CT IMAGING TECHNOLOGY – WHITE PAPER

UNLOCK THE FULL POTENTIAL OF YOUR ULTRA-HIGH-RESOLUTION CT AND PHOTON-COUNTING CT SYSTEMS

Building a better CT system with high-resolution imaging starts at the (X-ray) source

Small and at the same time stable focal spots are necessary for achieving high spatial resolution in ultra high-resolution computed tomography (UHRCT) and photon counting computed tomography (PCCT).

Introduction

Precise diagnosis of certain conditions requires CT images with high spatial resolution.[1,2] To achieve this, these systems must feature ultra small focal spots.[1,2,8,9] This white paper will demonstrate how the use and technical design of X-ray tubes with stable ultra-small focal spots can significantly contribute to improved image quality in ultra-high-resolution computed tomography (UHRCT)[1] and Photon-counting CT (PCCT).[2] Furthermore, it will detail the numerous advantages of high-resolution imaging.[2,3,4,5,6,7] The white paper will also discuss the challenges of using small focal spots for high-resolution applications,[8,9,10] focusing on the importance of power density[1,2,17] and focal spot stability.[18,19]

DUNLEE

1. The rising prevalence of ultra-high-resolution CT (UHRCT) and photon-counting CT (PCCT)

Ultra-high-resolution CT as an umbrella term encompasses both PCCT and standard energy integrating CT (EICT). PCCT has been shown to provide superior image quality in comparison to UHRCT with energy integrating detectors.[11]

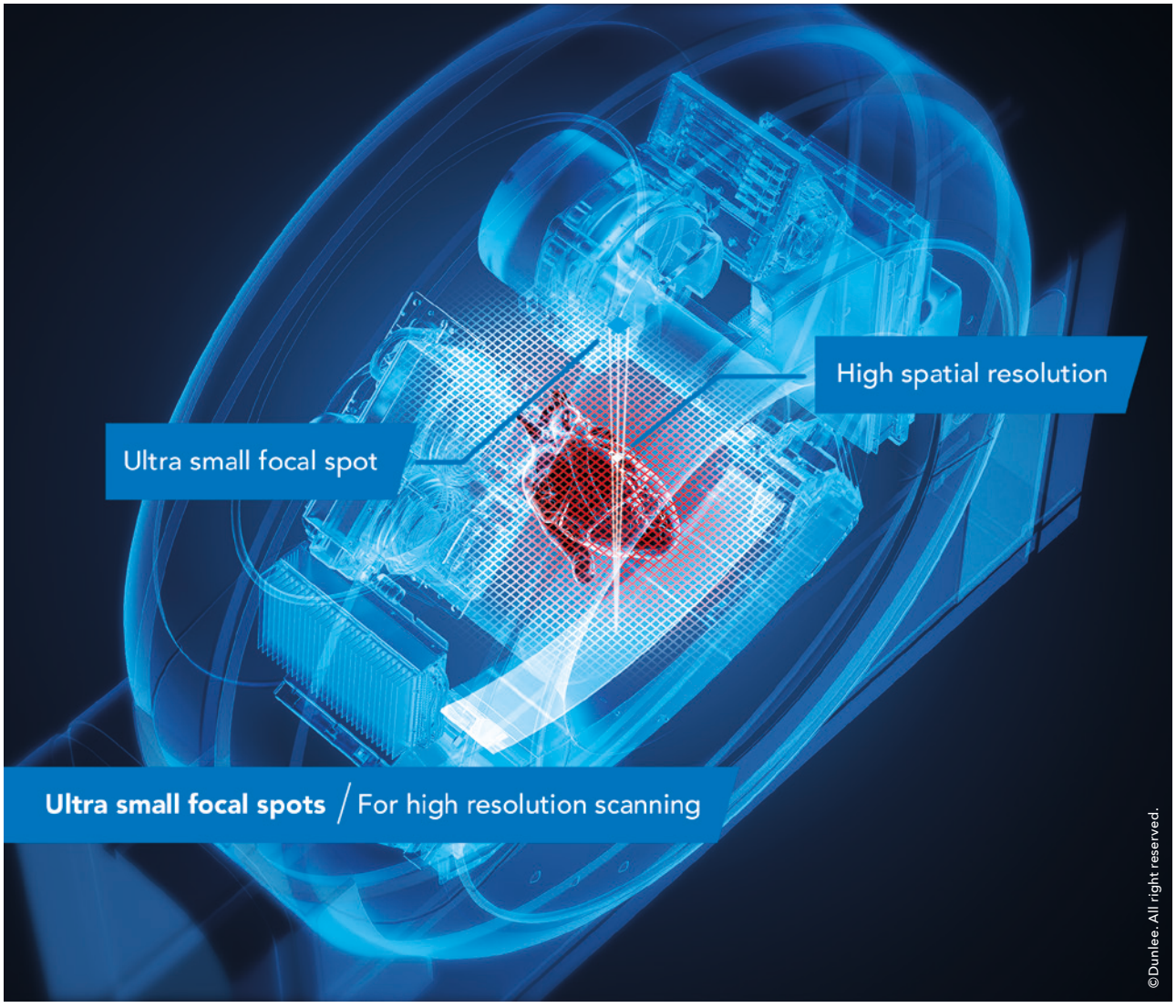
Conventional CT systems, which usually house energy integrating detectors (EID), first convert X-ray photons into visible light, which is then detected by photodiodes in a second step.[28] With advancements in tube and detector technology, conventional CT systems can now also achieve high resolution.[12] However, this process is associated with increased scanning times and higher radiation dose compared to non-high resolution scans.[12]

In contrast, PCCT is an advanced imaging technology that utilizes photon-counting detectors (PCD) to directly convert X-ray photons into electrical signals, enhancing image quality and reducing radiation dose.[4] This technology has been in clinical use since the approval of the first dual-source PCCT in late 2021.[4] Since then, PCCT has become more prevalent as a leading imaging technology.

PCCT has the potential to provide significant advantages over conventional EICT:

- It creates very high resolution[2] images
- It reduces image noise and thus can deliver quality images at significantly lower dose[2]
- It enhances capabilities in improving the precision in diagnosis as well as patient outcomes compared to conventional CT methods[13]
- It can provide spectral information [2]
- It is immune to electronic noise[2,31]

While generally superior in spatial resolution to EID CT, PCCT is associated with more complex data management and processing.[27]



2. Areas of application that benefit from high spatial resolution

High spatial resolution is recognized to facilitate the detection of pathologies and anomalies that were previously undetectable.[2]

Cardiology:
For visualization of coronary arteries and soft plaques

Oncology:
For identification and characterization of small lesions and tumors

Neurology:
For detection of cerebralmicrobleeds, small infarcts, and evaluation of fine neural structures

Pulmonology:
For detdetailed lung imaging and detecting interstitial changes

Orthopedics:
For visualization of complex bone pathologies, detection of microfractures, and assessment of implant placement

High spatial resolution for cardiovascular imaging

Coronary artery disease is one of the most prevalent diseases and has high mortality rates worldwide.[20] Cardiovascular diagnosis needs to be fast, requiring the CT imaging to be able to scan during the heart beats.[21]

One example where ultra-high-resolution is needed is cardiovascular imaging. Higher resolution can be useful in cardiac imaging to support the evaluation of cardiac stents[4,32] to diagnose in-stent restenosis[2,3,33] and is a proven method to quantify coronary plaques.[14]

Regarding pediatrics, a study found that high resolution imaging (PCCT) provides superior image quality and diagnostic accuracy compared to conventional CT, particularly in challenging pediatric cardiovascular cases.[5]

Characterization of cancer and differentiation of cancerous renal masses from benign cysts

Detecting, characterizing, and monitoring tumors with precision plays an important role in diagnosis, treatment planning, and monitoring the effectiveness of therapies in oncology.[22]

High spatial resolution assists in diagnosing many conditions.[2] This can help in the evaluation of lung cancer.[2,34] In a study this is further backed up: Compared to EICT, PCCT increased radiologists' ability to visualize higher-order bronchi and bronchial walls[15]. Higher resolution can also improve the differentiation of benign tissues from cancerous tumors.[2]

Visualization of fine structures in Neurology

Details of the brain give important answers for clinical decision-making in stroke and neurological care.[24]

A very high resolution pays off for many applications that require visualization of fine structures and details like brain imaging, lung fissures and evaluation of cardiac stents.[2]

Lung visualization and quantification of pulmonary diseases

High resolution and at the same time reduced dose are empowering healthcare professionals with the ability to evaluate patient's pre- and post-operative state in patients with lung disease.[23]

An important field of use for high resolution imaging in lung visualization is the quantification of chronic obstructive pulmonary disease. One study found PCCT to be superior in qualitative and quantitative performance compared to regular EID CT.[6]

Diagnosis of complex bone pathologies and complications

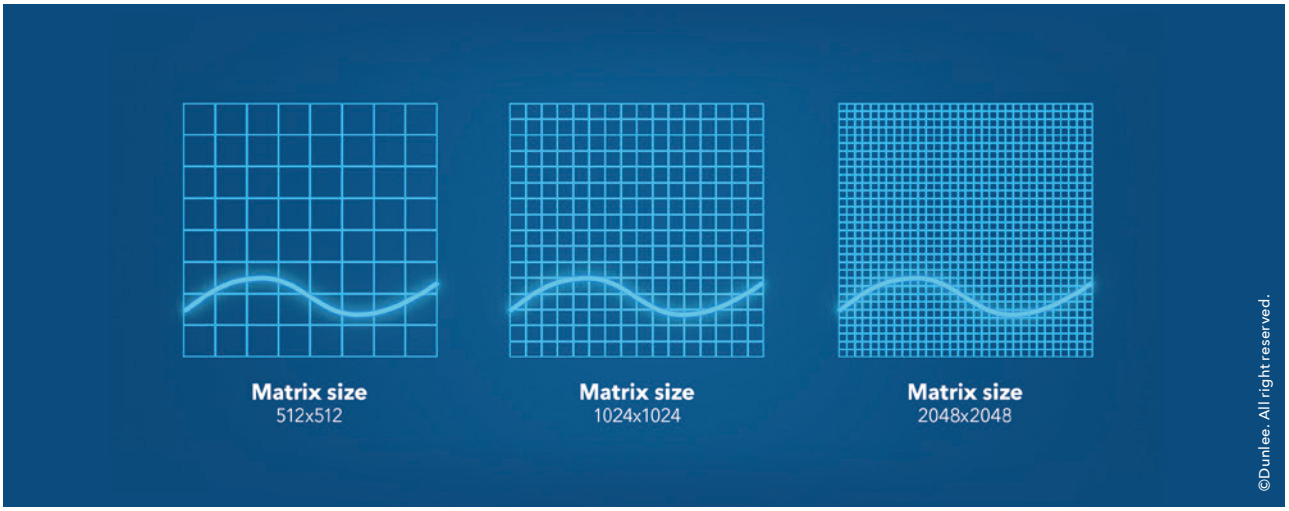
Soft tissue imaging[25] and visualization of metal objects[26] are just a few challenges in bone imaging.

Another example for new imaging possibilities is the diagnosis of temporal bone pathologies. A study praises PCCT's detailed imaging capabilities, which allow for earlier detection of complex pathologies and complications, leading to improved treatment outcomes.[7]

3. Technological challenges: Importance of imaging technology and why ultra small focal spots are needed

With traditional CT (EID CT), the detector is the determinant of spatial resolution. With high resolution and photon counting detectors, the resolution limit of a CT scanner no longer relies solely on the detector but shifts to the X-ray source.[2] Ultra small focal spots enable even higher resolution in UHRCT and PCCT.[2]

There are multiple technological challenges when designing imaging components for high resolution imaging and especially for ultra small focal spots in X-ray tubes.



New detectors with smaller pixels require tubes with smaller focal spots

Tube focal spot size defines spatial resolution

It is shown that the spatial resolution of photon counting detectors is limited by the size of the focal spots.[2,8,9] This also applies for high resolution EICT: A study explains that smaller focal spots contribute less to focal spot blur, therefore making the size of the focal spot an important contributing factor for high spatial resolution.[16]

Other important factors that determine CT spatial resolution are:

Detector Element Size	Smaller detector elements (pixels) result in better spatial resolution.
Reconstruction Algorithm	The algorithm used to reconstruct the image from raw data affects how well small details are preserved.
X-ray Beam Focus	The focal spot size of the X-ray tube, as well as focal spot motion and system vibrations influence spatial resolution.
Patient Size and Motion	Larger patients (due to increased beam divergence and scatter) as well as patient motion during acquisition time reduce resolution.

Focusing on the CT tube and generator exclusively, key physical drivers of spatial resolution include:

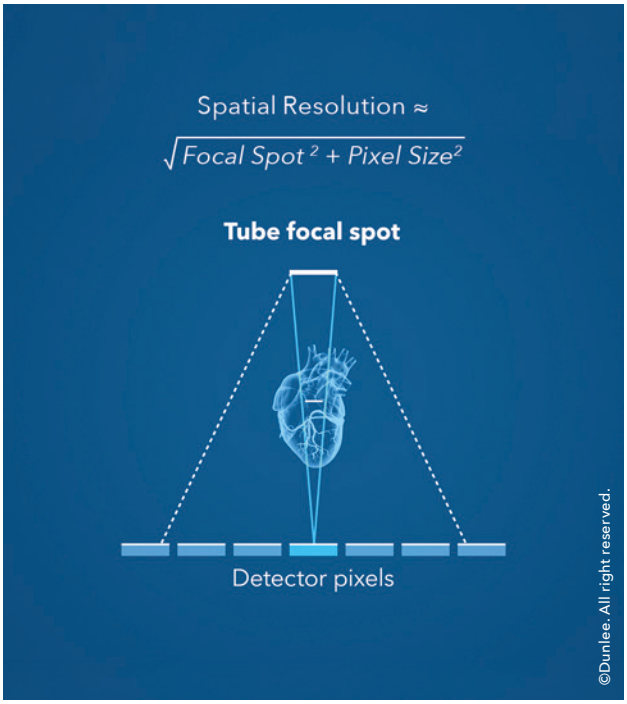
- **Detector pixel size:** Smaller pixels capture finer detail.
- **Tube focal spot size:** Smaller focal spots sharpen projections through reduction of blurring.

Focal spot and pixel size both contribute equally to spatial resolution.[35]
Figure 1: Simplified formula for spatial resolution of a projection within a CT scan[35]

$$\text{Spatial Resolution} \approx \sqrt{\text{Focal Spot}^2 + \text{Pixel Size}^2}$$

The balance between power density and tube wear out

To take full advantage of ultra-high resolution imaging technology, X-ray sources must have very small focal spots that can still provide sufficient power, supporting fast imaging protocols to reduce image blurring from patient motion.[2]



The focal spot is the limiting factor for spatial resolution

The technological challenge is that a reduction in focal spot size increases the power-density on the corresponding area on the anode disc. To quote a prominent scientific author on PCCT: "The native resolution of PCD CT could be easily made to be four times better than current EID CT, but a similar reduction in tube spot size (a 16-fold reduction in focal spot area) would be very difficult because the concentration of power on such a small area would melt the anode."[2] To minimize tube damage, the large amount of heat produced at the anode should be dispersed over a large area.[1] This is restricted in systems that carry tubes with small foci. In turn, this can lead to frequent interruptions due to overheating, high arcing rates and rapid wear that result in early tube failures.[1]

The need to balance high power and tube wear is not a new one: A 1982 study already described that heat accumulation in the tube housing appears to be an important contributor to CT X-ray tube failure.[17] This is particularly relevant for high power operation – as needed when using a small focal spot – as it generates substantial heat, particularly at the anode focal spot, which limits the maximum power of the X-ray tube.[10] This implies that manufacturing smaller focal spots requires special expertise to find a balance between high power and acceptable tube lifetime. Sophisticated tube design as well as intelligent control and monitoring during operation is required to create tubes with very small focal spots that meet the needs of daily use. A sophisticated tube design can include several different factors:

- A high anode rotation speed can allow higher power density on the anode disc[29]
- The material of the anode disc must be able to withstand high thermic conditions[30]
- Intelligent thermal management is crucial for high power operations[2]

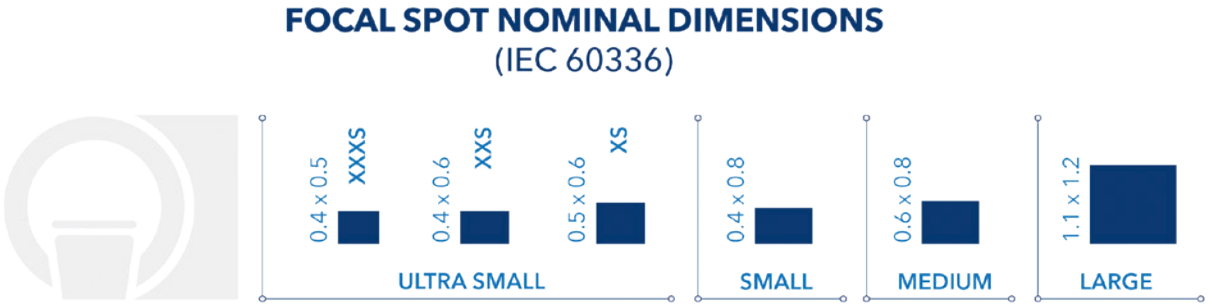
Dunlee's tubes are designed to support evolving clinical and technical demands. The Xpert Bundles with the CT8000, CT6000 and CT6500 tubes meet these requirements through **well-designed control mechanisms.** The small, stable focal spots of the Xpert Bundle are engineered to **balance optimization of image quality, throughput and heat management** to help you get the most out of your UHR-CT and PCCT systems. (See section 4)

Focal spot stability affects resolution

Another key factor to consider is focal spot stability, which affects the resolution of the imaging system.[18,19] High temperatures and gantry rotation can lead to mechanical deformation within the optical parts of X-ray tubes.[18] These deformations can cause deviations in distances between focal spot, X-ray beam and detector.[18] These deviations affect the resolution and image quality of the CT scan.[18] Focal spots with low stability that deviate during scans can decrease the image quality.[18] Greater stability in focal spots leads to a reduced negative **impact on resolution and image quality.**[18]

4. Technical abilities with the Dunlee Xpert Bundles: Extra small focal spot CT tubes for UHRCT and PCCT systems – pushing technology to its limits

Dunlee's Xpert bundles provide six different focal spot options to cover the entire range of CT applications. From its large 1.1 x 1.2 focal spot with 120 kW for fast scan acquisition to the smallest 0.4 x 0.5 focal spot for ultra high-resolution imaging, Dunlee's Xpert bundles offer full flexibility to meet all clinical needs.



Dunlee's extra-small focal spots address high resolution imaging

As shown in the technological challenges above, smaller focal spots increase the power density on the anode, making heat management essential to avoid system downtime. At the same time, high gantry rotation speeds for complex applications – such as heart scans – demand mechanical stability of focal spots, regardless of size. Dunlee's Xpert Bundles with CT6000, CT6500 and CT8000 tubes meet the challenge of balancing high power with focal spot size and stability – making them a perfect choice for UHR-CT and PCCT systems.

To enable high kW power on its extra-small focal spots without compromising tube lifetime and system uptime, Dunlee's Xpert bundles make use of sophisticated models to supervise and control all relevant tube and generator parameters during operation. Designed for the experts in imaging – pushing technology to the limits to achieve optimal performance of all components.

a. Balancing between power and overheating: small focal spots, built to maintain high kW output

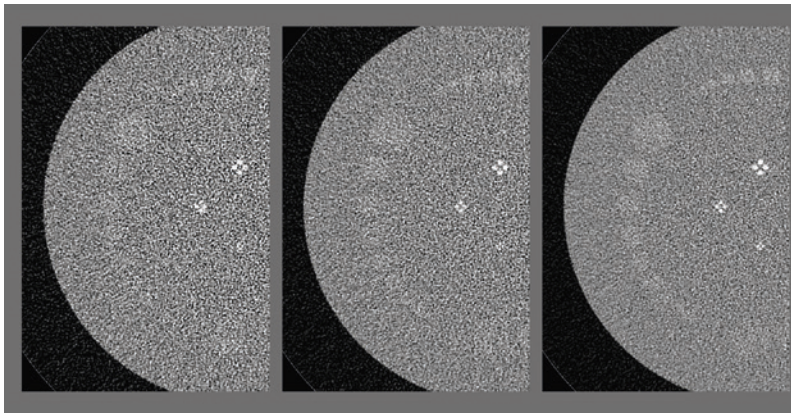
- To **unlock the full potential** of a UHRCT or PCCT application and to have **minimum limitations in clinical cases or patient types,** the essence of spatial resolution is the combination of high power with small focal spot size. If the tube output (mAs) is too low, fine details are no longer visible due to increased image noise although the system resolution (detector size and focal spot size) would be sufficiently high.

  + More power
  + Smaller Focal Spots } Higher IQ & Resolution

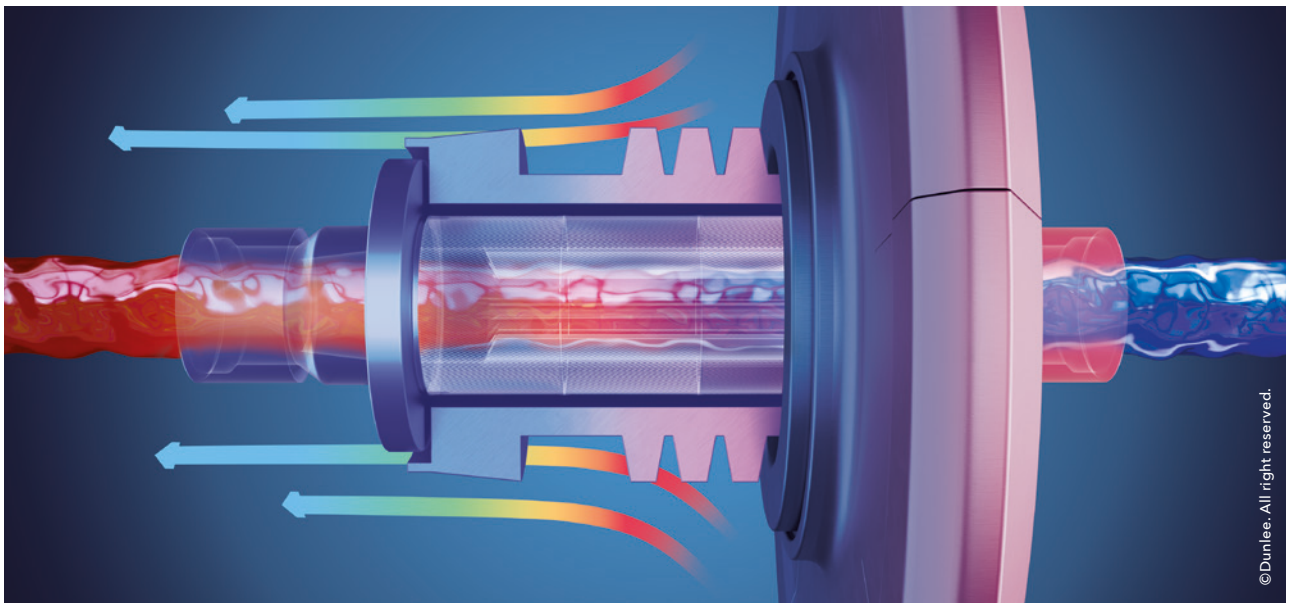
- The **high anode rotation speed of 180 Hz supports high power** even with small focal spots[36] (High track speed is usually ensured through the use of big anodes or fast rotation speed.)

b. Intelligent heat management – no overheating, no pause or interrupting scans

- **Cool Glide liquid metal bearing (LMB) technology** ensures smooth operation and heat dissipation for fast, uninterrupted scanning. The technology therefore supports a high number of scans.[36]
- An intelligent simulation mechanism ("thermal tube temperature simulation TTS") improves heat dissipation.[36]
- **The unipolar tube design and water cooling** increases conductivity. Water has an approximately 10x higher conductivity than oil, and no oil is needed as isolator.
- **The rhenium and tungsten anode disc** can withstand high thermic stresses.[36]



Lab simulation of different kW on a small focal spot: Why high power is relevant on small focal spot to unlock full potential of small focal spot (20, 30 and 40 kW with the Dunlee CT-8000 X-segment ultra small focal spot size XXXS 0.4 x 0.5)



Dunlee CoolGlide™ Liquid Metal Bearing – high throughput/excellent cooling capacity

c. High image quality through focal spot stability: Tube design made for high gantry speed of up to 250 rpm ensures high resolution and less blurring. Its size and stability directly affect image quality, particularly spatial resolution and the presence of artifacts. Focal spot movement, often caused by thermal expansion during operation, can degrade image sharpness and accuracy, especially in high-resolution CT. [36] A stable focal spot ensures sharp, well-defined images, while drift or instability can lead to image artifacts and reduced accuracy.

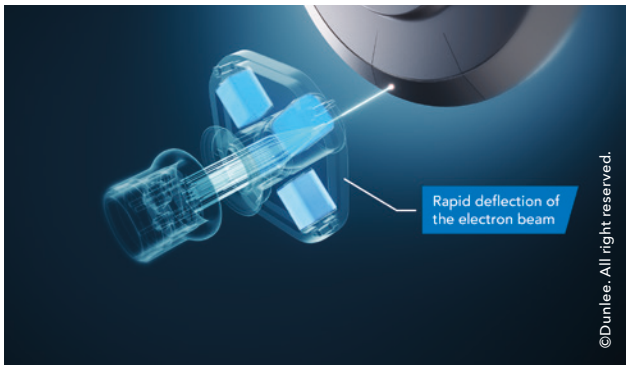
The design of the tube elements ensures focal spot size stability even under high thermal and rotational stress,[36] including:

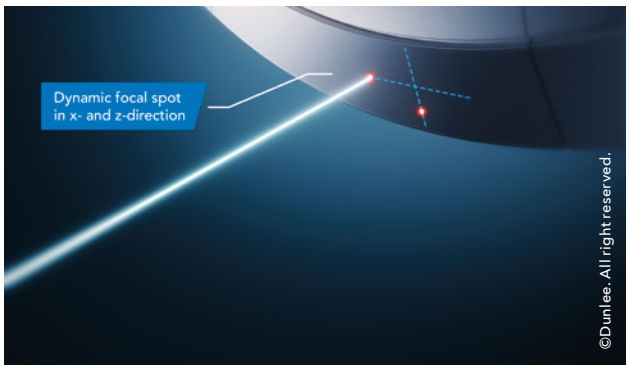
- the double-mounted bearing,
- the advanced quadrupole alignment,
- the flat emitter and
- the overall stable tube mechanics

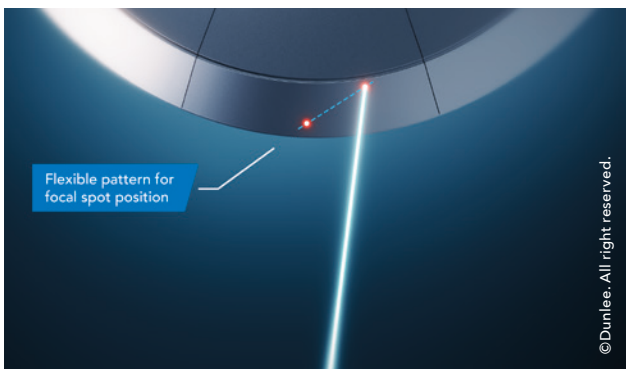
Deformation through G-force and thermal effects are limited through this mechanical design. Dual supported bearing enables high gantry speed because it gives higher stability to the anode disc.[36] Advanced double quadrupole technology enables different focal spot sizes from a single emitter and X as well as Z-deflection.[36]

The **focal spot stability of the Xpert bundle is significantly higher** compared to traditional CT X-ray tube designs. Particularly CT tubes with ball bearings often show lower stability due to inferior heat dissipation. As focal spot stability directly affects image quality, particularly spatial resolution, **Dunlee's Xpert bundles support High IQ and UHR CT imaging.**

- Focal spot variation due to anode heating in x-axis: CT8000, CT6500, CT6000 = 0.1 mm max
- Focal spot variation due to wobble, z-axis: CT8000, CT6500, CT6000 = 0.05 mm max







Use of thin-walled anti-scatter grids supporting image precision

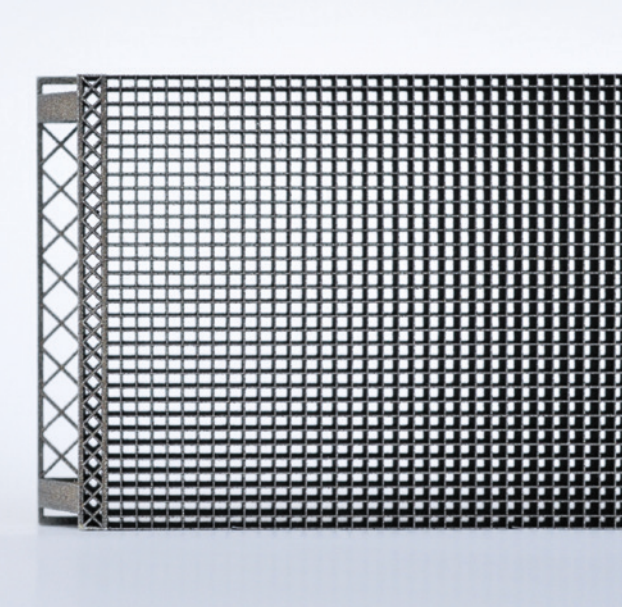
In addition to implementing ultra small focal spots for the X-ray source, the use of anti-scatter grids that are specifically designed for use in ultra high-resolution imaging can help to improve image quality and avoid shadowing. "Utilizing a detector without an anti-scatter grid is not an option, […] due to the degradation of image quality caused by scatter artifacts.[37]" The integration of 2D anti-scatter grid can reduce scatter artifacts and improve image contrast.[37]

The wall thickness has certain constraints, due to the manufacturing process or the rigidity to G-force at a high rotation speed.

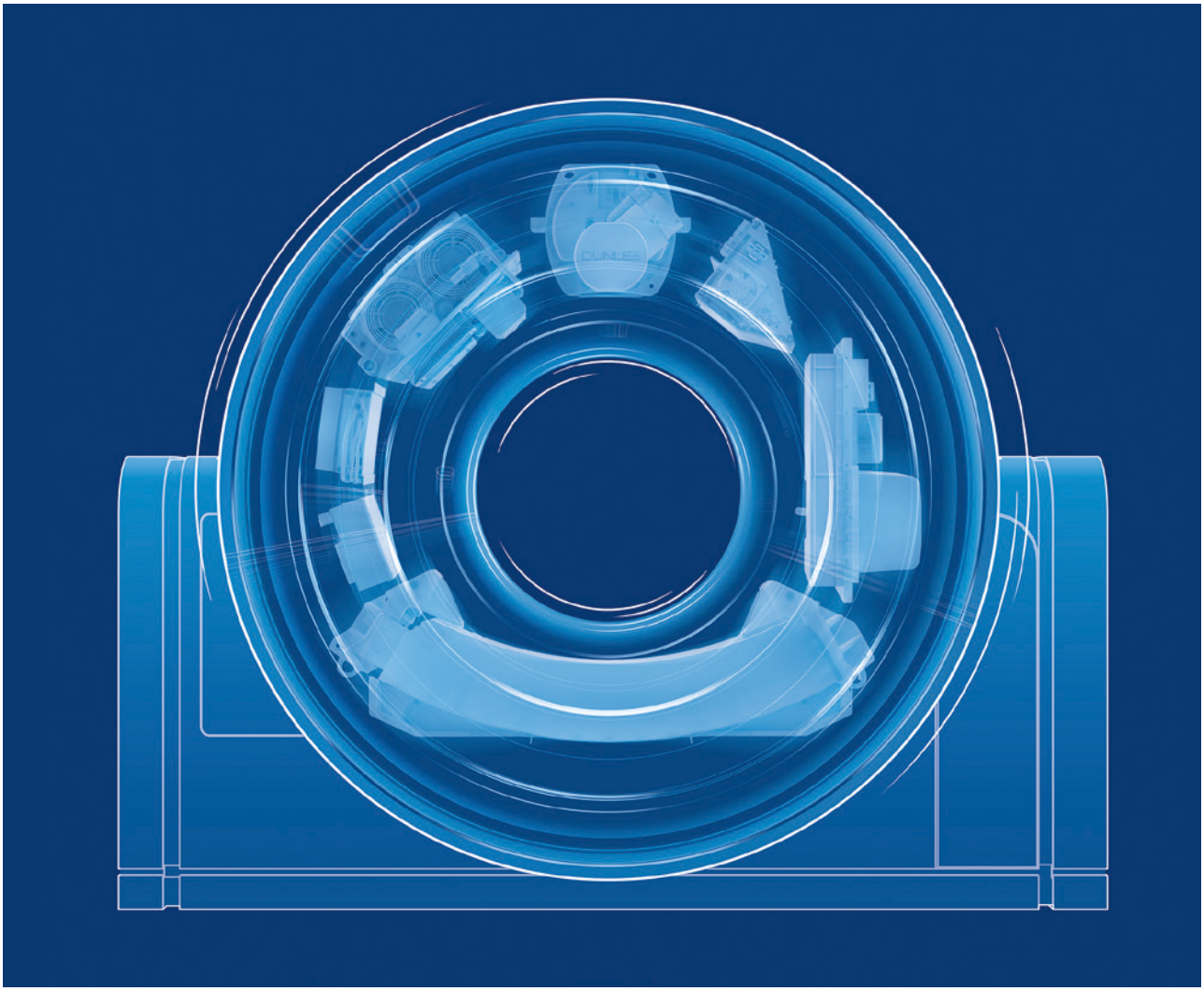
Dunlee's next generation anti-scatter grids for use in premium CT systems are made of 99.95 % pure tungsten with:

- thin walls down to <70 micron
- pixel size <300 micron
- wall tolerances down to +-15 micron.

These thin anti-scatter grids do not reduce the detector fill factor and thus ensure dose efficiency.[37] They reduce scatter and data processing load, which can increase throughput.

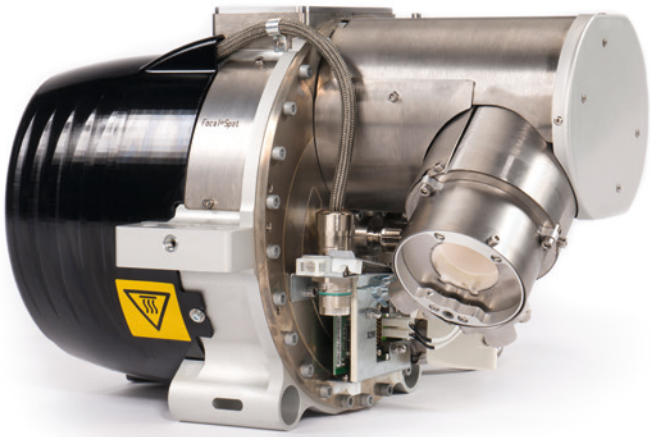


2D tungsten Anti-Scatter grid

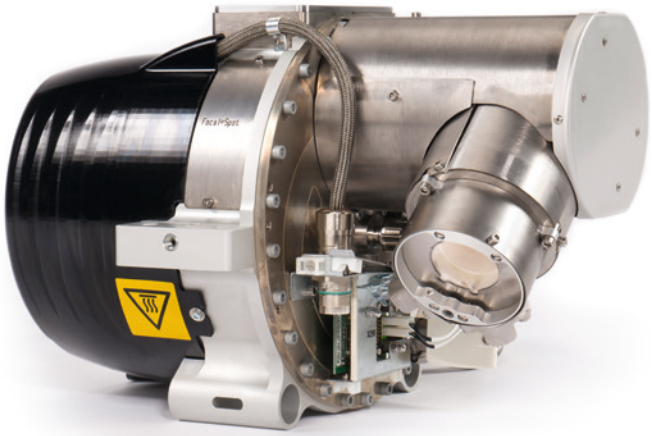


Dunlee's Solution: The Xpert Bundle

XPERT BUNDLE WITH CT8000
This bundle sets a new benchmark for your high-end CT scanners.



XPERT BUNDLE WITH CT6500
Its cutting-edge technology takes your CT system to the next level.



XPERT BUNDLE WITH CT6000
The answer for your mid-range to high-end CT system's needs.

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Executive summary

UHRCT and PCCT are fast developing imaging methods in the CT field and are highly recognized for applications where very fine details are relevant for diagnosis and treatment evaluation: like **cardiac procedures,**[3,4,5,14] visualization of fine details in organs like the heart and the lung[6] or the differentiation of benign tissue from **cancerous tumors.**[2] These aspects are also only scratching the surface of **PCCTs and UHRCTs** capabilities.

As recent research shows, **X-ray tubes with ultra small focal spots can improve spatial resolution** for both high-resolution energy integrating and photon-counting detectors significantly.[1,2,8,9] However, constructing focal spots with such small sizes **requires special expertise,** especially regarding power-density and heat-stress on the anode disc.[18,19] Smaller focal spots increase the power density on the anode, making heat management essential to avoid system downtime. At the same time, high gantry rotation speeds for complex applications - such as heart scans – demand mechanical **stability of focal spots,** regardless of size.

To fully leverage the capabilities of high-resolution detectors, the performance of the X-ray tube is critical. Dunlee's expert engineers have developed **small, highly stable focal spots that maintain sufficient power** and thermal performance for daily clinical operations.

Dunlee's **Xpert Bundles with CT6000, CT6500 and CT8000 provide ultra small focal spots** and meet these conditions, enabling modern UHRCT and PCCT systems to unlock their full potential.

Dunlee's Xpert Bundles with CT6000, CT6500 and CT8000 provide extra-small focal spots to address high resolution imaging:

	CT6000	CT6500	CT8000
Dunlee CoolGLide LMB	✓	✓	✓
Focal Spot Options [in mm]	Large: 1.1 x 1.2 Medium: 0.6 x 0.7 Small: 0.4 x 0.7 XS: 0.5 x 0.6 XXS: 0.4 x 0.6 XXXS: 0.4 x 0.5	Large: 1.1 x 1.2 Medium: 0.6 x 0.7 Small: 0.4 x 0.7 XS: 0.5 x 0.6 XXS: 0.4 x 0.6 XXXS: 0.4 × 0.5	Large: 1.1 x 1.2 Medium: 0.6 x 0.8 Small: 0.4 x 0.8 XS: 0.5 x 0.6 XXS: 0.4 x 0.6 XXXS: 0.4 x 0.5

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