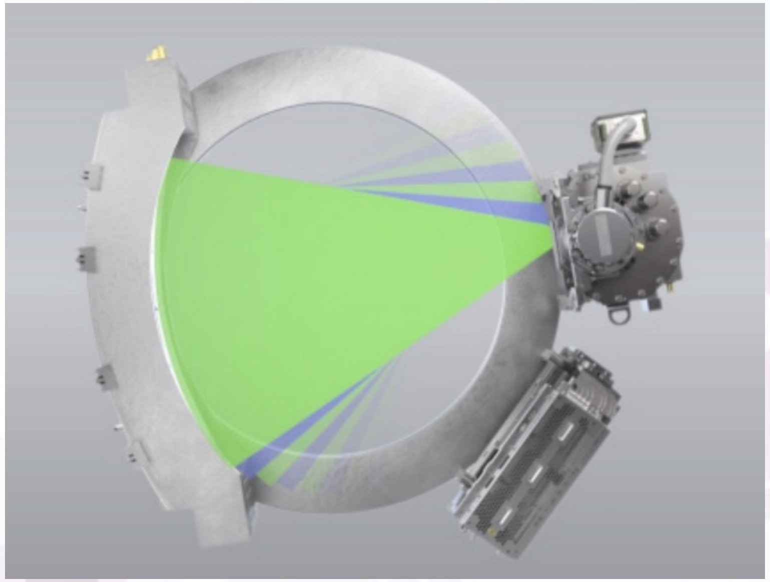
Topics

- Overview on CT Imaging
- Photon Counting and Spectral Imaging
- System Design Challenges & Solution Space
- SimEvents Digital Twin Model
- Example Simulation Results

How does a CT scanner work?

- A modern CT scanner consists of a
  - Gantry containing a slipring, detector, x-ray tube
  - A slip ring is an electromechanical device that allows the transmission of power and electrical signals from a stationary to a rotating structure.
  - Operator console for user control and image storage
  - Compute cabinet to house GPU-based image reconstruction
- Typical performance specifications:
  - Detector coverage up to 160mm to enable whole organ coverage
  - > 200,000 detector elements
  - ~10kHz sample rate
  - Image matrix sizes up to 1024 × 1024
  - >100 kW of x-ray tube power

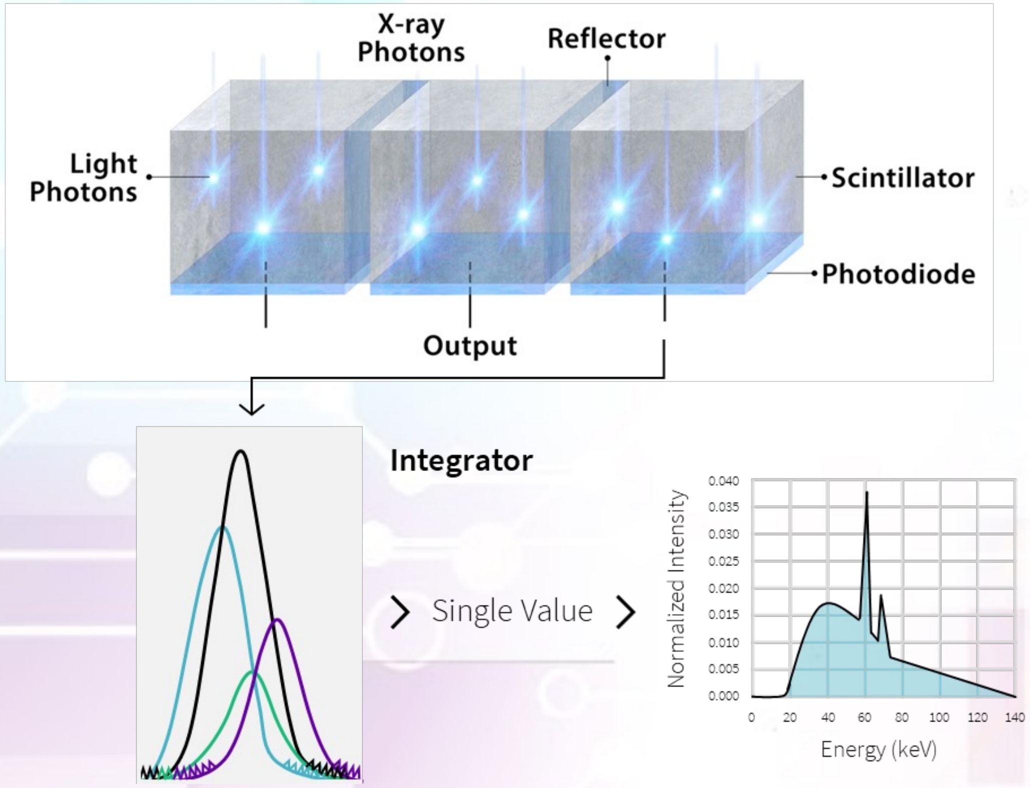




CT Physics 101

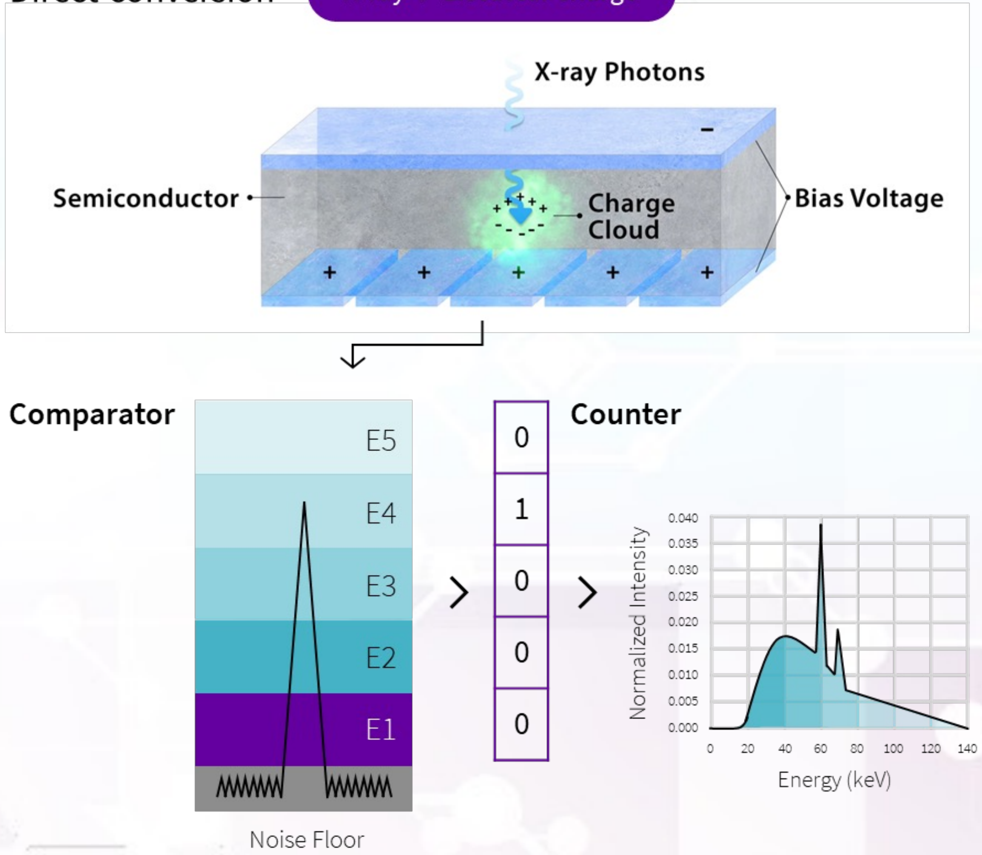
Energy Integrating Detector (EID)

Indirect conversion X-ray → Light → Electrical Charge



Photon Counting Detector (PCD)

Direct conversion X-ray → Electrical Charge

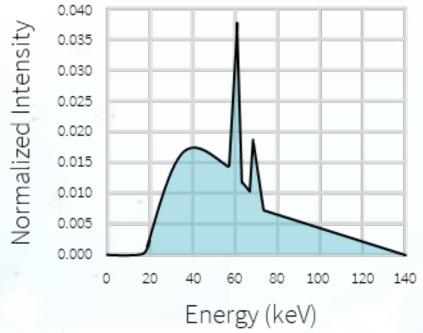


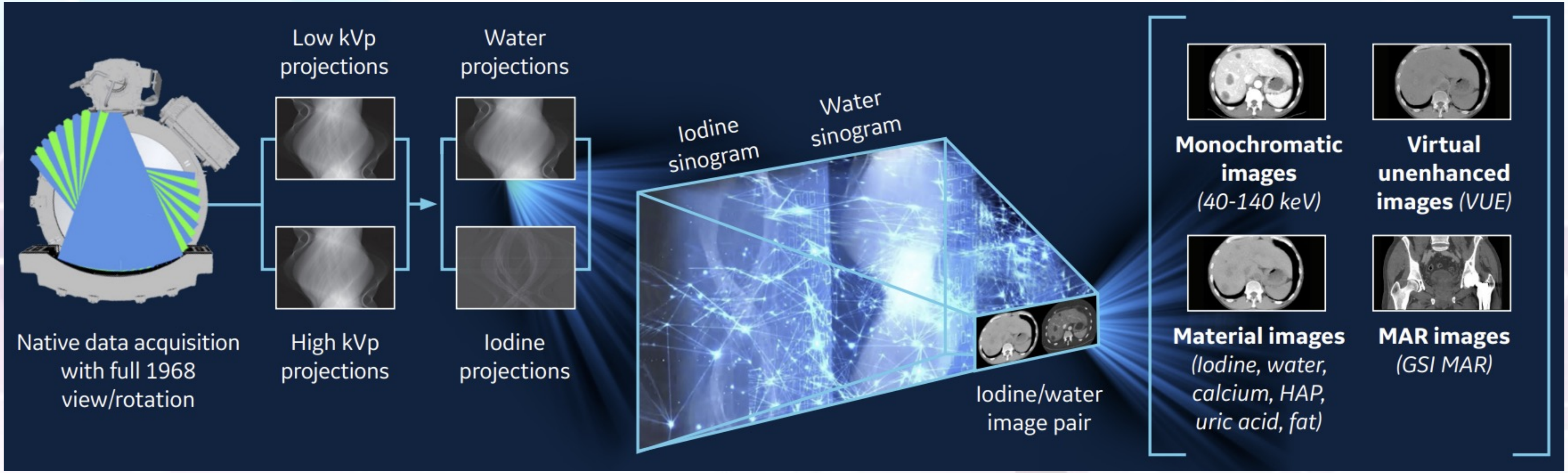
Photon Counting Detectors offer improve detection efficiency and spatial resolution and inherent energy discrimination.

Learn more, watch the documentary here: [YouTube Deep Silicon Project]

What is Spectral Imaging?

- Energy integrating detectors cannot differentiate the energy of the detected photons
- Current CT systems rapidly switch between the tube voltage to create samples separate spectral information that may be used to generate images with improved information about the material the x-rays passed through





IMAGES COURTESY OF UNIVERSITY HOSPITAL HENRI MONDOR (APHP), PR. ALAIN LUCIANI, CRETEIL (94), PARIS, FRANCE

Clinical Example: Using Spectral Imaging for Improved Liver Lesion Detection

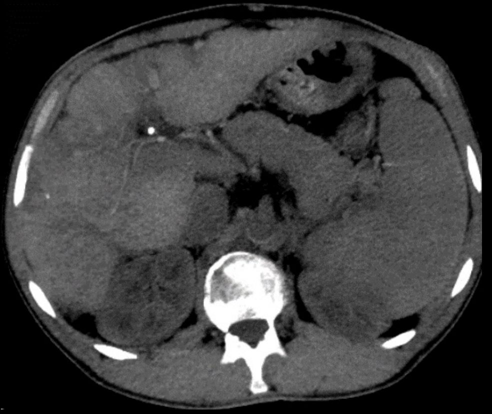
Scan type	GSI 80mm helical +
Rotation time, s	0.8
Pitch	0.992
Slice, mm	1.25
mA	275
Noise index	14/16/20
Kernel	GSI Std
ASiR-V, %	40
CTDIvol, mGy	4.5, 9
DLP mGy.cm	275, 336
BMI	23

History: Hepatic carcinoma (HCC)

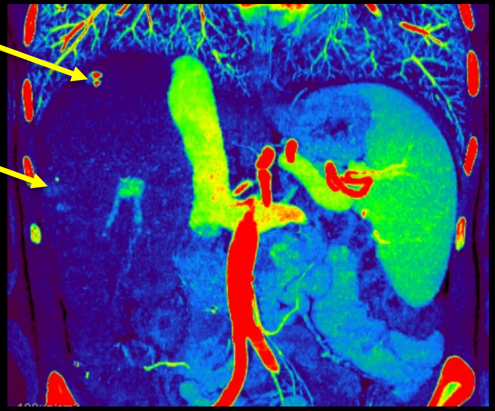
Scan purpose: HCC Follow-up with 3 phase chest, abdomen, pelvis exam

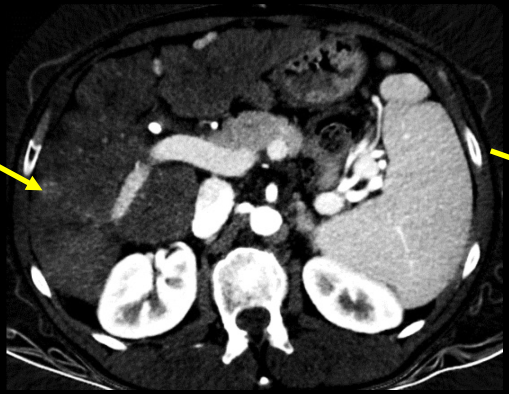
Findings: Small liver lesions are not well visualized on 120 kV images when compared to an iodine map and 50 keV images.

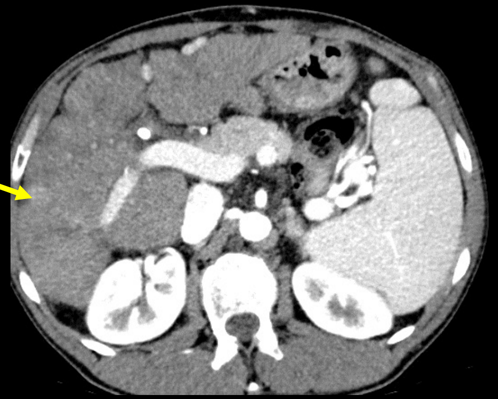
The use of low- energy monochromatic images and iodine specific images in oncologic CT can improve lesion detection by improving the contrast between a hypervascular lesion, a hypovascular lesion, and normally enhancing parenchyma.[1]

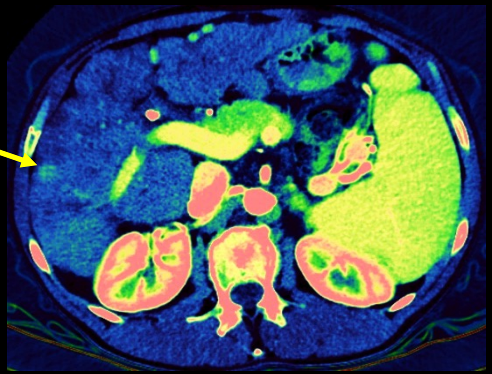

VUE


Arterial injected contrast phase 120 kV


Iodine overlay


Iodine map

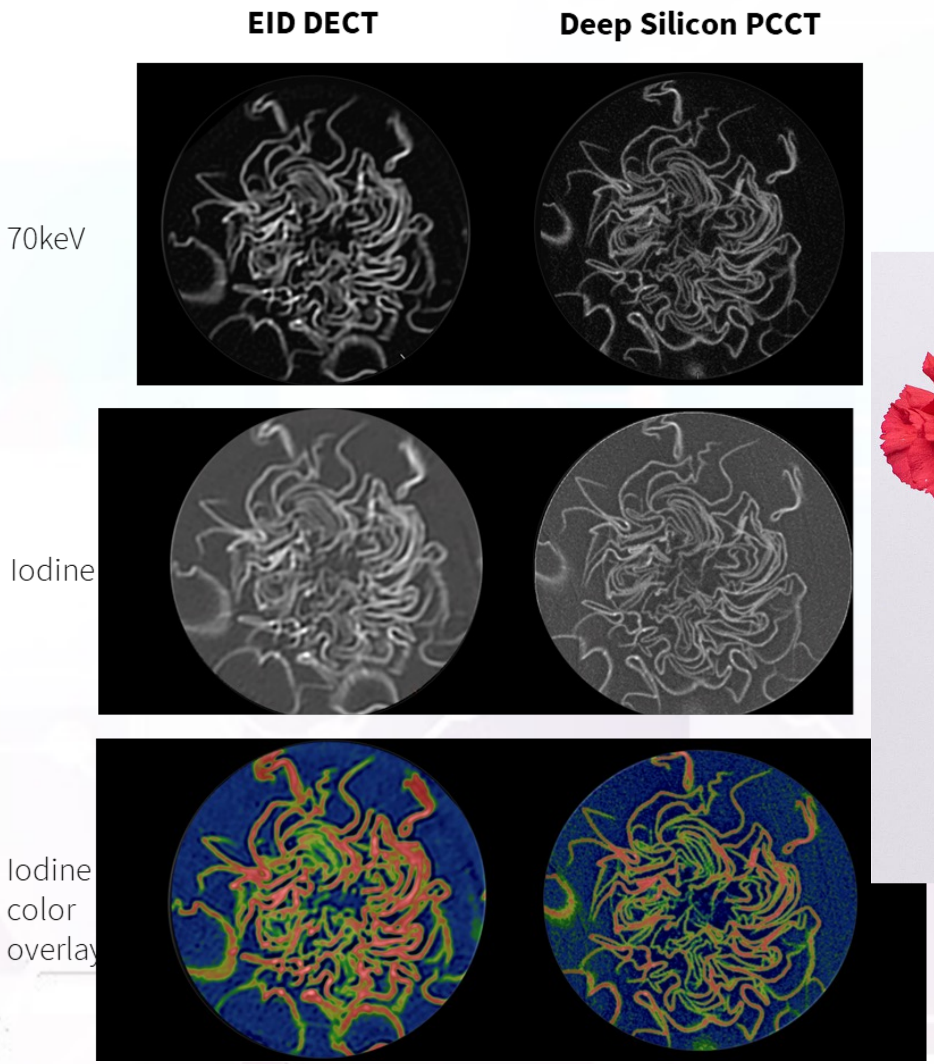

Arterial injected contrast phase, 50 keV


Iodine overlay

1. Agrawal, M. D., Sahani, D. V. (2014). Oncologic Applications of Dual-Energy CT in the Abdomen. RadioGraphics, 34(3), 589–612.

Photon Counting Potential Benefits

- The photon counting detector detection efficiency and energy discriminating nature allow for improved spatial resolution and spectral imaging capabilities
- The images to the right are of a carnation placed in an Iodine solution to absorb the imaging agent into the fine vasculature of the flower



System Design Challenges

- This creates numerous challenges in the overall data management system design of the CT scanner:
  - Data transmission
  - Efficient data storage and retention
  - Image reconstruction
  - Networking of reconstructed images
- All of these contribute to the overall clinical exam throughput capabilities and cost of the system.

CT Scanner Data Rates

- Scanner data rates are limited by the gantry slipring for challenging applications – e.g. imaging at gantry speeds as fast as 0.23 s per revolution
- Current generation sliprings are 40 Gb/s, ~1 GB of scan data per rotation at 160 mm of scan coverage along the patient long axis
- This presents a challenge for next generation photon counting scanners since increasing spatial and spectral resolution requires increased data bandwidth
  - Smaller detector elements for improved spatial resolution
  - Increasing the number of samples per rotation for improved azimuthal resolution
  - Increased samples per pixel for photon energy discrimination
- Next generation CT detectors could increase data rates by up to 2 orders of magnitude!

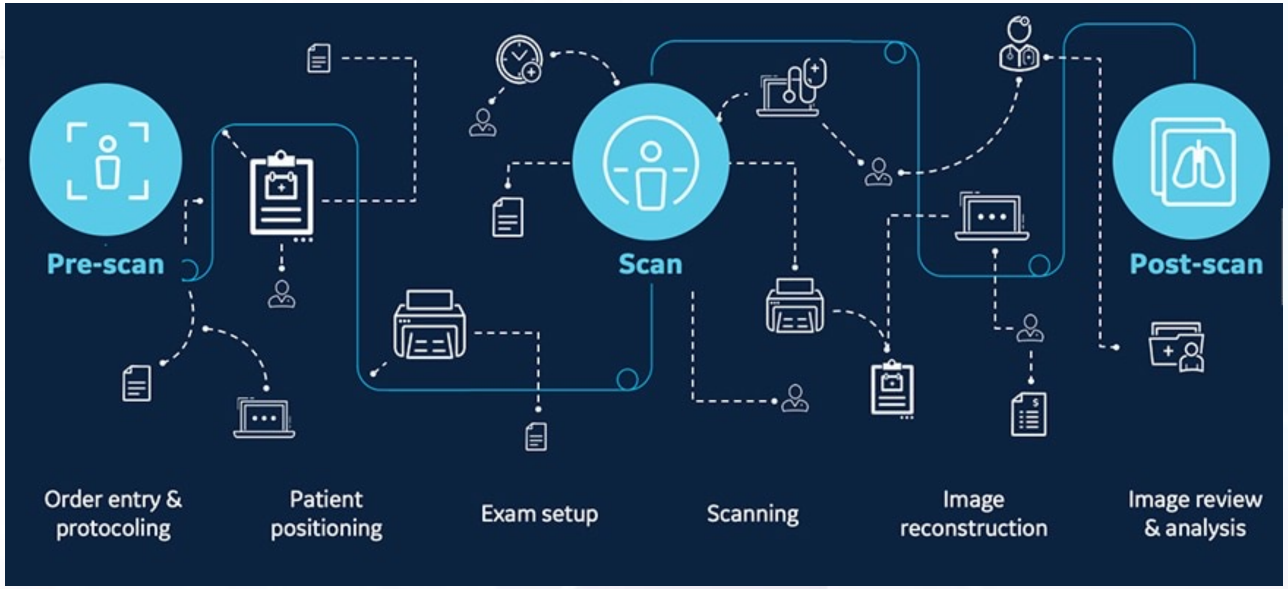
CT slipring

Solution Space

- Increase data rate
  - Slipring bandwidth could be increased, but limited by current technology and cost – up to 80Gb/s
- Reduce data dimensionality
  - Data compression
  - Combining data to reduce spectral and/or spatial resolution
  - Reducing detector coverage but preserve spectral/spatial resolution
- Buffer data
  - Data could be buffered at data transmission bottlenecks (e.g. slipring, recon processing)

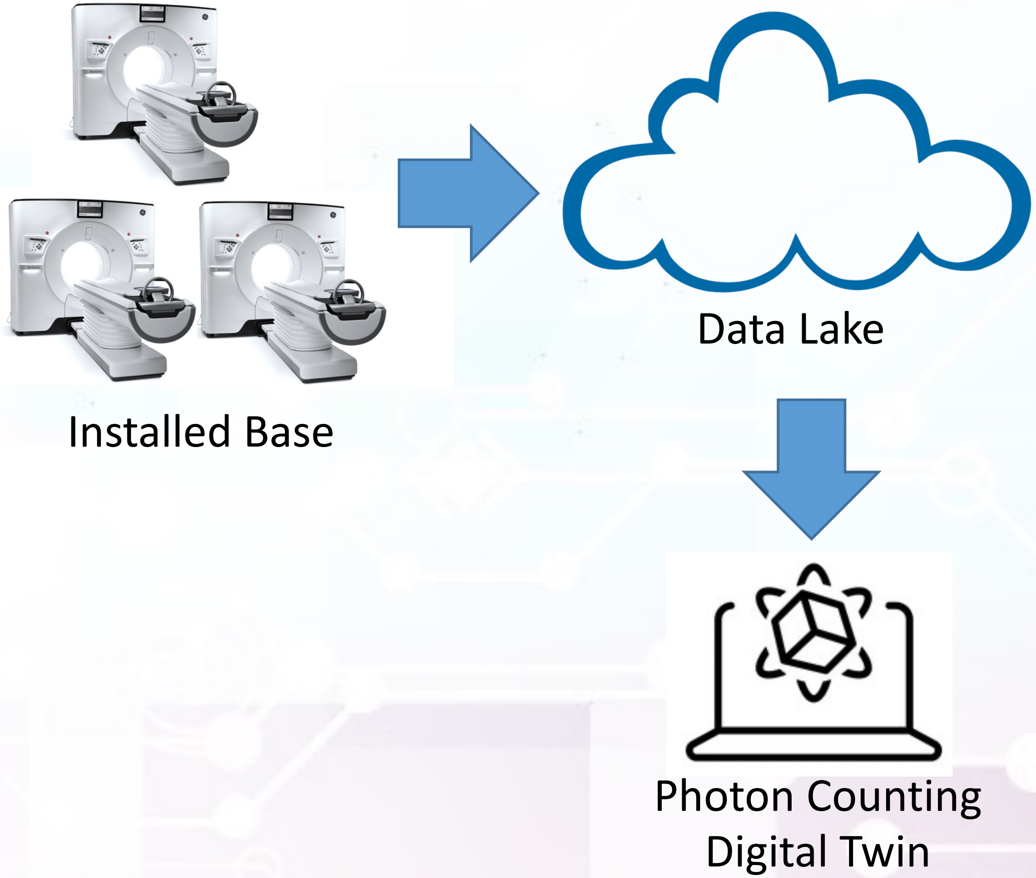
Requirement Discovery

- User requirements
  - Scan time performance
    - Inter-scan delays < 1s
    - Exams per hour
  - Real-time image review for scan status
    - Time to first image
    - Image latency
  - Diagnostic image reconstruction
    - Time to reconstruct image volume
    - Networking speed
    - Post-processing time
  - Data retention
    - Raw scan data
    - Image data
- System design goals
  - Support the same patient exam throughput as current scanners



Photon Counting Digital Twin

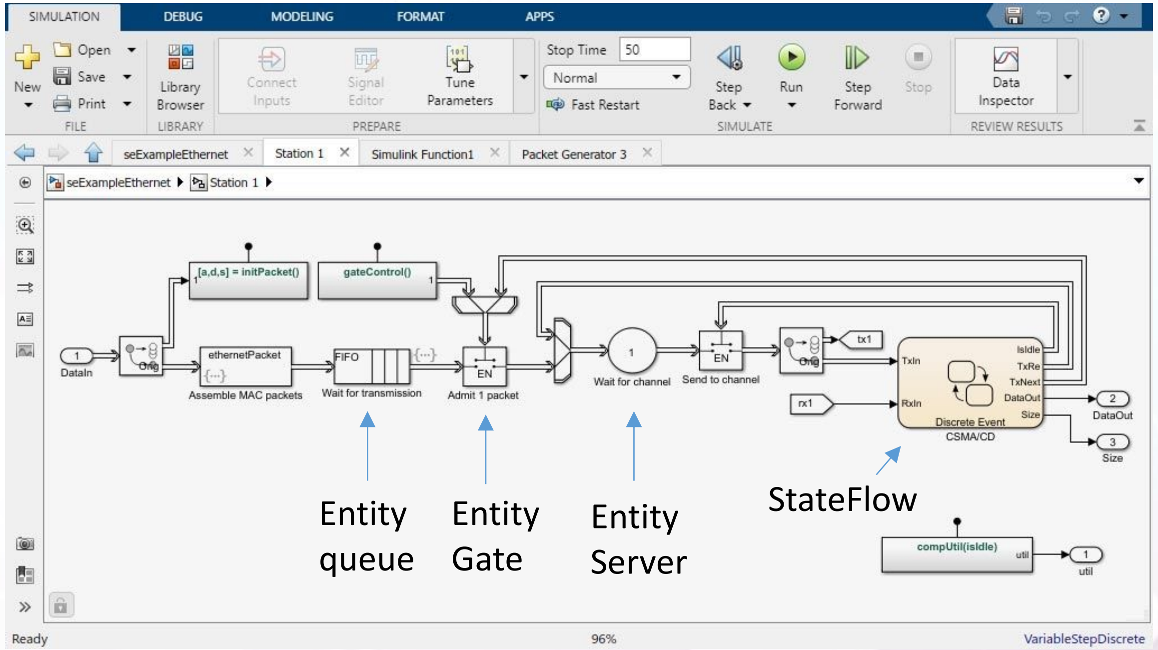
- To evaluate system design tradeoffs for a new photon counting CT platform, we clinical scan usage data from installed base systems.
- This anonymized data includes types of exams, exam timings, scan parameters and image reconstruction.
- This allows to virtually test drive our Photon Counting Digital Twin with real customer workflows and exam volumes to understand how system design tradeoffs will affect real world performance



SimEvents For System Modeling

From MathWorks website

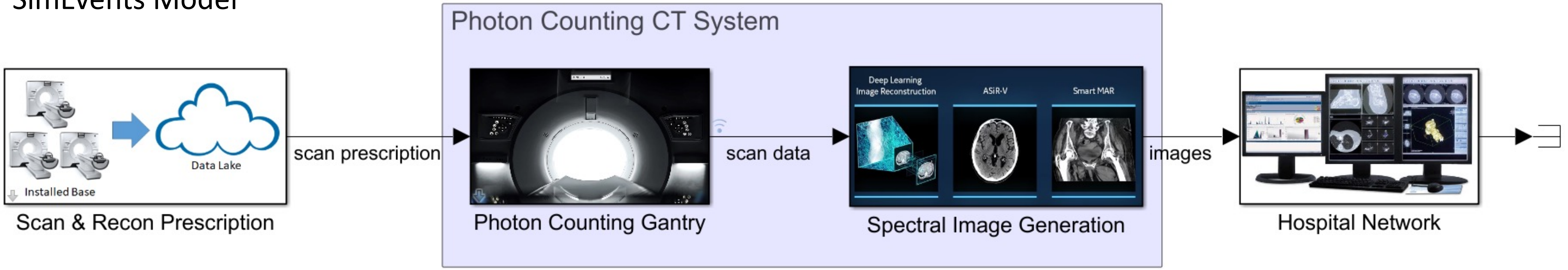
- SimEvents® can be used to model message-based communication in Simulink or any event-driven process with its discrete-event simulation engine and component library for analyzing event-driven system models and optimizing performance characteristics such as latency, throughput, and packet loss. Queues, servers, switches, and other predefined blocks enable you to model routing, processing delays, and prioritization for scheduling and communication.
- With SimEvents you can study the effects of task timing and resource usage on the performance of distributed control systems, software and hardware architectures, and communication networks. You can also conduct operational research for decisions related to forecasting, capacity planning, and supply-chain management.



SimEvents PCCT Digital Twin Model

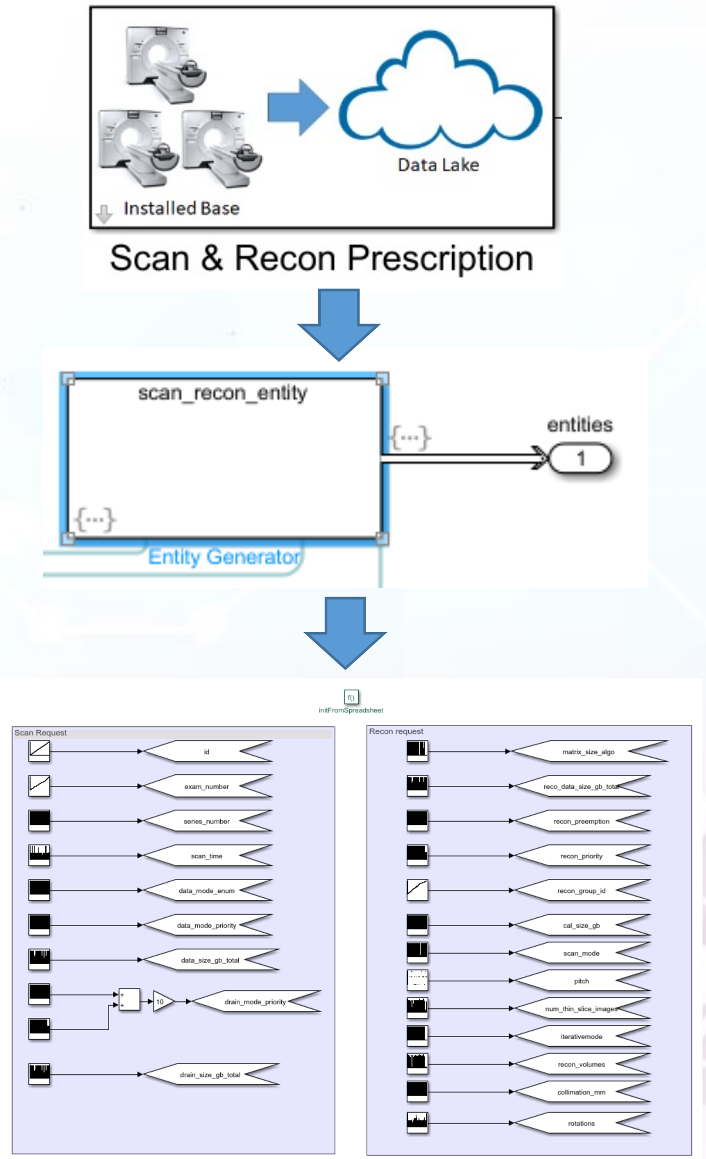
- To create the photon counting digital twin, the team decided to use MathWork's SimEvents to create a discrete events system model
- The model comprises 4 parts:
  - Transforming and augmenting legacy IB data into photon counting scan & recon request entities
  - The gantry model for generating and transferring raw scan data
  - Spectral image generation model for queuing and reconstructing scan data
  - Hospital network interface for image network queue management and post processing

SimEvents Model



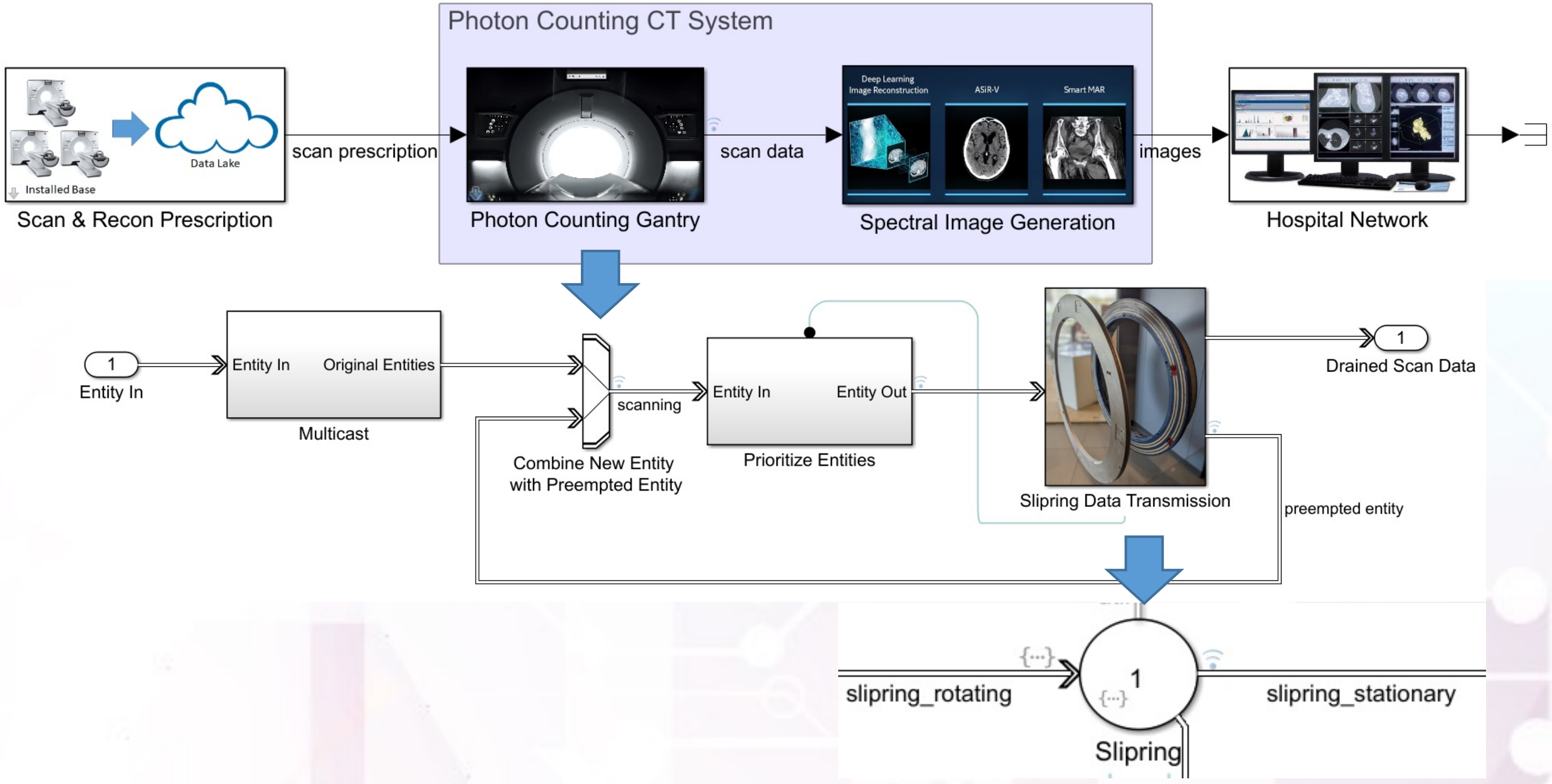
Scan and Recon Prescription

- Sites can opt-in to sending anonymized system usage information to the GEHC Data Lake
- Every scan and image reconstruction request is logged with relevant system parameters dictating scan duration, data rate, and recon complexity
- The timing of these events is logged and can be used to reconstruct clinical workflow timings for each exam and overall exam throughput
- IB installed base data is transformed-based on planned product changes
  - For instance, scan data and calibration vector sizes are much larger
- Structured CSV data is transformed to represent either a scan request and or a recon request
- Once the data is properly structured in CSV each row becomes an entity in SimEvents separated in simulation time by the timestamp of the original IB data fully simulating a customer's workflow



Photon Counting Gantry Model

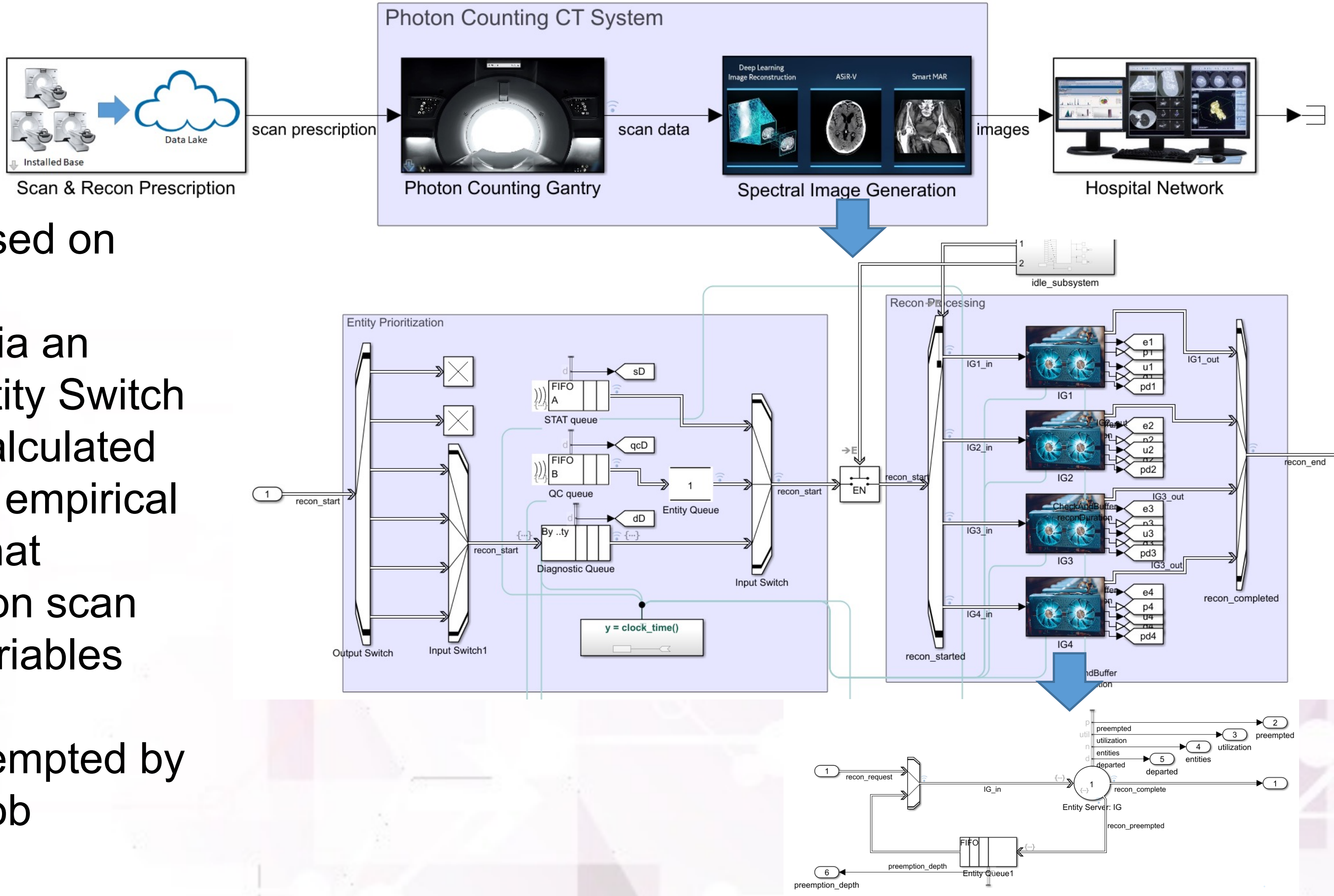
- The model of the gantry has an **Entity Server** representing the data transfer of the slipring and an **Entity Queue** to prioritize the transfer
- The entity server duration is calculated by a Matlab function that calculates data transmission duration by entity parameters (e.g. data size, scan duration) and workspace variables (e.g. slipring bandwidth)
- Data transmission can be preempted (e.g. a new scan) and queued if the data rate exceeds the slipring bandwidth



Server duration = f(entity.params, workspace variables)

Spectral Image Generation Model

- The Image Generation model has an **Entity Server** for each compute cluster (up to 4)
- Entity queuing is managed based on recon job priority
- Load balancing is performed via an Entity Gate and a Criterion Entity Switch
- The entity server duration is calculated by a Matlab function based on empirical performance measurements that calculates recon times based on scan parameters and workspace variables (e.g. compute performance)
- Each recon server can be preempted by higher priority reconstruction job



Model Execution

- The simulation test harness can manipulate both input entities and workspace parameters to explore solution space
- Input entities – scan & recon requests in CSV format from Data Lake
  - Entity timing (e.g. number of scans, recons, and timing for each request)
  - Scan data size
  - Calibration vector size
  - Recon complexity – number of projections, image matrix size, noise reduction algorithms applied, etc.
- Workspace parameters – control Entity server execution times
  - Slipring data transmission rate (Gb/s)
  - Data retention polity – number of scans/exams
  - Number of image generation compute nodes
  - GPU performance multipliers
  - Internal network link speed (Gb/s)
  - Post-processing duration (e.g. generating reformat images, 3D volumes, etc.)
  - External Image network transfer speeds (Gb/s)

Challenging Test Cases

The PCCT product requirement is to support existing user workflow and exam throughput rates.

Evaluated Data Lake to find sites with challenging examples of:

1. Cal vector Data size transferred (GB/day)
2. Raw Scan Data Transferred (GB/day)
3. Number of images generated (images/day)
4. Overall Exam Count (exams/day)
5. High Cardiac exam volume (exams/day)
6. High resolution exam volume (exams/day)
7. High Helical exam volume (exams/day)

Generate entity CSV inputs for a "day in the life" of a challenging site.

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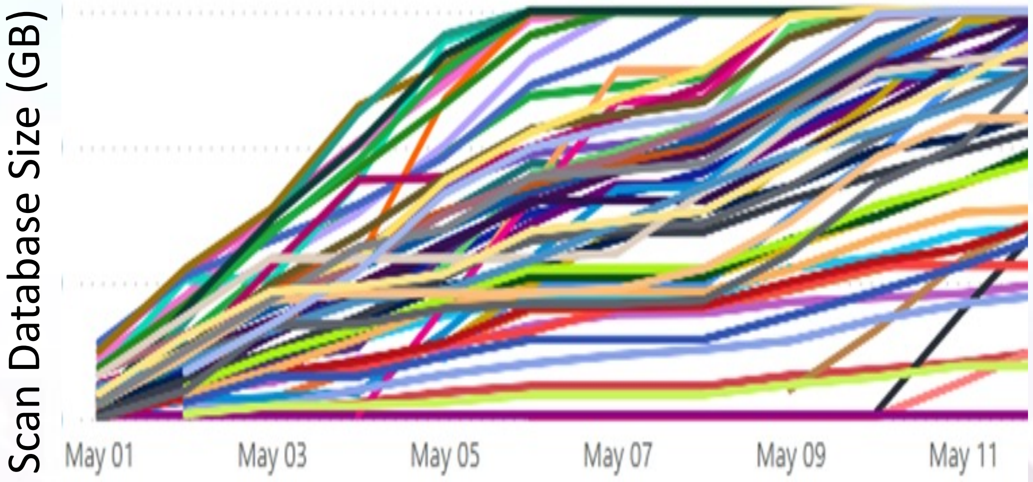
Data Retention Modeling

- One of requirements we modeled with this method is data retention
- User desires at least 3 days of raw scan data retention, but would like data to be retained longer
- The dramatic increase in scan file size and calibration vector size leads to much greater disk storage requirements
- Using field data, we can enhance our system requirements understanding
- Legacy requirements can be evaluated with new system design tradeoffs - e.g. more storage expense / meeting current user expectations
- Allows modeling of more complex data retention policies and management of data interdependencies – e.g. calibration vector to scan data relationships

Digital Twin Used to Model Effect of Data Retention Requirements on Disk Storage



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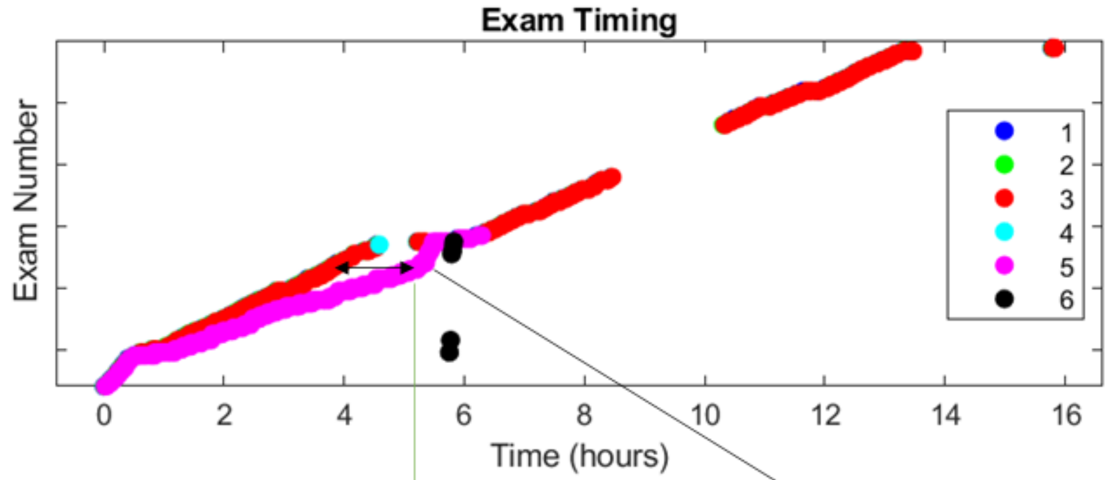
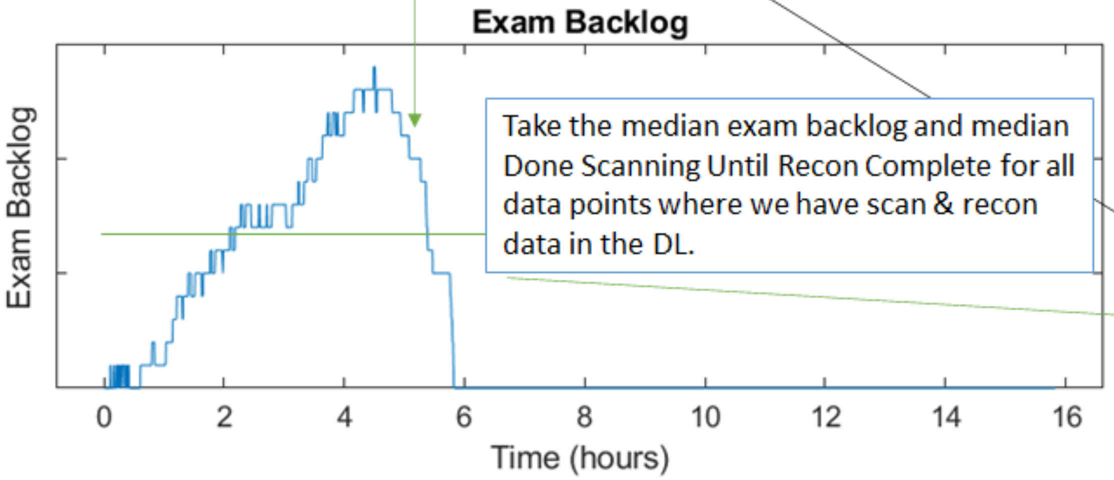
Evaluating Simulation Results

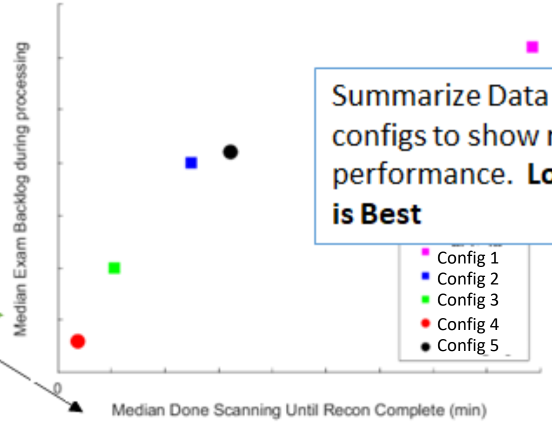
- Each simulation of a “day in the life” produces the overall scan and recon timings for the simulated system configuration, which is then summarized to compare different system architectures



Plot of each recon time vs. Exam number. If recon was infinitely fast, it would be a monotonically increasing line, with a slope equal to the exam rate at that point in time. A separation into 2 or more lines means that recon cannot keep up with the exam throughput.



Take the median exam backlog and median Done Scanning Until Recon Complete for all data points where we have scan & recon data in the DL.



Summarize Data across configs to show relative performance. **Lower Left is Best**

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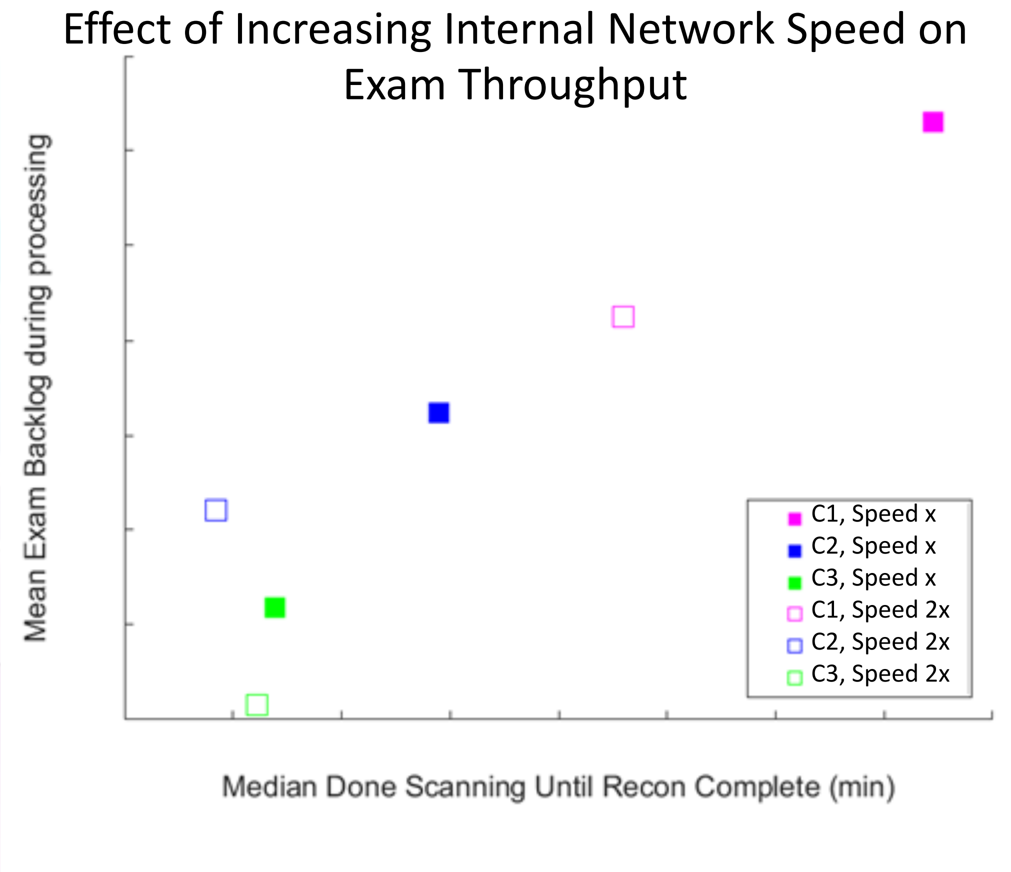
Individual Parameter Evaluation

- The effect of system design tradeoffs were also evaluated, such as slipring bandwidth, network bandwidth, etc.



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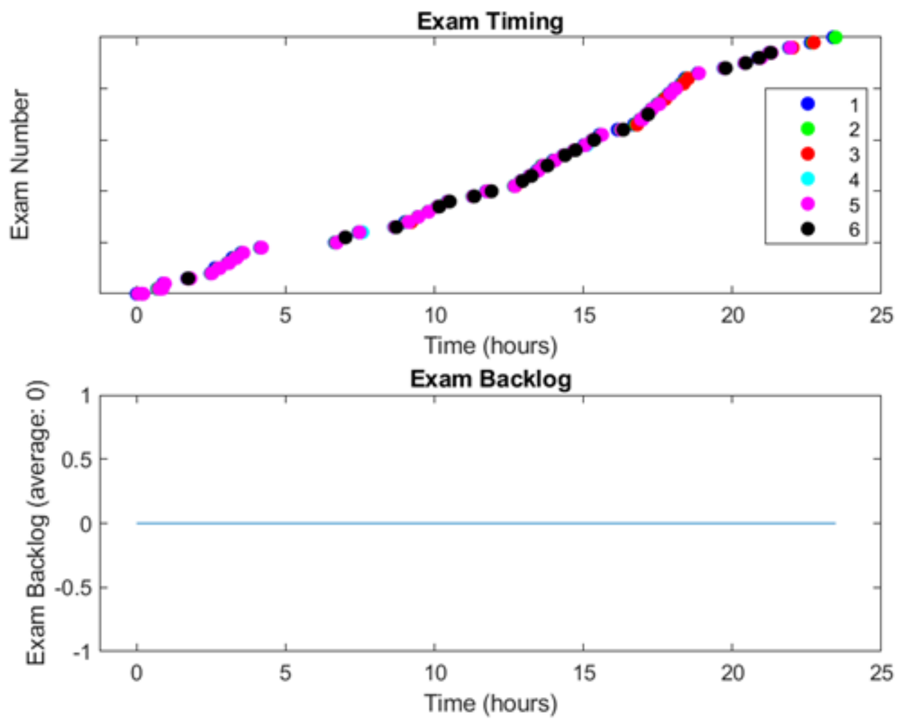
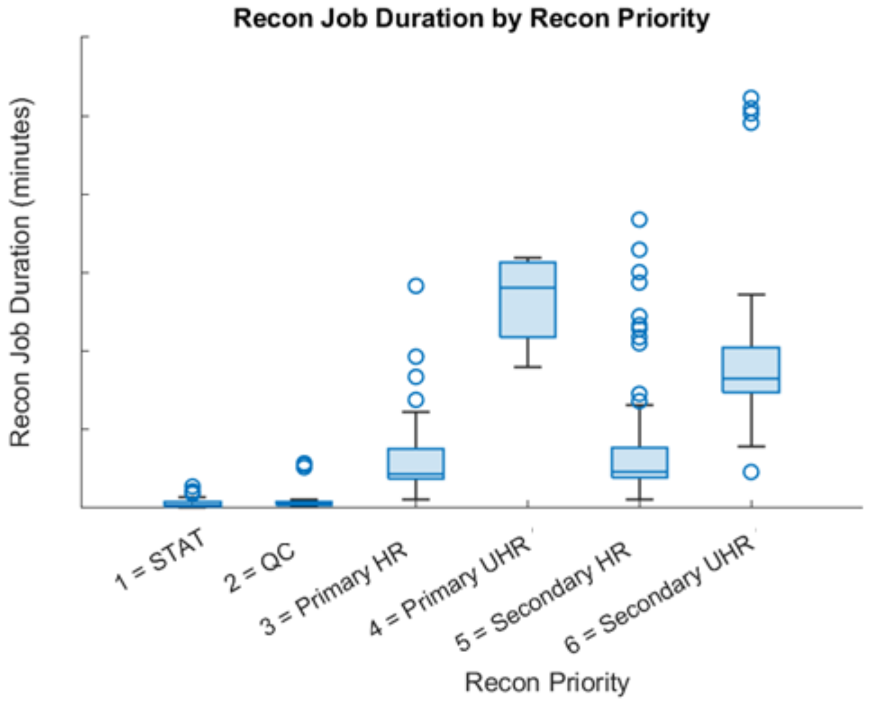
Queue Optimization

- The digital twin model was further used for optimizing job queuing logic for image reconstruction tasks
- Different job type have different recon durations are have different performance requirements for exam workflow
- Optimizing the queue prioritization level can help optimize individual task duration and overall exam throughput





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Conclusion

- SimEvents was an effective tool for developing a digital twin of the photon counting CT scanner.
- It was easy to take existing field system usage data to create event entities to simulate a site's scan and image reconstruction workflow.
- Entity servers and queues were parameterized to explore product architecture tradeoffs for:
    - Slipring data transmission rate (Gb/s)
    - Data retention polity – number of scans/exams
    - Recon job priority rules
    - Number of image generation compute nodes
    - GPU performance multipliers
    - Internal network link speed (Gb/s)
    - Post-processing duration (e.g. generating reformat images, 3D volumes, etc.)
    - External Image network transfer speeds (Gb/s)