**History of X-ray tube:** William Roentgen, who discovered x rays in 1895. Around this time, various scientists were investigating the movement of electrons through a glass apparatus known as a Crookes tube. Roentgen wanted to visually capture the action of the electrons, so he wrapped his Crookes tube in black photographic paper. When he ran his experiment, he noticed that a plate coated with a fluorescent material, which just happened to be lying nearby the tube, fluoresced or glowed. This was unexpected because no visible light was being emitted from the wrapped tube. Upon further investigation, he found that indeed there was some kind of invisible light produced by this tube, and it could penetrate materials such as wood, aluminum, or human skin.

**Design of CT scanner:** The CAT scanner is made up of three primary systems, including the gantry, the computer, and the operating console. Each of these is composed of various subcomponents. The gantry assembly is the largest of these systems. It is made up of all the equipment related to the patient, including the patient support, the positioning couch, the mechanical supports, and the scanner housing. It also contains the heart of the CAT scanner, the x-ray tube, as well as detectors that generate and detect x-rays.
X-ray tube in various generations of CT:

- **First generation**: CT scanners used a pencil-thin beam of radiation. The images were acquired by a “translate-rotate” method in which the x-ray source and the detector in a fixed relative position move across the patient followed by a rotation of the x-ray source/detector combination (gantry) by 1° for 180°.
  
  The thickness of the slice, typically 1 to 10mm, is generally defined by pre-patient collimation using motor driven adjustable wedges external to the X-ray tube.

- **Second generation**: The x-ray source changed from the pencil-thin beam to a fan shaped beam. The “translate-rotate” method was still used but there was a significant decrease in scanning time. Rotation was increased from one degree to thirty degrees.

  Because rotating anode tubes could not withstand the wear and tear of rotate-translate motion, this early design required a relatively low output stationary anode x-ray tube. The power limits of stationary anodes for efficient heat dissipation were improved somewhat with the use of asymmetrical focal spots (smaller in the scan plane than in the z-axis direction), but this resulted in higher radiation doses due to poor beam restriction to the scan plane. Nevertheless, these scanners required slower scan speeds to obtain adequate x-ray flux at the detectors when scanning thicker patients or body parts.
Third generation: Designers realized that if a pure rotational scanning motion could be used rather than the slam-bang translational motion, then it would be possible to use higher-power (output), rotating anode x-ray tubes and thus improve scan speeds in thicker body parts in which the 3rd generation become a Rotate-Rotate geometry. A typical machine employs a large fan beam such that the patient is completely encompassed by the fan, the detector elements are aligned along the arc of a circle centered on the focus of the X-ray tube. The X-ray tube and detector array rotate as one through 360 degrees, different projections are obtained during rotation by pulsing the x-ray source, and bow-tie shaped filters are chosen to suit the body or head shape by some manufacturers to control excessive variations in signal strength. Such filters generally attenuate the peripheral part of the divergent fan beam to a greater extent than the central part. It also helps overcome the effects of beam hardening and to minimize patient skin dose in the peripheral part of the field of view.

Fourth generation of CT scanner uses Rotate-Fixed Ring geometry where a ring of fixed detectors completely surrounds the patient. The X-ray tube rotates inside the detector ring through a full 360 degrees with a wide fan beam producing a single image. Due to the
elimination of translate-rotate motion the scan time is reduced comparable with third generation scanner, initially, to 10 seconds per slice but the radiographic geometry is poor because the X-ray tube must be closer to the patient than the detectors, i.e. the geometric magnification is large also scatter artifact is more than third generation since they cannot use anti-scatter grid.

-The disadvantages of poor geometry noted above have been alleviated very neatly by the so called nutating geometry. The X-ray tube is external to the detector ring but slightly out of the detector plane, this change resulted in increasing both the acquisition speed, and image resolution. The method of scanning was still slow, because the X-ray tube and control components interfaced by cable, limiting the scan frame rotation. Further, they were more sensitive to artifacts because the non-fixed relationship to the x-ray source made it impossible to reject scattered radiation.

**Sampling Geometries of the beam:** The sampling geometry of the beam in CT scanners along the different generations can be described as three configurations:

**Further advances:** Another limiting factor in image acquisition was the X-ray tube. The need for long, high intensity exposures and very stable output placed enormous demands on
both the tube and generator (power supply). Very high performance rotating anode tubes were developed to keep up with demand for faster imaging, as were the regulated 150 kV switched mode power supplies to drive them. Modern systems have power ratings up to 100 kW.

**Slip-Ring Technology**

Slip rings are electro-mechanical devices consisting of circular electrical conductive rings and brushes that transmit electrical energy across a moving interface. All power and control signals from the stationary parts of the scanner system are communicated to the rotating frame through the slip ring. The slip-ring design consists of sets of parallel conductive rings concentric to the gantry axis that connect to the tube, detectors, and control circuits by sliding contactors. These sliding contactors allow the scan frame to rotate continuously with no need to stop between rotations to rewind system cables. However, reduced inter scan delay increased the thermal demands on the x-ray tube; the innovations in slip-ring technology resulted in generation of Helical / Spiral CT scanner.

**Helical / Spiral CT scanner:**

![Diagram of Helical CT scanner](image)

**X-ray tube motion in different generations:**

- In conventional CT the tube & detectors moves clock wise & anti-clock wise 360° while in spiral / helical CT the tube & detector arrays continuously move with the table.

**Dual source:** CT uses 2 x-ray sources and 2 detector arrays offset at 90 degrees.
Hybird CT scanner generation:

**Electron beam tomography**

Patent illustration showing a cutaway view of an electron beam computerized tomography system. Components are 22. electron gun, 23. electron beam, 24. focus coil, 27. beam bending coil, 28-31. target rings, 14. detector array, 11. scan tube. The electron beam is reflected by the target rings through the patient, to the detector on the opposite end of the scan tube.

**Electron beam tomography** is a specific form of computed axial tomography (CAT or CT) in which the X-Ray tube is not mechanically spun in order to rotate the source of X-Ray photons. This different design was explicitly developed to better image heart structures which never stop moving, performing a complex complete cycle of movement with each heart beat.

As in conventional CT technology, the X-ray source still rotates around the circle in space containing an object to be imaged tomographically, but the X-Ray tube is much larger than the imaging circle and the electron beam current within the vacuum tube is swept electronically, in a circular (partial circle actually) path and focused on a stationary tungsten anode target ring.
EBT Design advantage:

The principal application advantage of EBT tomographic CT machines and the reason for the invention is that the X-Ray source is swept electronically, not mechanically, and can thus be swept with far greater speed than with conventional CT machines based on mechanically spun X-Ray tubes.

The major medical application for this design technology was invented in the 1980s, namely for imaging the human heart. The heart never stops moving, and some important structures, such as arteries, move several times their diameter during each heartbeat. Rapid imaging is, thus, important to prevent blurring of moving structures during the scan. The most advanced current commercial designs can perform image sweeps in as little as 0.025 seconds. By comparison, the fastest mechanically swept X-Ray tube designs require about 0.33 seconds performing an image sweep. For reference, current coronary artery angiography imaging is usually performed at 30 frames/second or 0.033 seconds/frame; EBT is far closer to this than mechanically swept CT machines.

EBT Design specifics: As in standard X-Ray tubes, part of the electron current energy when hitting the tungsten target is converted into photons. However, instead of spinning a small target anode in order to dissipate waste heat, the electron current focus spot is swept along a large stationary target anode.

The electron current sweep is aimed using wound copper coil magnetic deflection yokes, as in a cathode ray tube (CRT). However, the entire structure of the cathode, deflection yokes, anode and overall vacuum tube size is much larger, therefore made out of steel, not glass, with the main central open mid-section of the vacuum tube hollow, leaving room for the scan table and object or person to lie while the scan is performed.

EBT Design disadvantage: size and low production volume of the EBT design. The more widely sold CT design in which a small, more conventional X-Ray tube is mechanically spun.

Future: it increasingly appears that the spiral CT designs, especially those with (b) 64 detector rows, (b) 3 x 360°/sec rotation speeds and designed for cardiac imaging, are largely replacing the EBT design from a commercial and medical perspective. However, EBT still offers sweep speeds of effectively 50 x 360°/sec rotation speeds and lower radiation exposure.

X-ray source

The important variables that determine how effective an X-ray source will be for a particular task are the size of the focal spot, the spectrum of X-ray energies generated, and the X-ray intensity. The focal-spot size partially defines the potential spatial resolution of a CT system.
by determining the number of possible source-detector paths that can intersect a given point in the object being scanned. The more such source-detector paths there are, the more blurring of features there will be. The energy spectrum defines the penetrative ability of the X-rays, as well as their expected relative attenuation as they pass through materials of different density. Higher-energy X-rays penetrate more effectively than lower-energy ones, but are less sensitive to changes in material density and composition. The X-ray intensity directly affects the signal-to-noise ratio and thus image clarity. Higher intensities improve the underlying counting statistics, but often require a larger focal spot.

Many conventional X-ray tubes have a dual filament that provides two focal-spot sizes, with the smaller spot size allowing more detailed imagery at a cost in intensity. Medical CT systems tend to have X-ray spot sizes that range from 0.5 mm to 2 mm. The high-resolution system at the UT CT Facility utilizes a dual-spot 420-kV X-ray source (Pantak HF420), with spot sizes of 0.8 and 1.8 mm. The small spot has a maximum load of 800 W (i.e., 2 mA at 400 kV), whereas the large spot has a maximum load of 2000 W. The 225 kV tube used for ultra-high resolution work (Fine focus FXE-225.20) has an adjustable focal spot with a minimum size of <6 μm at 8 W total load, but at higher loads the spot size is automatically increased to prevent thermal damage to the target. In most cases a slightly “defocused” beam (larger spot size) can be used to improve counting statistics with little cost in resolution. Both sources have tungsten targets.

**X-ray tubes may all be classified in two general groups, gas tubes and high-vacuum tubes**

- **Gas tubes electrons:** are freed from a cold cathode by positive ion bombardment. For the existence of the positive ions a certain gas pressure is required without which the tube will allow no current to pass. Metals, such as platinum and tungsten, are placed in the path of the electron beam to serve as the target. Concave metal cathodes are used to focus the electrons on a small area of the metal target and increase the sharpness of the resulting shadows on the fluorescent screen or the photographic film. Many designs of gas tubes have been built for useful application, particularly in the medical field.

- **The high-vacuum x-ray tube:** The operational difficulties and erratic behavior of gas x-ray tubes are inherently associated with the gas itself and the positive ion bombardment that takes place during operation. The high-vacuum x-ray tube eliminates these difficulties by using other means of emitting electrons from the cathode. The original type of high-vacuum x-ray tube had a hot tungsten-filament cathode and a solid tungsten target. This tube permitted stable and reproducible operation with relatively high voltages and large masses of metals. A modern commercial hot-cathode high-vacuum x-ray tube is built with a liquid-cooled, copper-backed tungsten target.

**Raw Materials:** Tungsten is also used to make the cathode and electron beam target of the x-ray tube. Other materials found in the tube are Pyrex, glass, copper, and tungsten alloys.
Throughout many parts of the CAT scanner system, lead can be found, which reduces the amount of excess radiation.

The Manufacturing:

- The x-ray tube is made much like other types of electrical diodes. The individual components, including the cathode and anode, are placed inside the tube envelope and vacuum sealed. The tube is then situated into the protective housing, which can then be attached to the rotating portion of the scanner frame.
- To create the large amount of voltage needed to produce x-rays, an autotransformer is used. This power supply device is made by winding wire around a core. Electric tap connections are made at various points along the coil and connected to the main power source. With this device, output voltage can be increased to approximately twice the input voltage.

Quality Control; In addition to the quality specifications set by the manufacturers, the United States Food and Drug Administration (FDA) has regulations that require manufacturers to perform specific quality control tests. Examples of these tests include calibration tests of the x-ray tube.
**X-ray tube function:** As with any vacuum tube, there is a cathode to emit electrons into the vacuum and an anode to collect the electrons, thus establishing a flow of electrical current through the tube. A high voltage power source is connected across cathode and anode, for example 30 to 150 kilovolts (kV), such that the voltage can be quickly switched on, then off, for precise amounts of time, e.g. 0.001 to 1.0 second, and the current flow, often in the 1.0 to 1000 milliampere range, once started, can be controlled. Until the late 1980s, X-ray generators were merely high-voltage, AC to DC variable power supplies. In the late 1980s a different method of control was emerging, called high speed switching. This followed the electronics technology of switching power supplies (aka switch mode power supply), and allowed for more accurate control of the X-ray unit, higher quality results, and reduced X-ray exposures.

Electrons focused on the tungsten (and sometimes molybdenum) anode from the cathode, collide with and accelerate other electrons, ions and nuclei within the anode material and about 1% of the energy generated is emitted/radiated, perpendicular to the path of the electron current, as X-ray photons. Over time, tungsten will be deposited from the anode onto the interior glass surface of the tube. This will slowly degrade the quality of the X-ray beam. Eventually, the tungsten deposit will become sufficient enough to act as a conductive bridge, and at high enough settings, arcing will occur. The arc will jump from the cathode to the tungsten deposit, and then to the anode. This arcing will cause an effect called “crazing” on the interior glass of the X-ray window. As time goes on, the tube will become unstable even at lower potentials, and must be replaced. At this point, the tube assembly (also called the "tube head") is removed from the X-ray system, and replaced with a new tube assembly. The old tube assembly is shipped to a company that reloads it with a new X-ray tube.

The X-Ray photon-generating effect is generally called the Bremsstrahlung effect, a contraction of the German brems for braking, and strahlung for radiation.

The range of photonic energies emitted by the system can be adjusted by changing the applied voltage, and installing aluminum filters of varying thicknesses. Aluminum filters are installed in the path of the X-ray beam to remove "soft" (non-penetrating) radiation. The numbers of emitted X-ray photons, or dose, are adjusted by controlling the current flow and exposure time.

Simply put, the high voltage controls X-ray penetration, and thus the contrast of the image. The tube current and exposure time affect the dose and therefore the darkness of the image.

**X-ray tube with flying focus:** has a magnet system for deflecting and focusing the electron beam, whereby the magnet system including a carrier that is constructed as an iron yoke and that has four pole projections that are arranged around the axis of the electron beam offset from one another by 90 degree., on which two pairs of coils (z-coils and phi.-coils) are arranged so as to be offset from one another 90 degree.. The individual coils of each pair supplied with a common high-frequency alternating current that deflects the electron beam in the phi.-and z-directions, respectively, in a pulsed manner.
**X-Ray Tubes**

Timken bearings meet a variety of challenges in traditional X-ray equipment, as well as the more demanding CAT scan systems. The main location is the rotating anode of the X-ray tube. Ultra-high speed tool steels and solid film lubricants allow operation in a vacuum at temperatures up to 450°C. Ultra-clean manufacturing helps prevent contamination, where stray particles can impact bearing performance and cause tube arcing damage. The typical bearing assembly consists of an integral Unit. Materials are joined to the assembly to provide support for the rotating X-ray target. Timken® bearings meet high-speed requirements by withstanding the higher G-forces and stresses. Reduced vibration helps extend service life and maintain both quiet operation and optimal image resolution.

**High-Power X-ray Tubes**

X-ray tubes are subjected to far higher thermal loads in CT than in any other diagnostic x-ray application. In early CT scanners, such as in first- and second-generation, stationary anode x-ray tubes were used, since the long scan times meant that the instantaneous power level was low. Long scan times also allowed heat dissipation. Shorter scan times in later versions of CT scanners required high-power x-ray tubes and use of oil-cooled rotating anodes for efficient thermal dissipation. Heat storage capacities varied from 1 million to 3 million heat units in early third-generation CT scanners. The introduction of helical CT with continuous scanner rotation placed new demands on x-ray tubes.

Several technical advances in component design have been made to achieve these power levels and deal with the problems of target temperature, heat storage, and heat dissipation. For example, the tube envelope, cathode assembly, and anode assemblies including anode rotation and target design have been redesigned. As scan times have decreased, anode heat capacities have increased by as much as a factor of five, preventing the need for cooling delays during most clinical procedures, and tubes with capacities of 5–8 million heat units are available. In addition, improvement in the heat dissipation rate (kilo–heat units per minute) has increased the heat storage capacity of modern x-ray tubes. The large heat capacities are achieved with thick graphite backing of target disks, anode diameters of 200 mm or more, improved high-temperature rotor bearings, and metal housings with ceramic insulators among other factors. The working life of tubes used to date ranges from 10,000 to 40,000 hours, compared with the 1,000 hours typical of conventional CT tubes. Because many of the engineering changes increased the mass of the tube, much of the design effort was also dedicated to reduce the mass to better withstand increasing gantry rotational rates required by faster scan times.
X-ray tube in Multislice CT scanner

-Unlike to most of other technological factors, X-ray tube on multislice CT scanner is exceptionally benefited since the lord to the tube is reduced by the employment of multislice detector. In this aspect, the tube for multislice CT is not necessarily to be a bigger one. However, the situation may totally be changed when one goes to employ faster rotation in combination with multislice detector system. Aquilion was the first scanner to be equipped with half-second rotation. Because of these challenging specs, an entirely new tube design is required in terms of precision, safety, and product life.

Concept and design: During 0.5-s scanning, the anode of the X-ray tube is subjected to a force of 13-G, so that the conventional cantilever anode could not tolerate G force.
The shorter scanning time also requires an increased X-ray dose per unit time, so a high-output X-ray generation system is needed. Furthermore, faster scanning is expected to lead to an increase in the number of examinations, which means that the X-ray tube must have improved cooling efficiency. To satisfy these requirements, a completely new X-ray tube has been developed for Aquilion. This tube has a straddle bearing structure in which the anode is supported by bearings on both sides which provides a more precise and stable focus and a longer service life compared with the conventional cantilever anode type.
In addition, the new tube is anode grounded, so the voltage is applied only to the cathode. This design eliminates the risk of electrical discharge between the anode and the housing, allowing them to be moved closer together, which resulted improved cooling. In an anode-grounded tube, recoil electrons from the anode are prevented from re-entering the anode, minimizing heat buildup. As a result of the above design innovations, the new tube is able to offer a cooling efficiency comparable to that of a conventional tube rated at 20 MHU. Elimination of recoil electrons is also effective in eliminating off-focus radiation, which will improve accuracy of X-ray beam geometry.

Stability and performance: Since this is truly an innovative product, it is not strange that we had had numbers of difficulty to overcome at early stages of development. We have experienced several problems in stability and tube life. These problems were seen in the process to establish production lines, which were fixed after enthusiastic research. Our current tube is perfectly stable and no practical problem can be found. The performance is really amazing. We have never experienced waiting time for tube cooling in actual clinical practice.

Variable improvements within the different manufacturers:

- The 16-slice system of Philips also comes in a 'Power' configuration, which is capable of reconstructing 40 images per second, and uses the new MRC x-ray tube. Incorporating liquid metal spiral groove bearings, this tube has an 8 MHU heat capacity and a high cooling rate, producing an effective heat capacity several times higher than the nominal 8 MHU value. The MRC is Philips' own tube, developed from their image intensifier range. It incorporates a smaller focal spot than the tubes currently used in Philips systems, which will enable spatial resolutions as high as 24 lp/cm (MTF2).

- The Light Speed Pro 16 from GE is an upgraded version of the existing Light Speed 16. It is available in 60, 80 and 100 kW generator versions, and together with a new x-ray tube the system will be capable of scanning using at up to 800 mA at 120 kV, with a fastest gantry rotation time improved from 0.5 to 0.4 seconds.
One of the more interesting developments at RSNA was the **Siemens Straton x-ray tube**, which is currently available as an option on Sensation 16 scanners (Figure 2). The tube itself is a radical new design, where the entire tube body rotates, rather than just the anode, as is the case with conventional designs. This change allows all the bearings to be located outside the evacuated tube, and enables the anode to be cooled more efficiently. The Straton has a low inherent heat capacity of 0.8 MHU, but an extremely fast cooling rate of 5 MHU / min. This compares with typical figures of 7-8 MHU and up to 1.4 MHU / min for existing tubes. The heat capacity and cooling rate combine to produce a tube which Siemens claim is '0 MHU', implying that tube cooling considerations are a thing of the past. The design of this tube enables z-axis over sampling to be carried out - effectively flying focal spot in the z-direction. Flying focal spot is a well-established technique that is currently used only in the x-y plane to double the amount of projection data that is gathered, increasing the spatial resolution of the system. Z-axis over sampling extends this to the third dimension, and significantly suppresses spiral artifacts as well as improving z axis resolution. Sensation 16 scanners fitted with the Straton tube now have a fastest scan time of 0.37 seconds.
Dose issues:
GE, Siemens and Toshiba have expanded the capabilities of their automatic exposure control (AEC) systems, which work by varying the x-ray tube current in response to changes in the patient's attenuation.
The Toshiba system, now known as SUREExposure, has been expanded, and the operator can request a desired image quality by selecting an image noise level. The system then sets the appropriate mA for each rotation in order to achieve this image quality.
The Siemens CAREdose system is now capable of modulating the tube current along the length of the patient, and also accounts for overall patient size. CAREdose 4D takes a typical mAs value used for a standard sized patient as the starting point for modulation, and adjusts this based upon the patient size. This is in addition to the rotational modulation of the mA that was available in existing versions of CAREdose.
GE's SmartScan system has been expanded on the LightSpeed Pro 16 to allow rotational mA modulation, as well as the existing z-axis and overall patient size adjustment that is controlled by setting a desired image noise level.

Future Directions:
- With increased awareness about the radiation dose encountered during CT scanning, developments are under way to develop real-time exposure control to reduce radiation dose without loss of image quality by measuring attenuation within the patient during scanography or scout scanning and thereby adjusting the tube current during each gantry rotation.

References:
http://medgadget.com/wiki/wiki/Computed_tomography
http://www.iop.org/EJ/abstract/0031-9120/36/6/301
http://www.ele.uri.edu/research/biomedical/medimage/x-ray.html
http://heart.health.ivillage.com/noninvasivecardiactest/catscan4.cfm
http://radiographics.rsna.org/cgi/content/full/22/4/949#SEC1
http://CAT scanner Definition and Much More from Answers_com.htm
http://www.Computed_Tomography.htm
http://Computed_tomography-Medgadget_Wiki.htm
http://www.fujita-hu.ac.jp/~kkatada/index.html
http://www.answers.com/topic/cat-scanner

Collected by:
Afnan Malaih / Lamis Jada'a