

# Progress and Innovations in CT Detector Design: A Complete Review

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## Abstract

Computed Tomography (CT) scanners are widely used in symptomatic and therapeutic areas due to their quick scanning times, excellent spatial resolution, and broad availability. The X-ray detector is essential for capturing images and significantly affects radiation dose and image quality. All modern commercial scanners use solid-state detectors and are similar to third-generation technology. Detector features include efficiency, stability, response time, and brightness. CT scanners have been in use since 1971, and over the decades, the technology has advanced greatly. Notable improvements in detector technology have enhanced image quality and reduced radiation exposure. The EMI head scanner was initially equipped with Sodium Iodide (NaI) detectors, which required long scanning times and water cooling to manage detector immersion. These designs were improved in later generations, offering faster processing speeds and better image quality. While the fourth-generation scanners used a stationary ring of detectors to significantly reduce scan times, the third-generation models featured fan beams and rotary movement. The sixth generation, known as dual-source CT, allows for dual-energy imaging using Two X-ray tubes. The fifth generation, known as electron-beam CT, produced X-rays with an electron gun. The seventh generation replaced traditional X-ray film with Flat-panel Detectors (FPD), improving imaging capabilities. Advances in CT detectors include gemstone, stellar, photon-counting, and Nano Panel crystal detectors. The gemstone scintillator is manufactured by General Electric Healthcare (GEHC). The photon-counting detector (PCD) is a new CT detector technology that uses photon-counting X-ray detectors to record photon energies. The stellar detector is developed by Siemens Healthineers, and the Nano Panel crystal detector is by Philips. The article reviews recent trends in CT detector technology.

**Keywords:** Computed Tomography, Gemstone Detector, Nano Panel Prism Detector, Photon Counting Detector, Stellar Detector

## 1. Introduction

The CT has been widely used in the demonstrative and restorative fields since it was first introduced in 1971, due to its fast-scanning times, excellent spatial resolution, and broad accessibility [1]. A key part of a CT scanner, the X-ray detector, is essential for capturing images and significantly impacts both radiation exposure and image quality. With minimal variations in design depending on the scanner brand and model, all modern commercial CT scanners use solid-state detectors and have similar third-generation rotating configurations [2]. The focused X-ray beam is converted by CT scanner detectors into an electronic signal for computer processing [3]. Detector features include efficiency, stability, energy range, response time, and brightness [4]. The EMI head scanner consisted of a rotating and translating platform equipped with NaI detectors, each

used to gather specific segments of data [5]. Each segment collected a total of 160×180 readings (radial angular), which were processed by a minicomputer and reconstructed using Arithmetic Recreation Procedure (artistry) techniques [6]. The detectors moved in a straight line over the patient as the scans were performed. After this linear movement was completed, the tubes (and detectors) were rotated by 1° to complete the 180° rotation. It took approximately 5-6 minutes to acquire data for each scan with this type of system [6]. One major limitation of this first-generation CT scanner was its energy beam, which required a water bath around the patient's head (secured by an elastic cover) to prevent detector [7].

The second-generation system used multiple detectors and a wide, fan-shaped X-ray beam to enable faster rotation

speeds between scans. As a result, scan times were reduced to less than a minute [7]. Compared to the first-generation CT scanner, the second-generation, 320-detector push CT scanner produced high-quality images over a broader range of body sizes and heart rates at lower radiation doses [8].

The interpretation movement had to be dispensed with for faster checking, and in its place, a smoother, less difficult, and more accurate rotational movement was used (3rd era). The patient's entire breadth is secured by the fan pillar created by extending the X-ray pillar, which at that point is caught by a few finders. The X-ray tube and finder cluster are inflexibly associated, permitting them to rotate together around the persistent (a movement called rotation-rotation [9]). The third-generation geometry used in this system consists of linked tube-detector clusters that rotate together. In third-generation CT, the tubes and locators are rigidly connected; depending on the position of each locator in the cluster, each measures beams passing at a specific distance from the center of rotation [9]. By projecting along these beam paths and reinforcing along a ring where they meet, errors or drift in a detector's calibration relative to other locators can occur. The resulting image is known as a ring artifact [10,11].

Xenon finder clusters addressed this issue, the long metal chamber of a xenon cluster was divided into various smaller chambers by thin plates called septa [12]. Each septum was connected to a common positive voltage source. Detector collectors were linked to electronic readouts through the septa. Eventually, solid-state finders replaced xenon clusters [12]. Fourth-generation CT scanners avoid ring artifacts by dynamically calibrating detectors at any position before x-rays pass through the patient, unlike third-generation [2]. Fifth-generation CT scanners (also called electron-beam CT) use an electron beam that is electronically swept across a 360° tungsten target, producing x-rays focused into a fan beam. Solid-state detectors consist of a scintillating crystal, cadmium target, and silicon photodiodes with a preamplifier for signal conversion [2].

Dual-source CT is the sixth generation of CT, featuring two X-ray tubes and detectors. It gathers dual-energy data using a dual source computed tomography system [13]. The 7th generation advancement is the Flat Panel Detectors (FPDs), designed for radiography and fluoroscopy. A literature review analyzed performance metrics of different CT detector technologies, focusing on efficiency, stability, response time, and afterglow (SHAJI, FIDHA, KUMARI, DABHOLKAR, & GAONKAR, 2024). Future trends will focus on improving detector efficiency and performance.

A comprehensive literature review was conducted to evaluate the performance metrics and characteristics of various CT detector technologies—such as efficiency, stability, response time, and afterglow—by analyzing peer-reviewed articles, technical reports, and manufacturer

manuals [14]. The review covered key detector types, including gemstone, Stellar, photon-counting, and Nano Panel Prism [14]. Performance data were examined in relation to image quality, radiation dose efficiency, usability, and maintenance, the study highlights major advancements in CT detector development, from early NaI-based systems to modern high-resolution, multi-energy detectors, with future trends expected to focus on enhanced efficiency and imaging performance [14].

Spectral Detector CT (SDCT) uses a single X-ray tube and a dual-layer detector system: an yttrium-based garnet scintillator on top (absorbing low-energy photons) and a gadolinium-oxysulfide layer beneath (capturing high-energy photons) [14]. Application-Specific Integrated Circuits (ASICs) convert analogue signals from each layer into digital data, which are combined for image reconstruction. A major advantage of SDCT is that it eliminates the need for pre-selecting dual-energy protocols, unlike other systems (e.g., dual-source or fast kVp switching) [14]. However, SDCT requires a minimum of 120 kVp for effective spectral separation, making tube current reduction essential to minimize radiation dose, especially for smaller patients [14].

### 1.1. Gemstone Spectral Imaging (GSI) – GE Discovery CT750HD

#### • Technology Basis:

- o Uses projection-based material decomposition.
- o Employs fast kVp switching for dual-energy imaging.

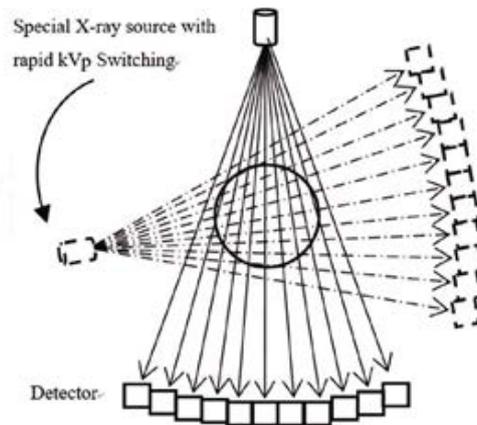
#### • Detector Features:

- o Utilizes Gemstone scintillator material, a rare earth oxide with a garnet crystal structure.
- o Offers high light output, fast primary decay time (30 ns), low afterglow, and resistance to radiation damage.

#### • Performance Advantages:

- o 30 ns decay time: ~100× faster than GOS (Gadolinium oxysulfide).
- o Afterglow: Only 25% of GOS levels, ensuring minimal image lag.
- o Ideal for fast sampling and high-speed imaging, crucial for spectral CT.

A new dual-energy CT approach called detector-based spectral CT uses two layers of detectors to acquire low and high-energy data from all patients. This method has clinical uses such as enhanced contrast visualization, artifact reduction, material decomposition, and radiation dose reduction [15]. It has applications across various organ systems, including improving vascular contrast, reducing artifacts, determining tissue composition, reducing radiation dose, and avoiding additional CT scans for lesion characterization [14]. GSI has significant medical applications in oncology, enhancing lesion detection, characterization, vessel evaluation, and perfusion data in vascular imaging. It also reduces metal artifacts, enhances myocardial perfusion, and aids in material decomposition [14].



**Figure 1: Gemstone Spectral Imaging (GSI) setup in the GE Discovery CT750 HD**

### 1.2. Stellar Detector

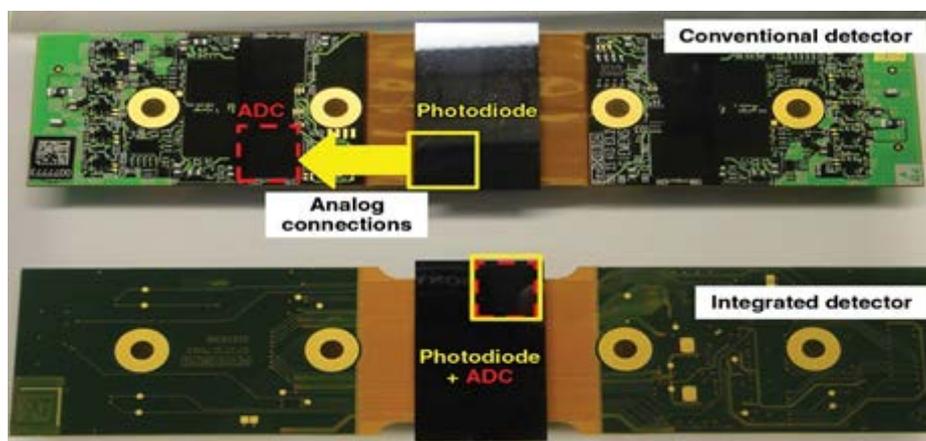
The Stellar detector by Siemens combines the photodiode and ADC into one ASIC, shortening the signal path for the first time in CT history [16]. This innovative design features a 3D package of electrical circuits using a Through-Silicon via (TSV), a high-performance technique for creating vertical connections that completely pierce the silicon wafer [16]. This design significantly improves detector performance and reduces electronic noise levels.

#### Technical Advantages:

- True Signal Technology: Reduces electronic noise → clearer images, especially in low-signal situations.
- Lossless Digital Transmission: Ensures high signal fidelity.
- Energy Efficient: Uses 70% less power and produces 30% less heat → reduced electrical noise.

#### Clinical Benefits:

- Coronary Stent Imaging:
  - o Reduces image noise and slice blurring.
  - o Improves visibility of calcified lesions and in-stent restenosis.
- Pediatric Imaging:
  - o Enables low-dose, high-detail imaging.
  - o Often eliminates the need for anesthesia.
- Bariatric Imaging:
  - o Higher signal-to-noise ratio for large patients.
  - o Enhanced X-ray utilization with dual-source imaging.
- High-Resolution Applications:
  - o Visualizes fine structures like the inner ear, pancreatic duct, and aortic dissections, even at low doses.



**Figure 2: The Stellar Detector's Element's Basic Set-up is Depicted in the Graphic Design**

### 1.3. Photon Counting

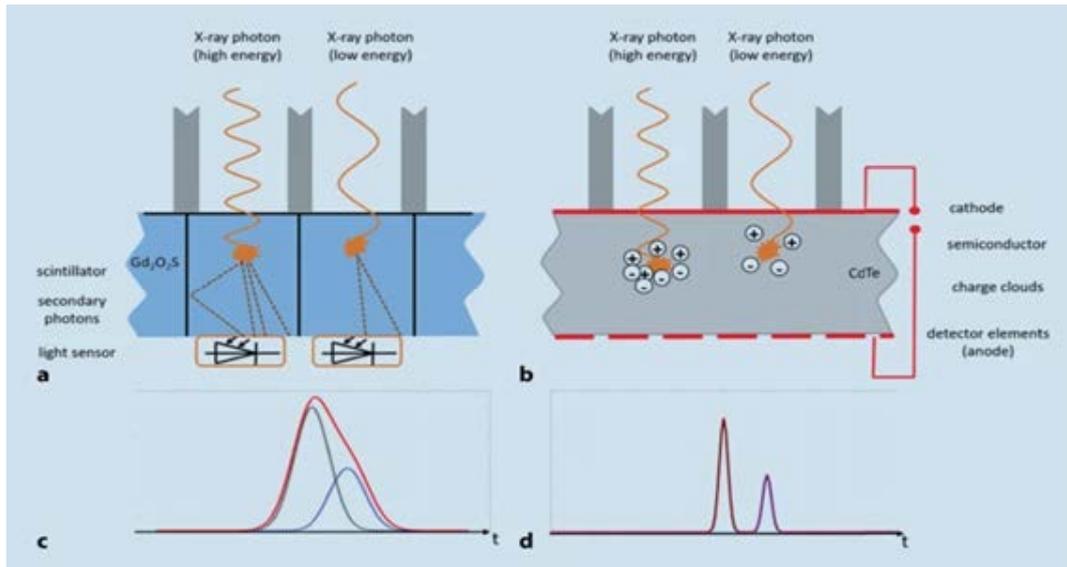
The Photon Counting Detector (PCDs)-CT is a novel CT technology that has been approved by the US Food and Drug Administration. It addresses several of the limitations of traditional Energy-Integrated Detectors (EIDs) [13]. This device converts incident X-ray photons into electrical signals by combining energy integration with Photon Counting Detectors. When a photon contacts the detector, a high voltage applied across the semiconductor generates electron-hole pairs, transforming the deposited X-ray energy into an

electrical signal [13]. In contrast, all other CT scanners make use of scintillator-based EIDs, which emit visible light when exposed to X-rays [17]. Reflective septa must be utilized inside the standard X-ray detector to steer this light toward the optical photon sensor.

PCDs provide greater signals to lower energy photons that may contribute significantly to a CT image because they consistently weigh detected X-rays of varied energies [17]. The electrical signal deposited by each X-ray is proportional

to its energy, which accounts for PCDs' ability to discern between different energies and serves two purposes [17]. The first advantage is that it allows for the removal of low-energy photons, which are part of electronic noise, using energy-specific thresholding. This elimination makes it easier to create ultra-low dosage CT regimens for both adults and children [18]. Second, the ability of PCDs to discriminate energy enables for the analysis of spectrum data with a single X-ray, this is possible because one or more energy thresholds can be applied to sort detected X-ray photons into discrete energy bins based on the amount of energy they deposit in the detector [18]. Photon counting detectors (PCDs) in X-ray

CT, also known as direct-conversion detectors, represent a significant advancement over traditional energy-integrating detectors because they convert X-ray photons directly into electrical signals without the intermediate step of converting photons into visible light [19]. This direct conversion is typically achieved using semiconductor sensors under an applied bias voltage, which generates charge carriers (electron-hole pairs) upon photon interaction [19]. An ASIC (Application-Specific Integrated Circuit) then processes these charge clouds, counting each photon and assigning it to an energy bin based on the energy deposited [19].



**Figure 3: In Computed Tomography a Conventional Energy-Integrating Detector Converts Incoming X-ray Photons to Numerous Visible Photons, which are Detected by a Light Sensor, Resulting in a Broad Signal (c). B X-ray Photons are Converted Directly into Observable Charge Clouds. D a Photon-Counting Detector Can Differentiate Nearly all Photons that Reach the Detector. Figure 4 Shows a Complete Overview of the Readout Modes for the Detector Elements. cdte: Cadmium Telluride**

**Converter Materials: Silicon vs. CdTe/CZT**

• **Silicon Detectors**

o **Pros:**

- Low cost
- High reliability
- Well-established technology
- Low electronic noise

o **Cons:**

- Less efficient for high-energy photons due to low atomic number (Z)
- Poorer energy resolution
- Performance sensitive to temperature fluctuations

• **Cadmium Telluride (CdTe) and Cadmium Zinc Telluride (CZT) Detectors**

o **Pros:**

- Better energy resolution
- Higher detection efficiency for higher-energy photons due to higher Z materials
- Larger usable energy range

o **Cons:**

- More complex and costly manufacturing

- Sensitive to temperature and material quality issues

Advantages of Photon Counting Detectors in CT

- Very high spatial resolution due to precise photon localization
- Simultaneous multienergy data acquisition enabling spectral imaging
- Reduced beam hardening and metal artifacts, improving image quality near dense objects
- Increased contrast-to-noise ratio especially with iodinated contrast agents
- Improved radiation dose efficiency, lowering patient dose
- Ability to distinguish multiple CT contrast agents simultaneously for enhanced diagnostic capability

Clinical Benefits

- Cardiac, musculoskeletal, and neurovascular imaging: Enhanced tissue contrast and resolution improve diagnostic accuracy.
- Pediatric and frequent scan patients: Lower radiation dose and improved image quality are safer and more effective.

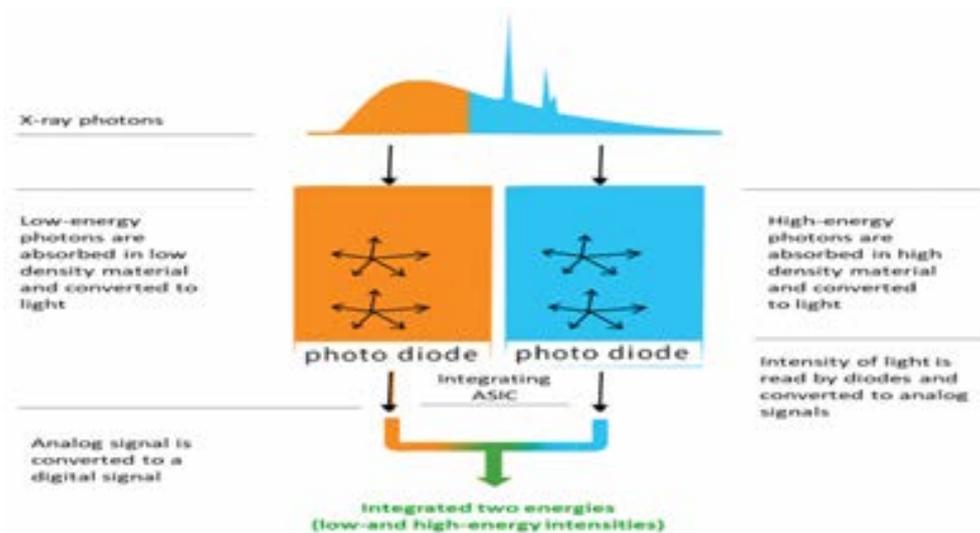
- Dental and orthopedic imaging: Reduced metal artifacts improve visualization around implants.
- Dual- and multienergy imaging: Enables material-specific analysis valuable in vascular and cancer evaluations.
- Functional imaging improvements: Enhanced liver and lung imaging, better perfusion studies for stroke and cardiac function.
- Material disintegration: Precise differentiation of substances aids in diagnosing conditions like gout and kidney stones.

Photon counting CT technology, through its superior resolution, dose efficiency, and spectral imaging capabilities, is rapidly becoming ideal for a broad spectrum of clinical applications, enhancing diagnostic precision and patient safety [19].

#### 1.4. Nano Panel Prism Detector

The Nano Panel Prism detector features a dual-layer scintillator design arranged in a 3D tile pattern: a yttrium-

based garnet scintillator for low-energy X-rays on top, and a gadolinium oxy-sulphide (GOS) scintillator for high-energy X-rays below. X-rays are converted into visible light by the scintillators, then into electrical signals by a vertically positioned front-illuminated photodiode (FIP) [14]. This design maintains high geometric efficiency, with fast rotation times (0.27 s) and thin slice capability (0.625 mm) [14]. Compared to earlier detectors, it offers 25% more light output and 30% less crosstalk, with improved stopping power and reduced intralayer scatter, allowing simultaneous detection of events in time and space. Splitting the X-ray spectrum into two smaller energy ranges reduces noise and beam hardening artifacts [20]. Clinically, it enables multiple spectral imaging outputs such as virtual non-contrast, monoenergetic, iodine density, calcium suppression, and electron density images. These improve tissue characterization, reduce radiation dose, enhance contrast, and support more precise diagnoses across various applications [20].



**Figure 4: Diagrammatic Representation of The Principal Scheme of Dual-Layer Based Spectral Detection**

#### Physics Behind the Spectral Detection

- Layered Absorption:
  - Incoming X-rays interact differently in each scintillator based on energy:
    - Low energy absorbed in top layer.
    - High energy passes to and is absorbed by bottom layer.
- Signal-to-Noise and Energy Separation:
  - Carefully selected scintillators yield high signal-to-noise ratio (SNR) and clear energy distinction.
  - Splitting the energy spectrum reduces beam hardening and photon noise.
- Lower Spectral Variance:
  - Dividing X-ray spectrum reduces overall variance, improving image consistency.

#### Clinical Benefits

- Spectral Imaging Modes:
  - Virtual Non-Contrast (VNC): Removes iodine digitally to lower dose.
  - Monoenergetic (MonoE): Simulates monochromatic

images for improved contrast and reduced artifacts.

- Iodine Density / No-Water: Precisely maps iodine, suppresses water for better soft tissue and calcium contrast.
- Calcium Suppression: Helps visualize bone marrow lesions and disc herniations.
- Electron Density Maps: Estimate tissue composition for advanced diagnostic support.
- Key Outcomes:
  - Improved diagnostic precision.
  - Reduced radiation dose.
  - Better artifact suppression.
  - Enhanced material differentiation.

#### 2. Conclusion

The “slice war” in CT imaging has ended, with manufacturers now focusing on increasing the number of energy bins rather than slices in next-generation scanners. Detector improvements are central to this progress. CT detector technology has evolved from early NaI crystal detectors to advanced flat panel detectors in the seventh generation. Key

advancements include:

- Gemstone detectors: Use fast kVp switching for dual-energy imaging.
- Stellar detectors: The first fully integrated detectors that significantly reduce electronic noise, enabling high-quality diagnostic images at low doses.
- Photon counting detectors: Provide very high spatial resolution, no electronic noise, better contrast-to-noise ratio, and reduced radiation dose.
- Nano Panel Prism detectors: Feature minimal intralayer scatter and can detect signals simultaneously in time and space.

This review highlights the major milestones in CT detector development and the technological direction toward spectral imaging with improved detector designs [21].

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