
X-RAY TUBES DEVELOPMENT - IOMP HISTORY OF MEDICAL PHYSICS

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Content

Studying the history of medical X-rays and the evolution of the technology of its sources has been sparking fascination and heuristic insight over more than a century, see e.g.[1–10]. Today vacuum electronic X-ray tubes remain the dominant and affordable sources of medical diagnostic X-rays, see [9] and [11], despite of their deficiencies, see [12]. This article will illustrate the various branches of the development of the technology, and briefly mention a few of those scientists, craftsmen, business leaders, and artisans, who have driven this field of innovation.Although many other physical processes are employed to generate X-rays for special applications, it is expected, that bremsstrahlung (stopping radiation) from X-ray tubes will remain the dominant agent in medical X-ray diagnostics for the decades to come, see [11].

After initial remarks on the way X-rays entered the clinical routine, this paper, a part of the IOMP Project “History of Medical Physics”, willdiscuss in depth the paths taken for improvement of medical X-ray tubes for radiography, angiography, dental and mammography application.

1. Enabling technologies and physics in the 19th century

Ongoing technical evolution culminated in Conrad Wilhelm Röntgen’s discovery of X-rays, what happened at dawn of Friday, November 8th, 1895 in the Physical Institute of the University of Würzburg, Germany, see **Figure 1**. **Figure 2** shows the greenish glowing glass wall of a Crooke’s tube, similar to the one which Röntgen used. The greenish color signals generation of X-rays by the electrons impact on the glass target. Their interaction with the atomic nuclei is essential to generate the highly energetic X-ray photons which are capable of penetrating at least portions of a human body, see e.g. [9], [13,14]. The required ingredients for this X-ray generation are free electrons, an accelerating electric field and a suitable target material.

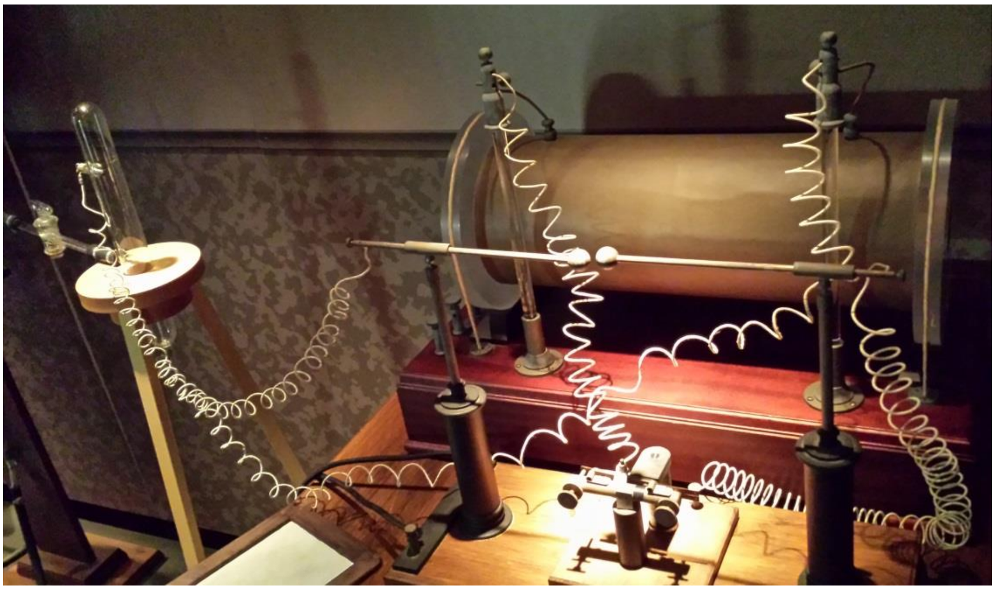

Figure 1 Replica of C.W. Röntgen’s first experimental equipment in his laboratory in Würzburg, Germany. It shows an actively pumped simple Crookes tube and a “large” Rühmkorff inductor. Röntgen discovered X-rays at dawn of Friday November 8th, 1895. (Photo taken at the German Röntgen Museum, Remscheid-Lennep, Germany.)

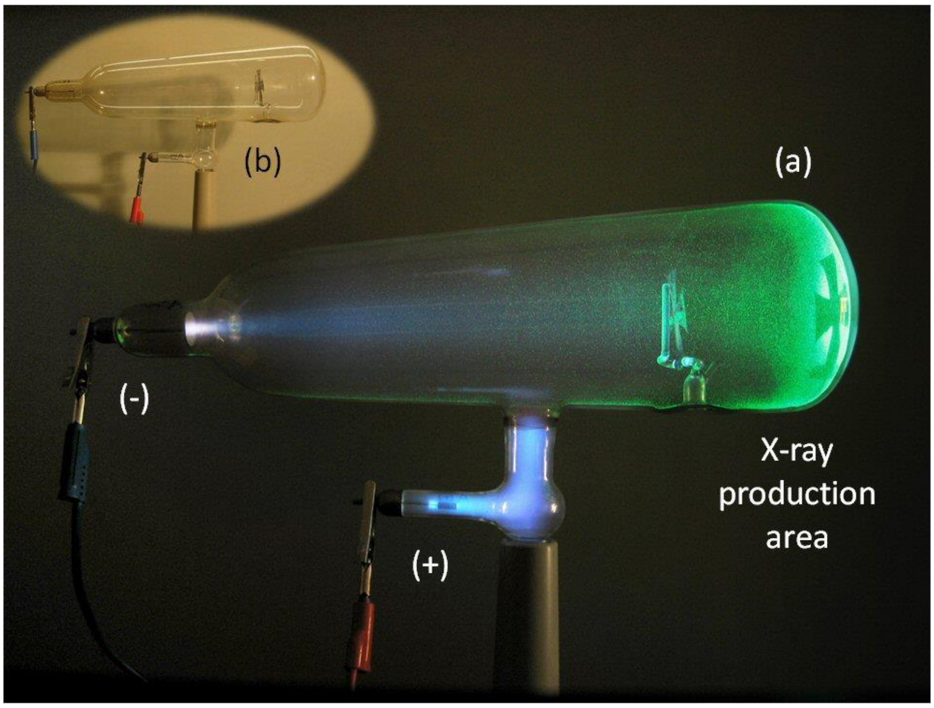

Figure 2 Crookes tube with shadow cross in use. X-rays emerge upon impact of electrons (cathode rays) on the glass wall at the right. Sub-picture: the uncharged tube. (Credit: D-Kuru, https://commons.wikimedia.org/w/index.php?curid=3068002, accessed Aug. 10th, 2017.)

Ancient Egyptians had already dealt with high voltage associated with the electric eel, as early as 2750 B.C. By 1644, Evangelista Torricelli evacuated glass tubes with falling mercury. In 1657, O. von Guericke attempted to separate large evacuated "Magdeburger" half spheres with horses, and failed. In 1705 F. Hauksbee, the elder, discovered sparks of light through partly evacuated vessels. W. Morgan may well have generated X-rays in 1785 during experiments on insulation by vacuum. Since the mid of the nineteenth century, voltages of tens of kilovolts at powers of tens of Watts have become available. J. Plücker generated free electrons in partial vacuum ("cathode rays") from 1858. Later J. W. Hittorf extended these experiments from 1869. Sir William Crookes deflected electrons magnetically. P. Lenard sent them through thin sheets of metal into free air.

1. Röntgen's discovery

Röntgenrepeated Lenard's experiments on cathode rays using a partly evacuated Crookes glass tube, a Hittorf tube or a Lenard tube, charged by a "large" Rühmkorff inductor, see [15]. He noticed a peculiar yellowish-green glow of a remote scintillator screen, see [13,14,16]. Without knowing, already five years before Röntgen's discoveryA. W. Goodspeed and his assistant W. N. Jennings had exposed photo plates to X-rays in Philadelphia, USA[17]. But, then, the team failed to have a final clue on the cause of the "destruction" of the plates. Also about five years beforeRöntgen's discovery I. Puluj from University of Strasbourg observed effects of X-rays and published a paper "Luminous Electrical Matter and the Fourth State of Matter", but he did not recognized the received rays as the X-rays. Röntgen, instead, identified the source of the miraculous agent. He experimented with different kinds of tubes, varied electrical and geometrical parameters, vacuum conditions, objects downstream of the obvious origin of X-rays, detection technology and identified key characteristics of the newly discovered radiation in a period of weeks. Although he speculated and, in part, misinterpreted, Röntgen laid the firm ground for early diagnostic and therapeutic application of X-rays. Many of the effects, which he saw for the first time under controlled conditions, are still being employed. For instance, he shifted the origin of the X-rays by magnetic deflection of cathode rays, and, thus invented the magnetic focal spot deflection, which serves to this date to improve image quality in computed tomography (CT).Röntgen's discovery, and its application in medicine, triggered the establishment of the Nobel Awards, the first one being present to him in 1901.

2. Early clinical use and industrialization from 1896

Within the first year from the discovery, more than one thousand articles on X-rays were published worldwide. On January 12th, 1896 the first X-ray picture on the American continent was produced intentionally at the Davidson College, North Carolina, see [18]. On February 3rd, 1896 a diagnostic X-ray of the broken wrist was taken at Dartmouth College, Hannover, NH, USA. Yale University in New Haven, Connecticut, USA.

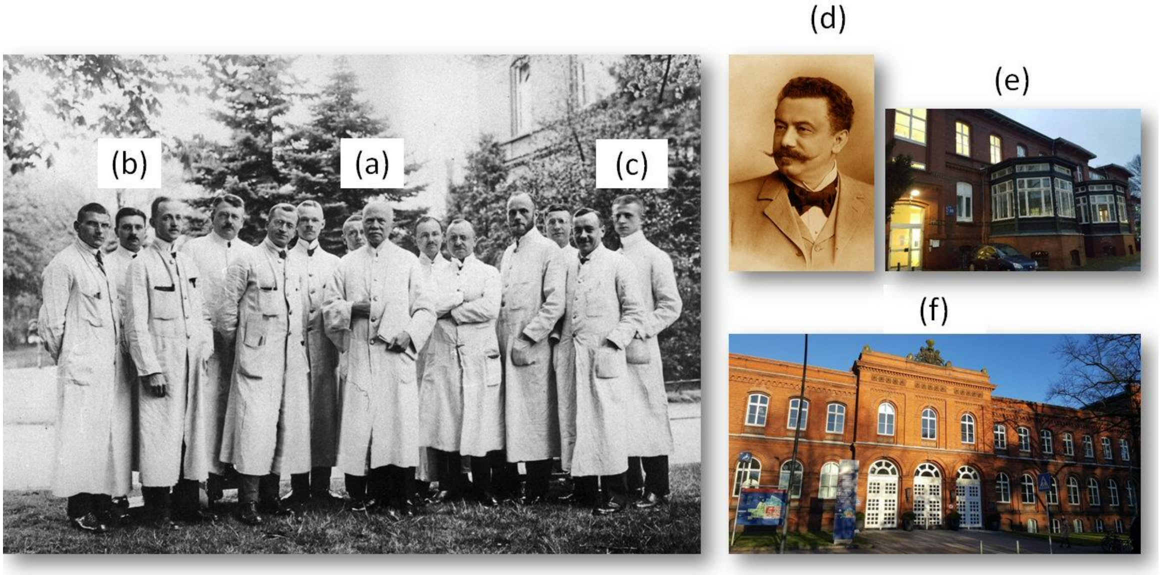

Figure 3 On March 20th, 1896, Hermann Kümmell (a), head of the surgical department and his team of the New General Hospital in Hamburg, Germany, initiated the first installation of an X-ray system worldwide - in a clinical setting in the preparation room of the new operation theater. Hermann Gocht(b), assistant of Kümmell and his friend and colleague Gustav Opitz (c) bought the first tubes from the glass blower C.H.F. Müller (d) in downtown Hamburg, and installed the system. (e) Actual pictures of the former operation house and (f) entrance of the hospital, now University Medical Center Eppendorf, UKE. (Photo (a) picture archive of Medizinhistorisches Museum Hamburg, Germany, UKE.)

Upon the initiative of the head of one of the surgical departments, Prof. Dr. Hermann Kümmell, the first sustained installation of X-ray equipment globally (in a public clinic) was put in operation on March 20th, 1896 in the "New General Hospital" in Hamburg, Germany. This institution still exists as the University Medical Center Hamburg Eppendorf (UKE, see [3],[16], [19], [20] and **Figure 3**). Kümmell had sent his assistants H. Gocht and G. Opitz to downtown Hamburg, who met with the glass blower C.H.F. Müller, whose company was later acquired by Philips, The Netherlands. Gocht, Optiz and Müller enthusiastically experimented with the new radiation and its sources and installed the first clinical equipment in a preparation room of the new operation theatre [1]. In those days, key users had to have a

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[1] Translation from [20], page 779. Herman Gocht, recalling in 1914 the events which happened eighteen years before: *Meanwhile, March 20th, 1896, had arrived; on this day the first X-ray apparatus was put into service in the surgical department of Kümmell at the*

wide set of competences. They mastered medical physics, vacuum physics, high voltage electronics, and radiology. Later Gocht became a leading radiologist. Unfortunately, all three and many of their co-workers and staff died later from radiation-induced illness.

Work in physics laboratories went on as well. Less than a week after the first clinical installation in Hamburg, Siemens and Halske, Germany, filed the first X-ray tube patent, DE91028 on March 26th, 1896, see [8].**Figure 4**shows a sophisticated ion tube from C.H.F. Müller with automated gas "regulation" to reduce the energy of the emitted X-ray photons. The discharge process started at lower high voltage when the gas pressure was elevated. Many other companies also began producing X-ray tubes, see e.g. [21].

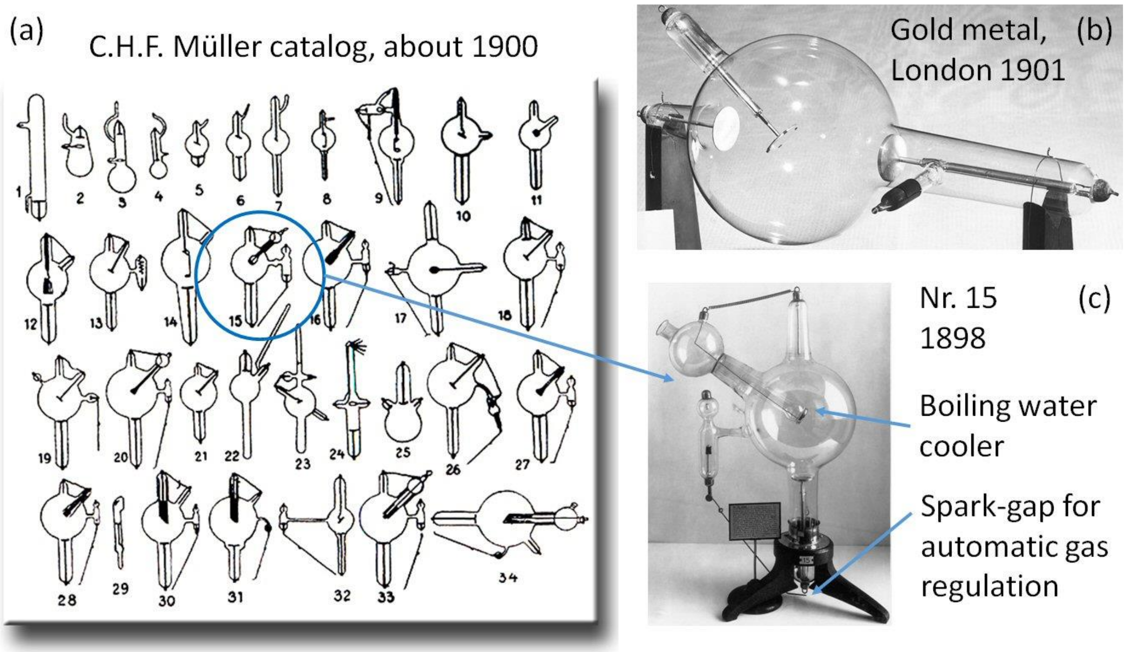

Figure 4 Ion tubesproduced bythe C.H.F. Müller AG, Hamburg, Germany (later Philips), about 1900. (a) Catalog from about 1900. (b) Müller ion tube, which won the gold medal for the best tube out of 28 in the London Roentgen Society competition 1901. The tube is on exhibit in the Science Museum, London, UK. (c) First water cooled tube after Prof Dr. B. Walter (physicist, Hamburg Germany). The automatic gas regulator is activated with an adjustable spark gap when the tube voltage rises due to falling gas pressure inside the glass envelope.

Figure 5illustrates how the high electron current density in an ion tube nearly destroyed the anode by surface melting. The C.F.H. Müller tube shown in **Figure 5** (a), serial number 82456, was produced in Hamburg, Germany, around the year 1910, and had indeed been in use. During the phase of negative charging of the cathode by the inductor, residual gas was ionized. Every ion impacting on the cathode cup at the right in **Figure 5** (d) released up to a dozen of initially slow electrons. The electrostatic field formed by the concave cathode cup accelerated the electrons between cathode and anode at the left in **Figure 5** (d), and focused them into the focal spot on the copper target (b). A melting pattern of the overheated focal spot is clearly visible. As copper evaporated and chemically reacted with residual gas,

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Eppendorf Hospital. Kümmell had acquired the Rhümkorff apparatus (inductor) from the company Keiser and Schmidt in Berlin (Germany). It generated 25 cm long sparks (remark: this corresponds to a peak tube voltage of 80 kVp) *with the help of a Deprez platinum circuit breaker. We used two existing accumulator batteries from Reiniger, Gebbert and Schall, Erlangen, (Germany), which were otherwise used for light and cauterization in surgical manipulations. Florence Müller delivered the tubes to us.*

1.

and as ions were implanted in the cathode, the gas pressure inside the sealed vessel dropped over time. Manufacturers devised sophisticated countermeasures to overcome this problem. Gas releasing material in a remote appendix (c) was heated to re-fill the mobile tube such that the tube was “softened” again, i.e., it was then able to spark discharges at reduced high voltage and deliver photons with lower energy for better contrast of soft tissue.

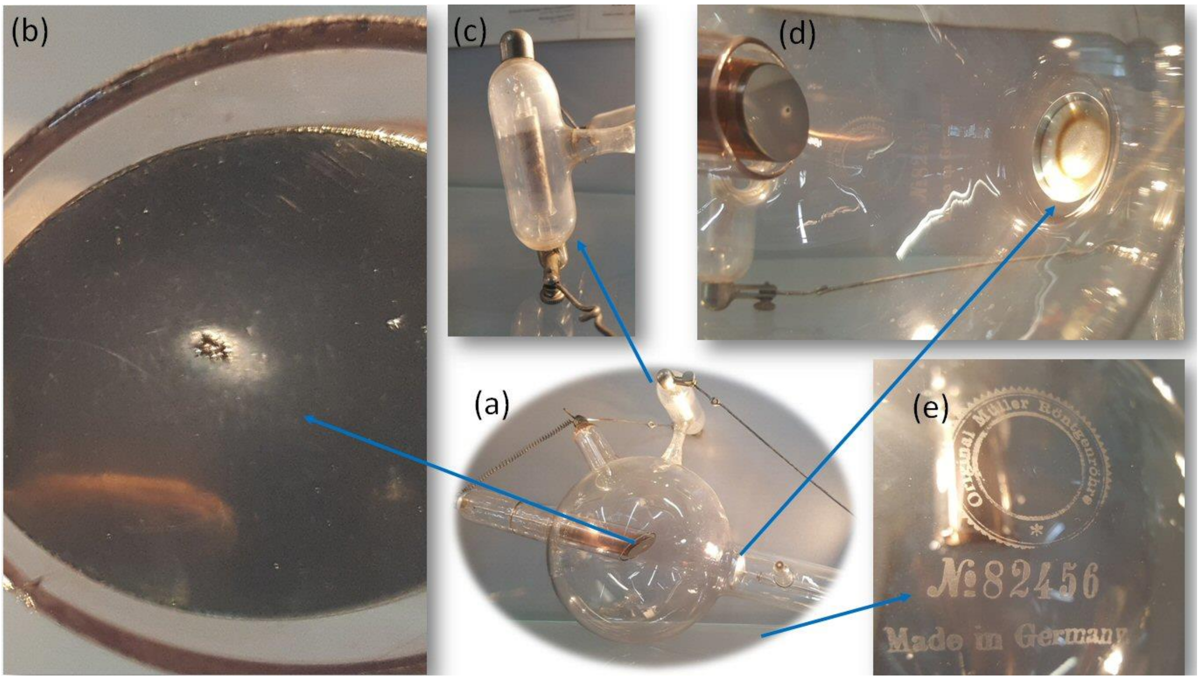

Figure 5(a) Ion tube similar to the one depicted in Figure 3. (b) Close-up view of the copper target. Repeated heavy electron impact overloaded the ellipsoidal focal spot. Melting and re-solidification led to cracking of the surface. (c) Regulator for gas production from heated potassium hydroxide, which engaged automatically when the discharge between anode and cathode ceased at insufficientgas pressure andthe inductor voltage exceeded a predefined level. (d) The concave cathode cup showssigns of oxidation and areas cleaned by ion impact. (e) Production label and serial number 82456 of the C.H.F. Müller AG, Hamburg, Germany (later Philips).

Reiniger, Gebbert and Schall AG, Erlangen, later Siemens, Munich, Germany, delivered tubes and scientific equipment to Prof. Röntgen as early as 1896. **Figure 6** demonstrates the ingenuity at the time, an ion tube for stereoscopic viewing.

Figure 6 Ion tube for stereoscopic imaging from 1912 after Dr. Fürstennau produced by the H. Bauer GmbH, Jena, Germany or Radiologie GmbH, Berlin, Germany. (Picture taken at the Siemens X-ray tube museum Rudolstadt, Germany.)

The company of E. Gundelach in Thuringia, Germany, another competitor, claimed to have produced 45,000 tubes by April 1905; C. H. F. Mueller, Hamburg, Germany - 50.000. Machlett New York, NY, established in 1897 (which became a division of Varian in 1989, now Varex, Salt Lake City, UT, USA) was probably the first producer in the United States, see [22]. Toshiba, Japan, began producing X-ray tubes in 1915, see **Figure 7**(this “Giba” tube was the predecessor of a large variety of products from the company).

Figure 7 Toshiba “Giba” x-ray tube, the first Japanese domestic x-ray tube, developed and commercialized in 1915by Toshiba Denki, later Toshiba Electron tubes & Device Co., Ltd (TETD, now Canon, Japan, group). Many types of x-ray tubes have been developed originating from this “Giba X-ray tube”. (Courtesy of Toshiba Science Museum.)

3. Victims of X-rays and safety measures

The biological harm caused by high doses of the new radiation became obvious early on, see [18]. Many of the pioneering surgeons, scientists, and manufacturing staff, suffered severely. About 360 casualties have been reported at that time. Some radiographers sacrificed their own health when adjusting the equipment by imaging their hands before exposing patients. The exhibit of the cancerous hand of a radiographer can be seen at the German Röntgen Museum in Remscheid-Lennep, Germany. A number of people were also killed or injured by electrical shock. The increasing quest for reduction of the dose of ionizing radiation resulted in improvements of the X-ray beam quality by X-ray filters and radiation shields against primary radiation. X-ray sources were encapsulated and measures against scattered radiation taken. High voltage supply was shielded and improved safety standards were defined. Philips presented the “fully protected” Media^{TM} and Rotalix^{TM} tubes in the 1920s, see **Figures 12** to **14**. The Media^{TM} tube allowed for changing the beam quality by an X-ray filter changer in a rotatable sleeve. Later, beam limiting devices (like the modern one depicted in **Figure 15)** were introduced, which allowed for adding selectable filters. Over the years, X-ray beams became harder and more monochromatic. Whereas, Röntgen first generated X-rays with a tube voltage of 80 kVp and a glass filter of a few millimeters thickness only, the minimal required equivalent filtration for typical radiographs grew to the current 2.5 mm aluminum equivalent. This helped reducing the skin dose of patients without jeopardizing the photon flux at the detector. Powerful angiography tubes, like the Philips MRC 200 0508 from 1990, shown in **Figure 36 (**with liquid bearing cooling and a large anode disk of 200 mm diameter) allowed for enhancing the thickness of the X-ray filter further to up to 0.9 mm copper. Still, no wait time for cooling was necessary. The workflow was even improved. The spectrum for this high-dose application became more and more monochromatic. For a comparison of spectra and intensities see [9], Figure 3.5.

4. High vacuum vs. semi-vacuum

In the era of ion tubes, discharge ionization of a well-adjusted amount of residual gas within a sealed glass envelope produced electrons at the cathode by ion impact. The discharge process dependedstrongly on the volatile gas pressure. Tube current and X-ray photon flux varied with the tube voltage in an unfavorable manner. They grew steeply with the high voltage applied. The X-ray intensity varied even more strongly. Instead, one wished to have the inverse correlation to optimally employ the thermal capacity of the focal spot area. Higher tube voltage, which causes a harder photon spectrum with better penetration of the object, would allow for lowering the current.

Already in the year 1882, E. Goldstein had successfully maintained gas discharges for the production of cathode rays (electron beams) at comparatively low gas pressure by heating the cathode, see [23]. But, given the required temperatures of much beyond 1000°C to provide for the full electron current, stable emitter material was missing. Instead, ions served to release the majority of electrons from the cathode to bear the main discharge. As many other scientists and engineers, J. E. Lilienfeld and W. D. Coolidge aimed at “softening” the X-ray tubes independent of the individual vacuum condition. This meant, enabling high tube current at low high voltage, in other words reducing the resistance of the tube. Lilienfeld attached an incandescent lamp to an ion X-ray tube.**Figure 8**depicts one of the many Lilienfeld tubes produced. A comparatively weak thermionic cathode, shown in **Figure 8 (b)**, comprised a heated filament and sent a small electron current through an auxiliary anode ring through a hollow cathode to pre-ionize the residual gas in the tube. This starting process ignited and controlled the main gas discharge between cathode and anode inside the pink colored glass envelope shown at the bottom of **Figure 8 (a)**. The amplified electron impact from the main discharge on the tungsten inlay in copper eventually generated high X-ray flux. For the first time, Lilienfeld decoupled tube voltage (X-ray spectrum) and tube current (X-ray intensity) in abetter way than using the gas regulator.

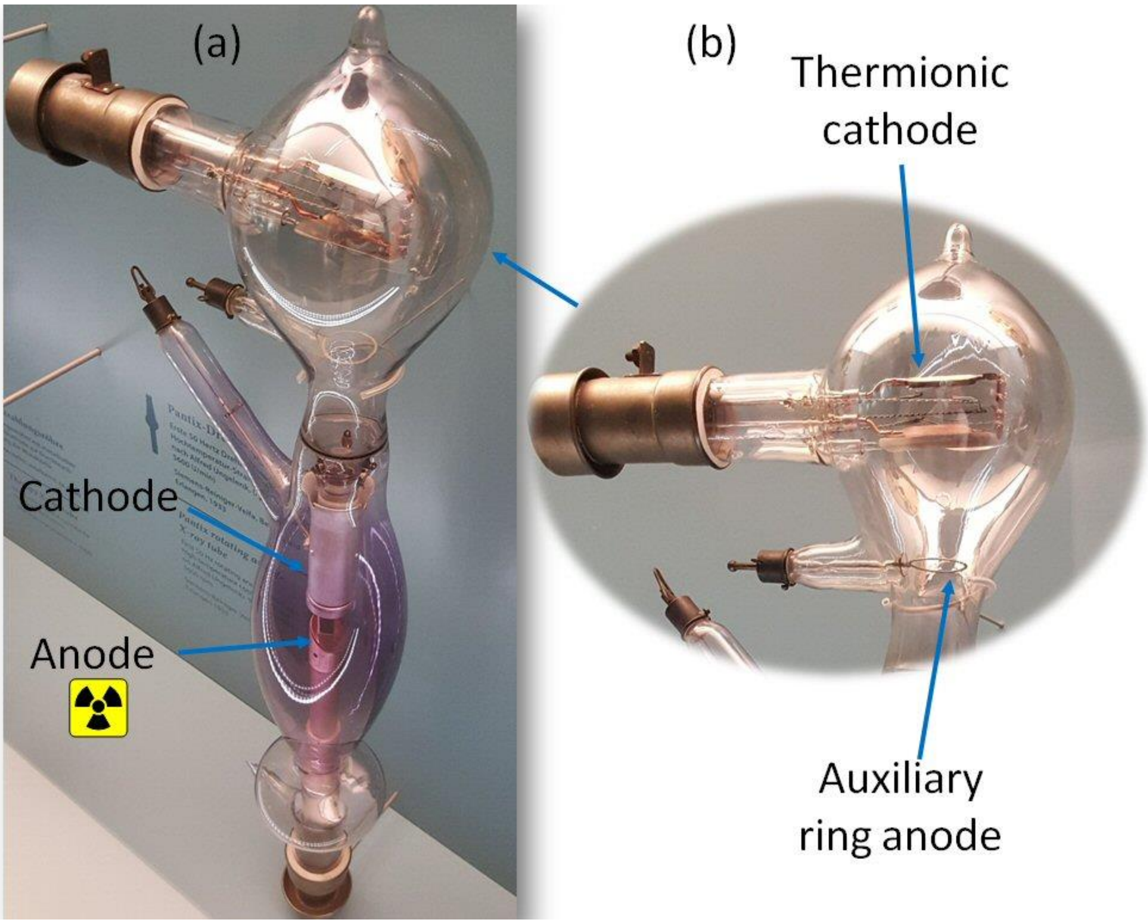

Figure 8 (a) Lilienfeld ion X-ray tube with thermionic electron production to pre-ionize residual gas. (b) Thermionic electron X-ray “softener”, an electron source with auxiliary anode to pre-ionize the residual gas. This model marks the transition between ion tubes and high vacuum tubes. (Photo taken at the German Röntgen Museum, Remscheid-Lennep, Germany.)

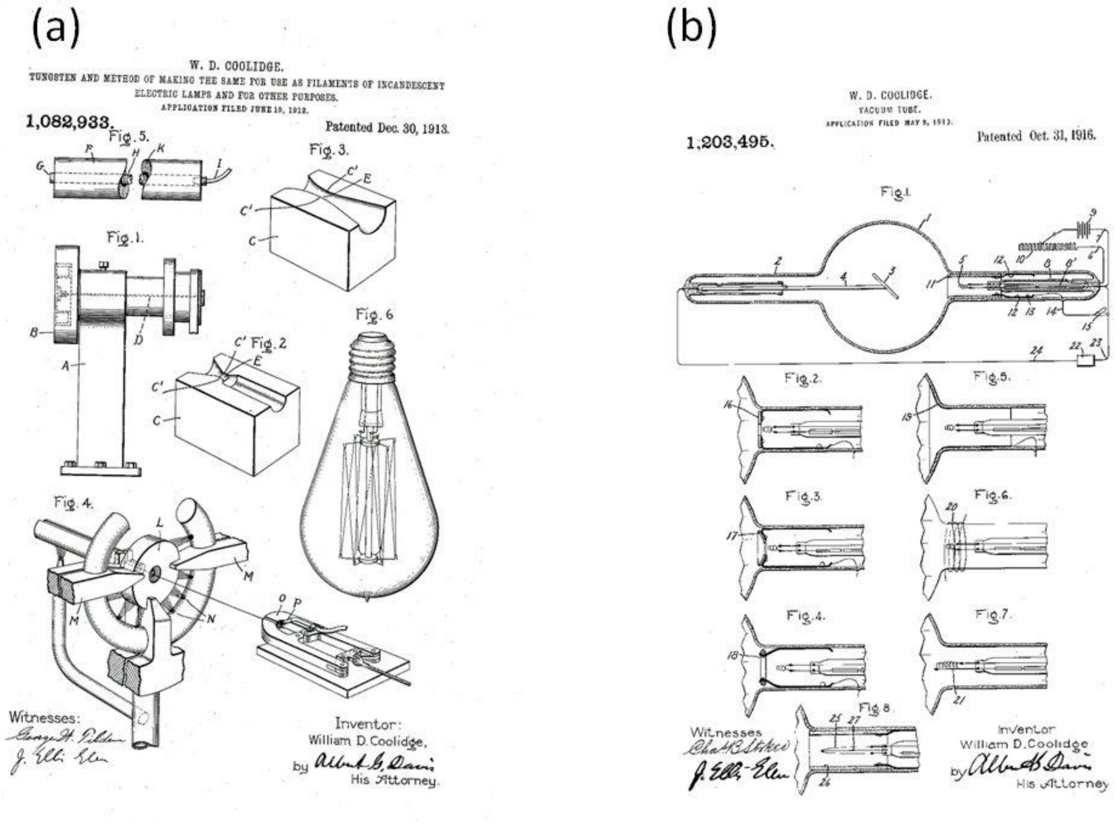

Figure 9 Photo of the illustration page of W.D. Coolidge's patent for the production of ductile tungsten, US1082933, filed in 1912. (Source: https://patentimages.storage.googleapis.com/pages/US1082933-0.png, accessed October 12th, 2017). (b) Photo of the 1913 patent of Coolidge for the hot cathode high vacuum x-ray tube.

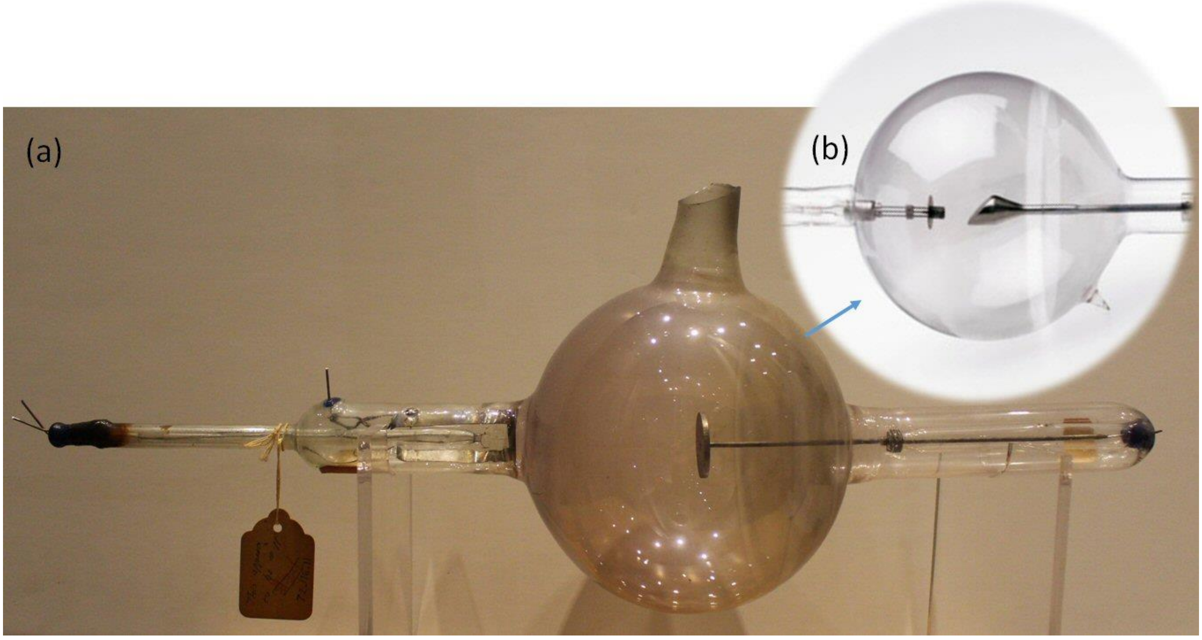

Figure 10 Photo, taken on April 30th, 1913, of one of the original experimental X-ray tubes used by W.D. Coolidge at the GE Research laboratory (Schenectady, NY, USA). It incorporated a tungsten thermionic emitter inside a highly evacuated sealed glass envelope. This concept allowed for very stable operation and repeatable results during imaging. For the first time, X-ray production was easily controllable by setting tube current independently from penetrating power and image contrast, which are a function ofthe tube voltage across the anode-cathode gap. Another "first" for this tube was the use of tungsten as a target material. (b) Close-up photoof a series production unit delivered from 1914. (Pictures courtesy of GE.)

Since 1905 W.D. Coolidge, who had before studied at the same institution as Lilienfeld (the University of Leipzig, Germany) was working at the GE Research Laboratory in Schenectady, NY, USA, primarily on incandescent lamps. Employing his invention of light emitting ductile tungsten wires, see **Figure 9**, he proposed a simplified X-ray tube. Coolidge demonstrated it publicly on December 27, 1913 for the first time in New York City at a dinner party given in his honor by Dr. Lewis Cole, who was the first physician to have his office equipped with the new tube. A ductile heated tungsten wire was capable of emitting the full tube currenteven at low tube voltage, without amplification by a gas discharge. Unlike the previous tubes, this one was highly evacuated. The tungsten wire withstood the high temperatures of about 2000°C, which were required according to Richardson's law of thermionic electron emission, see [9]. Coolidge cooperated with I. Langmuir (Nobel Prize for Chemistry 1932)at GE, who had graduated from the University of Göttingen, Germany in 1906. Coolidge was also able to reduce the distance between anode and cathode to avoid current limitation by electronic space charge, according to the Child-Langmuir law, see [9]. X-ray production became much better controllable, the tubes - more compact. **Figure 10**shows an ancient exhibit in the GE X-ray tube museum in Schenectady, NY, USA.**Figure 11** depicts Langmuirand Coolidge at GE Research in 1923, with the visiting J. J. Thomson.

Figure 11 I. Langmuir (left), W.D. Coolidge (right) from GE Research, Schenectady, NY, USA in 1923 with the visiting J.J. Thomson (middle), who discovered the electron, (Picture courtesy of GE.)

However Ion tubes were still improving.In 1916, the Victor X-ray Company of Chicago, IL (later to be acquired by General Electric, USA), produced ion tubes filled with hydrogen (to reduce the ion sputtering effect from electrodes) aiming to improve durability, to have better high voltage stability and to shrink the parallel spark gap. Reportedly there were instances of cold cathode tubes being employed as late as the 1960's. In the meantime, thermionic cathodes have taken over. Despite of many attempts to lower the emitter temperature by material with lower work function, notably barium and thorium, tungsten has remained the electron emitter material of choice in the chemically and physically harsh environment of an encapsulated X-ray tube. In the meantime, field emission cathodes captured some niche space in diagnostic X-ray tubes. Dedicated control grids in front of the emitters were needed for these field emitting devices to preserve the independency between tube voltage and tube current, the great former achievement of Lilienfeld and Coolidge.

The new technical simplification of the workflow altered the professional landscape. Before, the selection of the right ion tubes and adjustment of the technique factors required high technical skills. Radiographers had to be both physicians and physicists in medicine. The inventions of Lilienfeld and Coolidge marked the separation between radiologists, medical physicists and engineers.

5. Götze's line focus

Given a size of a typical imaging geometry of about a meter distance between X-ray source and detector, the X-ray fan beam is usually in the order of approximately 10° to. 20° wide in axial direction, perpendicular to the target. The surgeon O. Götze concluded from the nearly isotropic polar distribution of X-ray intensity from the anode and from the factthat we use only a small portion of the generated X-rays (max ca. 20° axial), that it would be beneficial to primarily use only a portion of X-rays, namely those which are emitted under a grazing angle. He proposed an axially elongated physical line focal spot, which maintains its (apparent) optical shortness when seen from the patient perspective (effective focal spot). A mapping of a rectangular Götze focus on the damaged target of a rotating anode tube is shown on **Figure 22**. The anode with blocked ("frozen") rotor was destroyed with two shots taken without rotation, which mapped the thermal focal spot by melting the tungsten top layer. Götze's patent from 1918 was first used by C.H.F Müller, later Philips, from 1922 onwards. Compared with a usual elliptical focal spot, the thermal capacity of the anode and the space charge limited electron current grew by nearly an order of magnitude. By May 1915, Elof Benson had filed the application for US patent 1174044, which may be interpreted as an early realization of a line focus. He proposed to direct cathode rays (the electron beam) onto a rectangular array of plane surfaceson the anode target, the cross section of which would resemble a saw-tooth pattern. However this structure was never commercialized.

This line focus concept has become standard. The anode angle is always minimized to maximize the power rating, adapted to the system geometry. Röntgen's first anode was an X-ray transparent sheet of glass with an "anode angle" of about 90°. He took off X-rays normal to the glass wall. As the available sources of X-rays became more powerful, the distance between tube and detector could be enlarged. As mentioned before, the characteristic angles of the X-ray fan beam shrunk to about 20° to 30° in each direction. The anode body produces a shadow in the image. The small fan angle allowed for limiting the fan of used X-ray photons to those, which are emitted very closely to the direction along the cone of the anode at a grazing angle of 10° to 15° of the center beam. It turned out beneficial with respect to image sharpness and power rating to use X-rays close to the shadow which the anode produces. Compared with Röntgen's glass anode, the physical focal spot size and its thermal capacity could be improved by nearly an order of magnitude. This attempt finds its limit in the socalled "heel effect". A few degrees close to the anode shadow,the X-ray intensity drops by intrinsic attenuation in the target. X-rays are generated several micrometers below the surface of the target and have to pass a few tens of micrometers of target material. This process also modifies the spectrum. Therefore, the anode angle has to match with the system geometry.

In 1923, Siemens patented a dual focal spot tube, which allowed optimizing the spatial resolution in the image. With this Biangulix^{TM} tube, the company further introduced an anode target with two radially separated focal spot trackswith different anode angles in a rotating anode tube, see below, which allowed to fine-tune the trade-off between width of the X-ray fan beam, the desired spatial resolution and the power rating. Such a tube is depicted below in **Figure 18**. The image projection (and resolution) changes when a different focal spot is selected. Therefore, most of the modern tubes comprise superimposed focal spots with identical anode angle, typically between 9° and 15°. The small anode angle allows for a greater gain of X-ray flux than employing the relativistic forward enhancement of the X-ray production. Thus, shortly after Röntgen's discovery with a tube similar to the one shown in **Figure 2**, reflection targets have become standard for diagnostic imaging. X-rays are produced at the same side of the anode where the electrons impinge, see e.g. **Figure 4**.

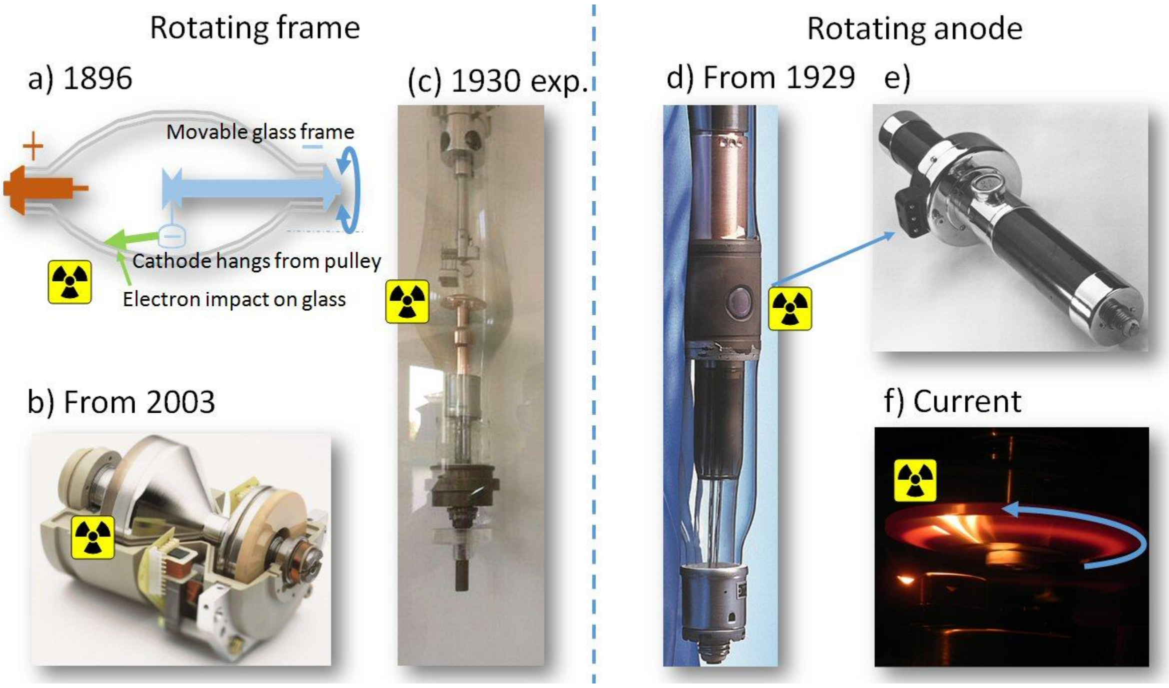

Figure 12 Competing concepts. Left: rotating frame, right rotating anode tubes:

(a) Firstidea of a movable target byR.W. Wood (before Nov. 1st, 1896): The cathode hangs from a pulley while the area of electron impact on the glass frame and may oscillate. (b) Siemens rotating frame tube of the Straton™series for CT with magnetic fixation of the electron beam. (c) Experimental rotating frame tube, with magnetic fixation of the cathode (1930), Phönix AG, Rudolstadt, Germany, and later Siemens. (d) 1st commercialized rotating target tube Rotalix™(1929) from Philips, (e) tube housing assembly for this tube. (f) Close-up view of a current rotating anode glass tube in operation.

(Figure (a) adapted from [22], Fig. 91), (b) courtesy of Siemens, (c) taken in the Siemens X-ray tube museum Rudolstadt, Germany, (d) and (e) courtesy of Philips.)

6. Rotating targets

The concept of the rotating target probably originated with R.W. Wood, see [24]. The point of electron impact determines the origin of X-rays in space. Moving the target with respect to the stationary electron beam, and introducing convection cooling in addition to heat conduction, leads to significant increase of electron beam intensity and reduction of exposure times of stationary anode tube by up to two orders of magnitude. A comparison can be found in [9]. Given the thinking in the year 1896, see **Figure 2**, Wood proposed a rotatable glass frame which acts as the anode, see **Figure 12 (a)**, while the cathode hangs from a pulley. Wood's concept is a precursor of the Siemens' Straton™ rotating frame tube for CT, see [25] and **Figure 12 (b)**. Notably, W. Coolidge from GE filed a patent application in 1915 for US patent 1,215,116, where he suggested rotating the tube frame, while keeping the focal spot stationary in space through deflection of the electron beam. Exactly this principle was realized 90 years later by Siemens for the Straton™, see also[9], paragraph 6.1.4. Siemens and Dunlee, Aurora, IL, USA (later Philips) experimented with other rotating frame tube concepts, using a magnetically fixed cathode. Such an experimental tube is shown in **Figure 12 (c).**

Another suggestion, rotating only the anode in the vacuum space inside the X-ray tube, came reportedly from E. Thompson at GE in 1896. But, it was not realized in practice until 1915 by W. Coolidge, who rotated the anode with a speed of 750 r.p.m. (12.5 Hz) and a focal track radius of 19 mm. The tube was not put on the market, however.

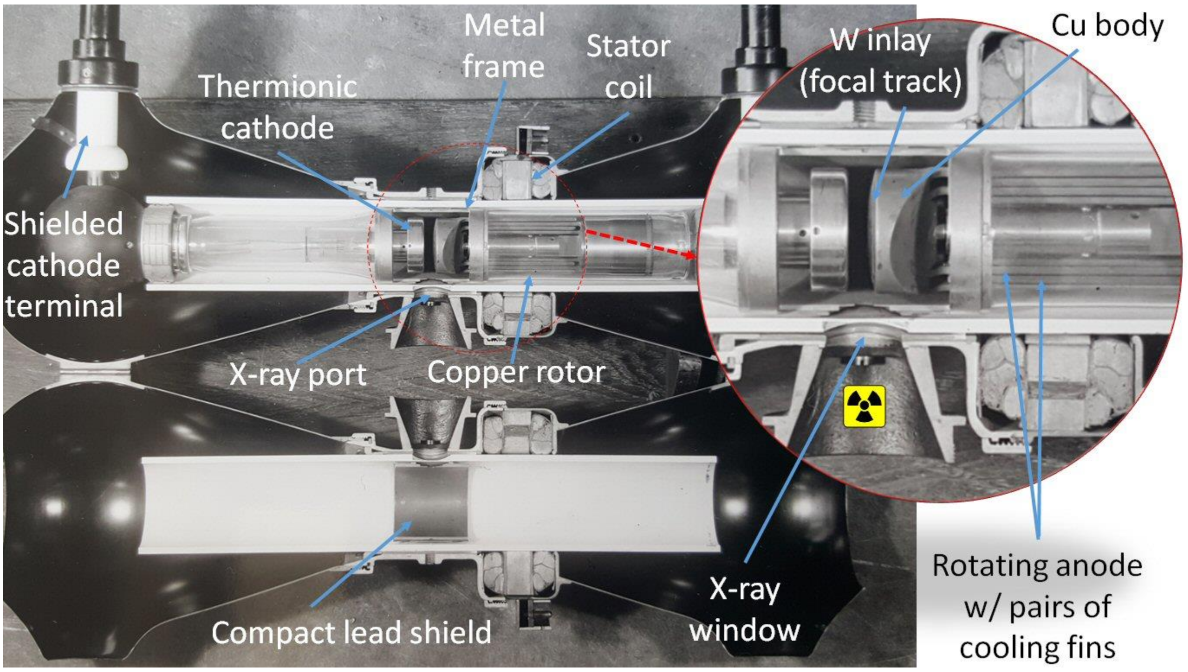

Figure 13 Cut out model of the first industrialized rotating anode tube in **Figure 12** (d). It allowed better heat dissipation at moderate temperatures, which otherwise the copper anode material restricted, A. Bouwers attached cylindrical cooling finsto the rotor, interleaved with stationary fins. Varian (now Varex), Salt Lake City, UT, USA, employed this concept again from the late 1990's for the MCS 7xxx CT tube series. Philips marketed the Rotalix^{TM} tube as "fully" protected against leakage radiation and electrical shock. It was rated with peak power of up to 30 kW ina 2 mm wide focal spot (area 15 mm^2, focal track radius 2.5 cm,20 Hz rotor frequency). Compared with the stationary anode Metalix^{TM}(predecessor tube), the Rotalix^{TM} tube featured a 9-fold improvement of the power rating, see also [9], figure 6.43.

Figure 14 "Fully protected" Philips Media^{TM} tube from the 1920ies. A rotatable sleeve allowed for selecting the X-ray filter thickness. (Photo taken at the Medizinhistorisches Museum Hamburg, Germany, UKE.)

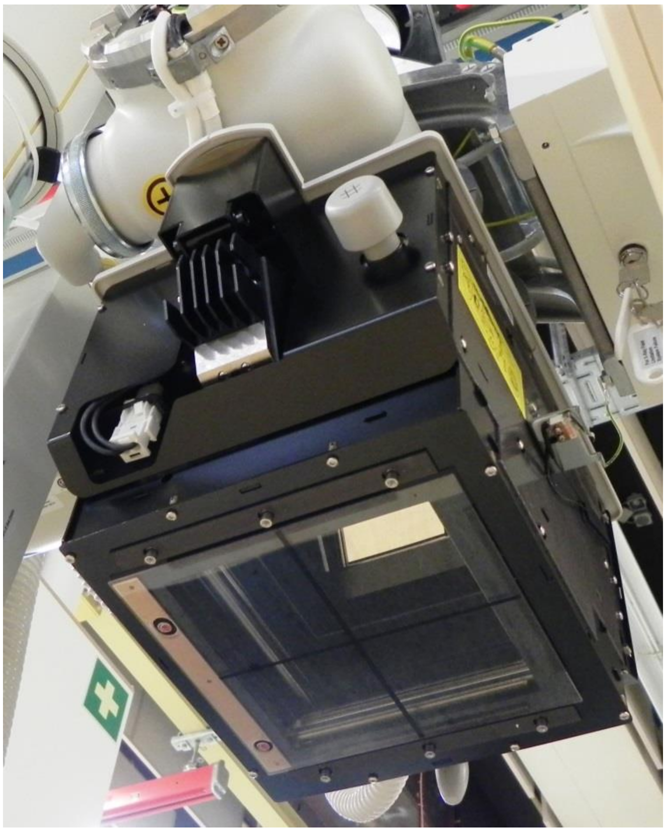

Figure 15 Current beam limiting device from Philips, with beam limiting apertures which allows adding of additional X-ray filtration. The cover was removed.

E. Pohl publicly demonstrated a rotating anode tube in Stockholm, Sweden in 1928. After this A. Bouwers of the newly established Philips National Laboratory in Eindhoven, The Netherlands, commercialized it with Philips under the commercial name Rotalix™ in 1929. This was the starting point of commercial availability of rotating targets. Bouwers introduced a rotating copper anode with tungsten inlay, see **Figure 12 (d)**, **(e)**, and **Figure 13**. However uncoated ball bearings in vacuum are subject of cold welding of steel with steel. After a few rotations, the rotors were blocked(“frozen”). Bouwers solved this problem by using highly refined grease for lubrication. In these tunesa “squirrel-cage” motor transferred mechanical torque inside the vacuum, see [26]. As a downside of this concept, ball bearings practically interrupt the heat conduction from the anode to ambient. Moreover, the copper stem of the anode limited the allowable temperature to about 400°C. The low temperature hampered heat dissipation by thermal radiation. From a heuristic perspective, Bouwer’s anode was a stationary anode on ball bearings. To improve this he introduced a finned anode structure, with interleaved stationary and rotating fins to maximize the heat radiating surface area. This idea was re-used in the 1980’s by Varian (now Varex, Salt Lake City, UT, USA) for their high-end CT tubes with graphite-backed grooved anodes, see [9]. Four years after Philips , Siemens also launched rotating anodes by taking a slightly different pathsee [21]. Instead of a bulky large area radiator at moderate temperature, A. Ungelenk from Siemens in Rudolstadt, Germany, tried rotating high temperature tungsten disks to exploit the special characteristics of the Stephan-Boltzmann law, which states that the rate of heat dissipation is proportional to about T_{anode}^4 - $T_{ambient}^4$, T_{anode}

being the anode surface temperature and $T_{ambient}$the temperature of the environment. The first attempt with a rotating tungsten foil failed, see **Figure 16**. Instead, from 1933 on, the Siemens Pantix^{TM} tube shown in **Figure 17**was delivered with a thicker and more stable all-tungsten anode. GE introduced a similar tube RT 1-2 in 1936, when Coolidge served as the director of the Research Laboratory.

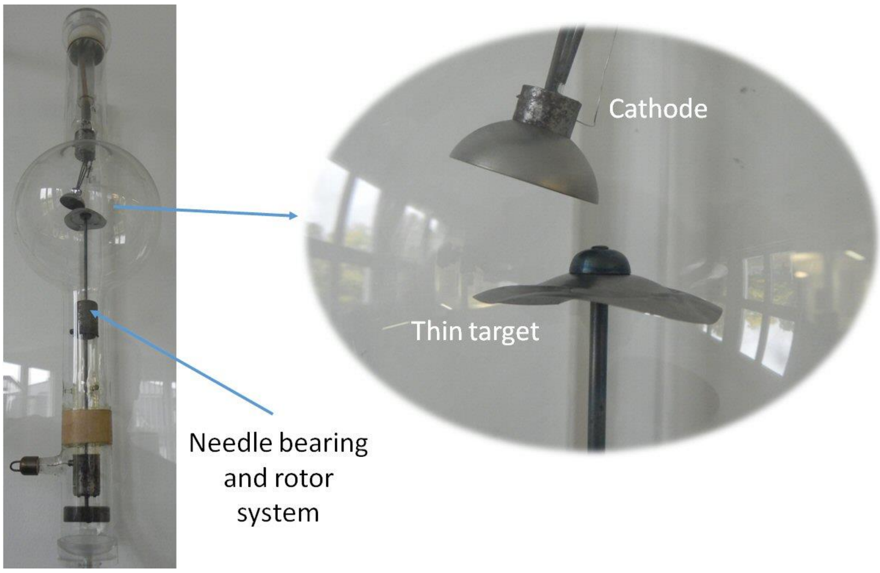

Figure 16 Experimental rotating target tube from 1927 by PhönixRöntgenröhrenfabriken AG, Rudolstadt, Germany, later Siemens. (Picture taken in the Siemens X-ray tube museum Rudolstadt, Germany.)

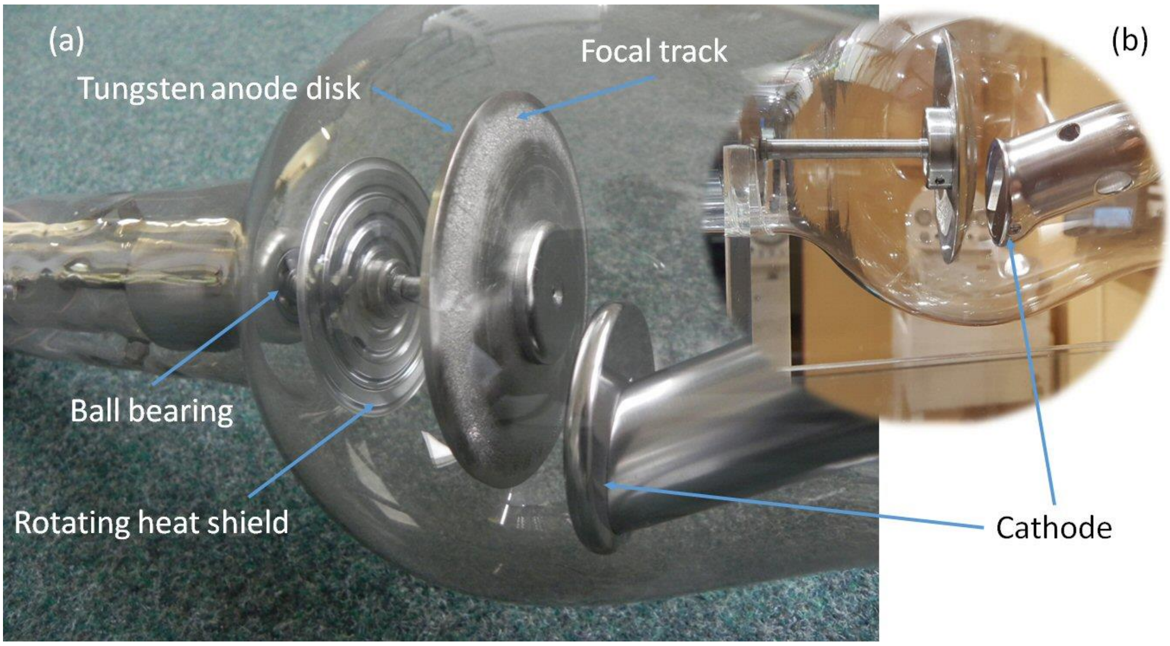

Figure 17 (a) Rotating anode system of a Siemens Pantix^{TM}tube, equipped with an all-tungsten high temperature anode disk and produced from 1933 by Siemens-Reiniger-Werke AG, Rudolstadt, Germany. While the Rotalix^{TM} tube primarily stored enthalpy at moderate temperatures in the finned copper / tungsten anode and radiated heatfrom a large surface area, the Pantix^{TM} design aimed at employing the Stephan-Boltzmann (“T^4”)law to achieve high heat radiation from a hot disk. (b) Earlier version without a heat shield at the rotating anode. (Picture (a) taken in the Siemens X-ray tube museum Rudolstadt, Germany, (b) taken at the Medizinhistorisches Museum Hamburg, UKE, Germany.)

Figure 18 Siemens Biangulix^{TM} tube. Its anode has two separated focal spot tracks with different anode angles. (Picture taken at the Medizinhistorisches Museum Hamburg, Germany,UKE.)

The benefit of this high temperature concept is high heat dissipation when the anode is at its thermal limit, see **Figure 19** of a Philips tube. Philips used the high temperature concept with the Super Rotalix Ceramics^{TM} tube series, see below in**Figure 51**, delivered from 1980 onwards primarily for angiography and cardiology work, and avoided graphite backing of the all-metal anode, as shown with the Siemens Opti 150 tube in **Figure 20**. But, given the melting point of tungsten, the allowable temperature difference between focal spot and bulk anode of Ungelenk's high temperature tube is lower than with Bouwer's. This reduces the permitted thermal pulse power for comparable focal track speed and focal spot size. To diminish this effect, Siemens enhanced the rotor speed to more than 90 Hz in 1934. 150 or 180 Hz rotor frequency have become standard in the industry since the late 1950's. **Figure 21** depictsa typical current X-ray tube assembly and describes its major components. In 1982 Siemens delivered the Opti 110/12/50 tube with even 280 Hz rotor frequency, used for magnification imaging. However, this high speed is a challenge for ball bearing systems.**Figure 22**illustrates the effect of a bearing failure.

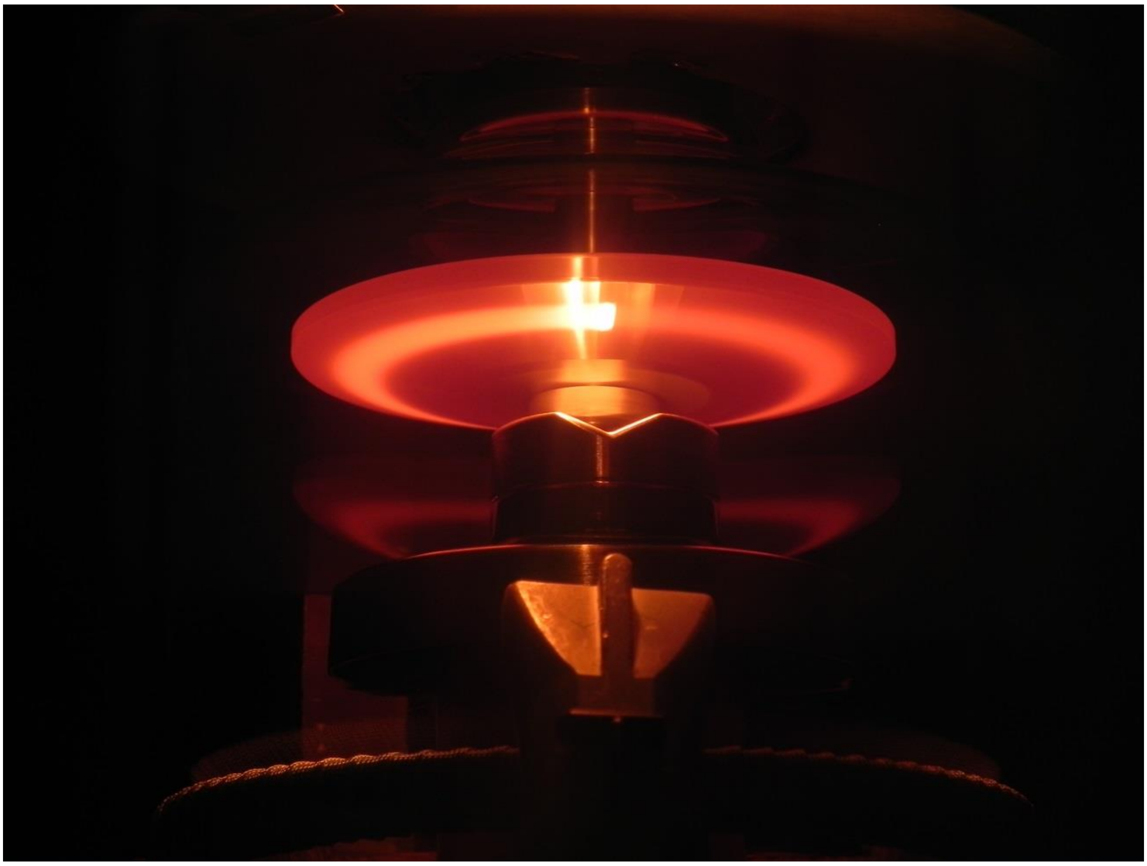

Figure 19 Thermal picture of a rotating anode tube during the exhaust process. The rectangular thermal focal spot and the hot trail of the focal track are visible on top of the light from the filament of the cathode at the bottom, reflected from the anode.

Figure 20 Brazed graphite-backed RW/TZM compound anode in a Siemens Opti 150 30 50 radiographic tube.

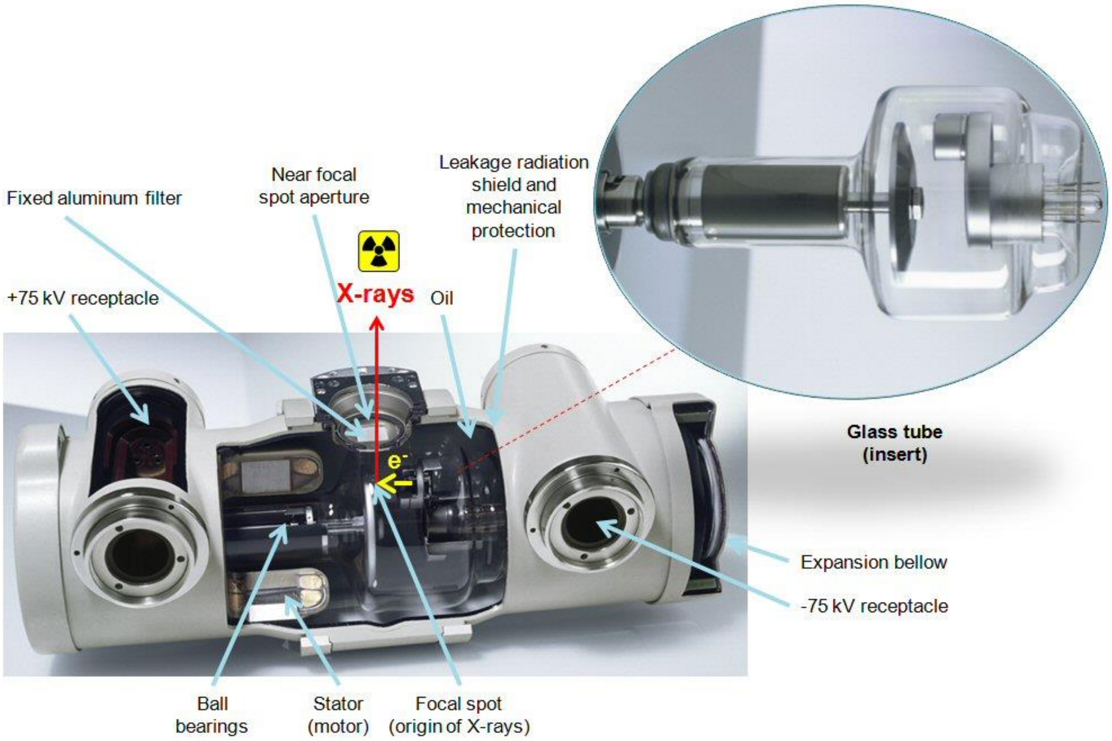

Figure 21 Function and major components of a conventional radiographic X-ray tube assembly from Philips, which has been in production in similar form since the 1950's.

Figure 22 Eroded focal track of a rotating anode. Malfunction of the rotor during two subsequent trials to rotate caused two marks of molten target material (the marks map the shape of the rectangular electronic focal spot).

7. Stationary anode tubes

Since the late 1920’s, the concept of rotating anodes, either spinning in vacuum or as part of the tube frame, has become the basis for all modern high performance X-ray tubes. The stationary focal spot remained the thermal weak point, mainly due to the limited heat conduction and heat capacity of tungsten. The industry devised sophisticated cooling mechanisms for the back of the target, like tungsten-in-copper brazed structures and water coolers. In any case, an about one millimeter thick layer of tungsten remained necessary as the first heat spreader. Some attempts were made to cool the tungsten slab directly, but without using hazardous overpressure, steam quenched the dissipation of heat from this hot interface. The gain of performance of stationary anode tubes leveled off over time. However, stationary anode tubes are still important elements of the tube portfolio for surgery C-arm and dental application, where either low and steady photon flux is required, or the system geometry is short enough. **Figure 23**shows the Siemens ERG 80 ö stationary anode tube from 1942, which has the benefit of large long-term heat dissipation through cooling fins. **Figure 24**is a picture of the Philips tube FO 17 with superimposed dual focal spots for surgery C-arm systems and employs a scattered electron trap.**Figure 46** demonstrates a small dental tube for 50 kV tube voltage without such a trap. With such a small tube voltage and current, backscattered electrons may impinge on the glass wall without causing major discharge problems.

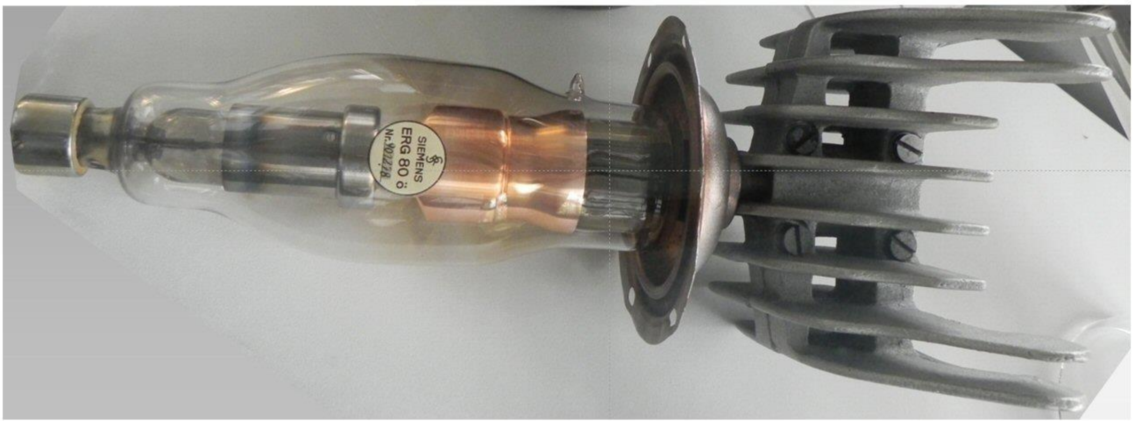

Figure 23 Siemens stationary anode tube ERG 80 ö with cooling fins from 1942. (Photo taken in the Siemens X-ray tube museum Rudolstadt, Germany.)

Figure 24 Close-up photo of the Philips superimposed dual focal spot stationary anode tube FO 17 for surgical C-arm systems.

8. Components development

8.1. Anodes

All-tungsten rotating anodes, first introduced with Siemens' Pantix tube in 1934, lack ductility of the material and are prone to rupture when cold. The high specific mass makes them heavy and brings a large momentum of inertia, a disadvantage when the tube rotor has to start before an exposure. On the other hand, such anodes can be heated to extremely high temperatures beyond 2000°C, and radiate heat well, but require pre-heating to prevent rupture from thermo-mechanical stress. The introduction of specifically lighter molybdenum backed rhenium-tungsten compound anodes in the 1960's was therefore a big step forward. A one millimeter thick top layer of rhenium-tungsten (RT) alloy, backed by an up to several millimeter thick powder sintered titanium-zirconium-molybdenum (TZM) body, has become common and is still the basis technology for most rotating

Anode tubes. Modern tubes often employ segmented rotating anodes to minimize residual strain, see **Figure 38**.

Figure 25 GE-CGR vascular tube with graphite target, coated with tungsten and rhenium.(Photo courtesy of GE.)

From the 1960's, Thomson-CGR, France, later GE, produced a vascular tube with a light weight target, depicted in **Figure 25**. This type of tube was the first in the market to incorporate a rotating anode whose target structure was made principally of graphite. This weight reduction was key to prolonging the life of the ball bearings in vacuum. The great thermal emissivity of graphite is also a beneficial. This first type of graphite anode comprised a coating of tungsten directly onto a graphite substrate using an electrochemical salt-bath process, with a thin rhenium layer interposed. Later designs were produced through chemical vapor deposition of tungsten from tungsten and rhenium hexafluoride gas.

Philips took a side path and used their high pressure forging facility in Eindhoven, The Netherlands, to produce heavily forged Trinodex™ material, see **Figure 26**. Its benefits are extreme mechanical strength, very low porosity in the top layer and, thus, excellent durability.

For heavy-duty application in angiography, Siemens first and later other vendors introduced graphite-backed RT-TZM, material as depicted in**Figure 20**. Metal center section tubes enabled trapping of backscattered electrons on a stationary structure, primarily close to the X-ray port, see below, **Figures 43**, **Figure 44**. Liquid bearing technology, which emerged in 1990, helped as well to efficiently dissipate heat instead of storing it in the anode.

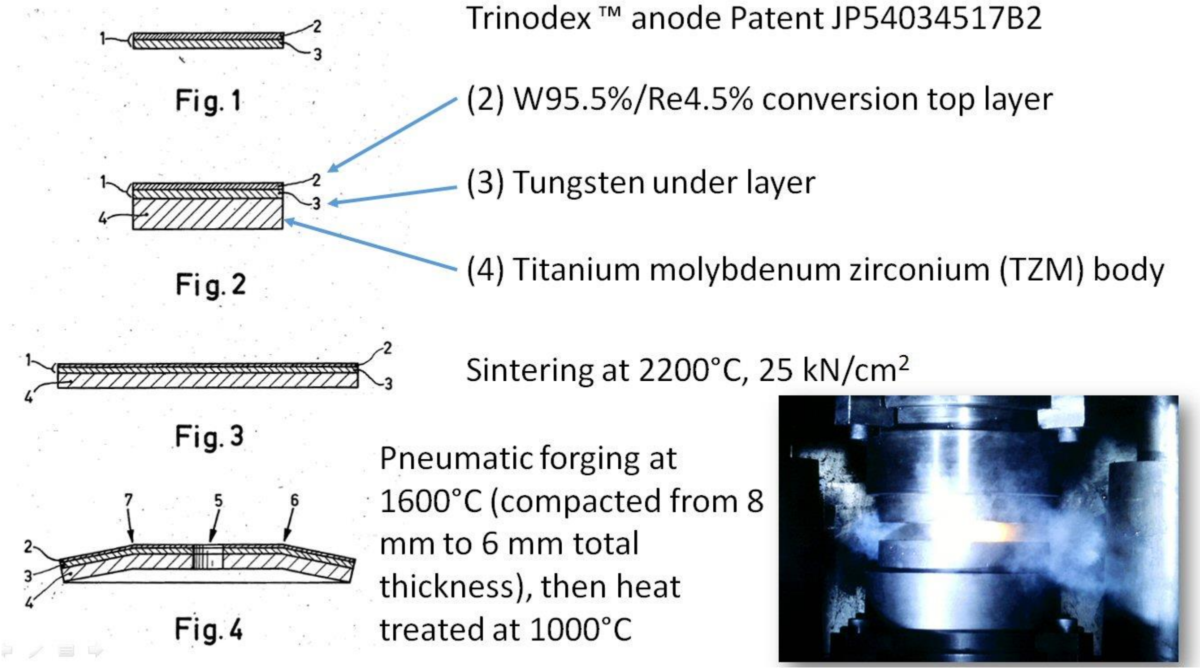

Figure 26 Philips Trinodex™ anode, in production from 1973, hot forged from three metal slabs.

8.2. Cathodes and electron focusing

Improvements of the anode demanded improvements of the cathode. Producers like C.H.F Müller in Hamburg, Germany, improved the spatial image resolution already in the first year after Röntgen’s discovery by introducing the so-called “Focus-Tube”, similar to the one depicted in **Figure 5**. The metallic cathode plate, which spills out electrons upon ion impact, was given a concave form, such that the negative charge carriers, starting normal to the surface, were focused into a millimeter-sized spot on the anode. The Victor X-ray Company of Chicago, Il (later to be acquired by General Electric to become GEXCO, the forerunner of today’s GE Healthcare) used hydrogen as the gaseous species inside the tube to reduce sputtering effects, and applied a ring-shaped pull electrode in connection with the anode, which enhanced the electron current, see **Figure 27**.

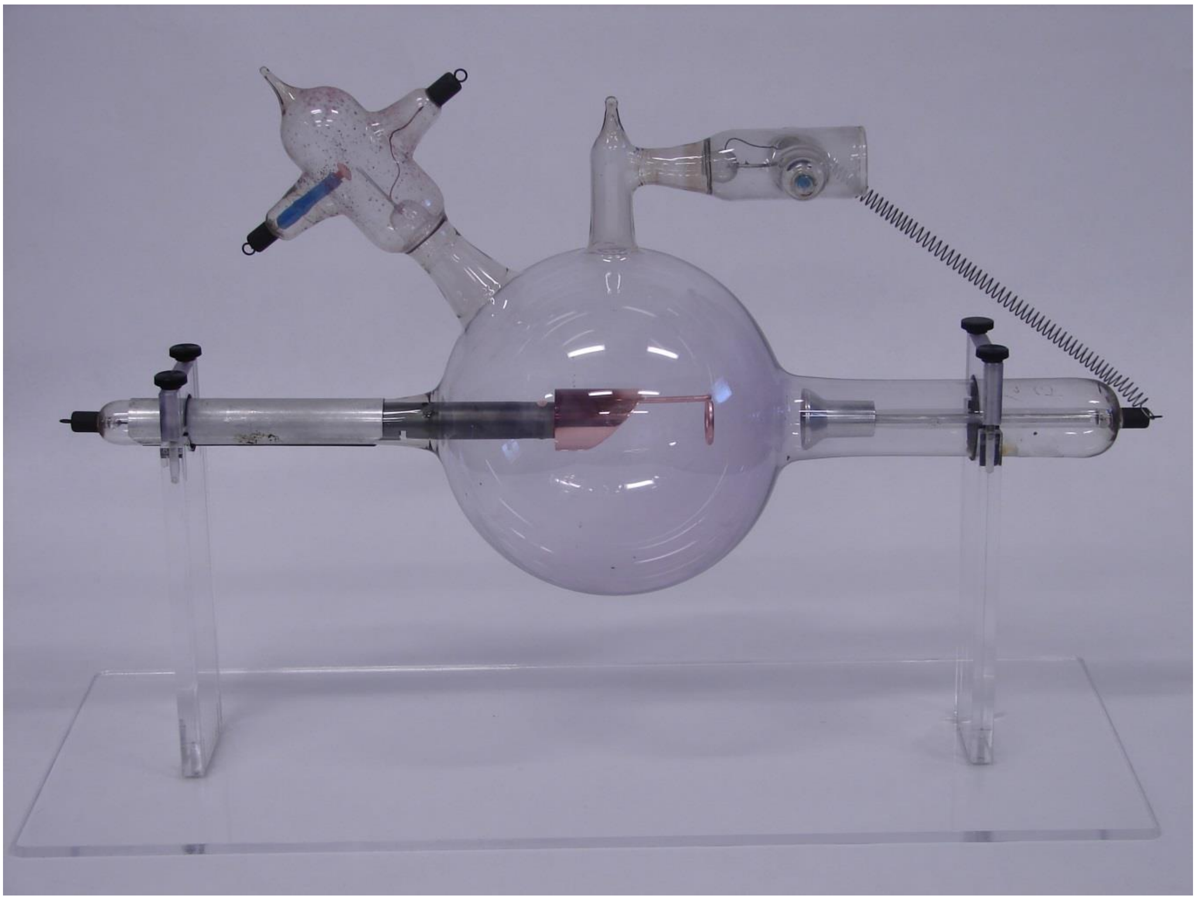

Figure 27 Hydrogen ion X-ray tube with field enhancing pull ring on anode potential, introduced in 1916 by the Victor X-Ray Company of Chicago, IL, later to be acquired by General Electric to become GEXCO, the forerunner of today’s GE Healthcare. (Photo courtesy of GE.)

Figure 28 Photo of an original laboratory Coolidge tube, taken on April 30 1913, showing a Wehnelt type focusing ring about the thermionic tungsten emitter. (Photo courtesy of GE.)

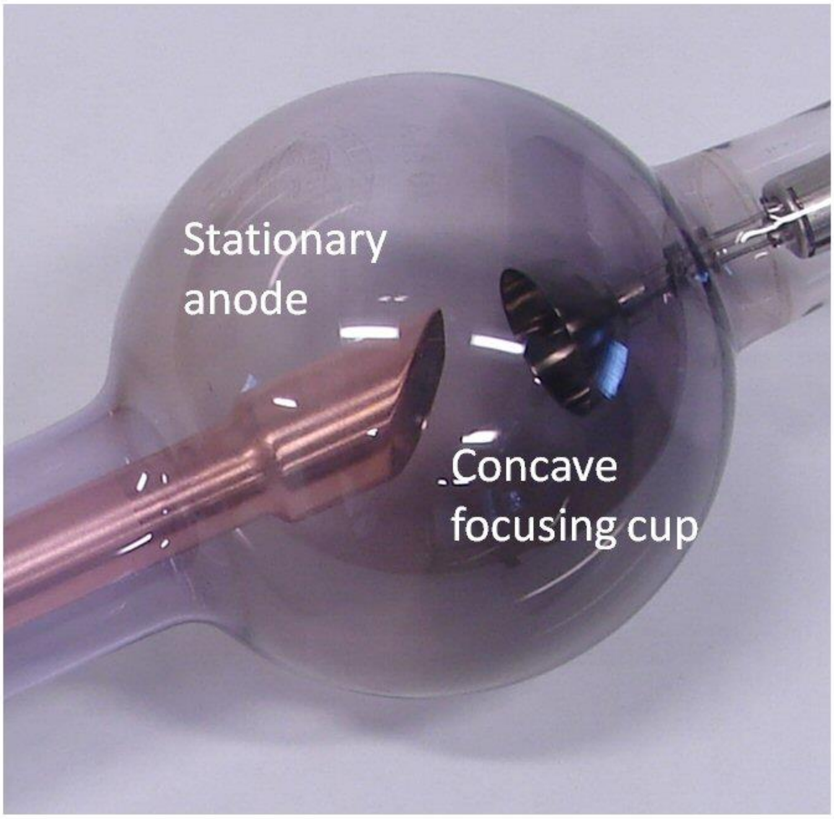

Figure 29 Bell-shaped focusing elements of a stationary anode of a Coolidge tube. (Photo courtesy of GE).

Figure 30 Focusing elements of a stationary anode tube with line focus from C.H.F. Müller, Hamburg, Germany, later Philips. The line focus is mapped in the melting structure on the anode.

After introducing thermionic electron emission, W. Coolidge first encapsulated the tungsten thermionic emitter coil by a small metallic cylinder, as can be seen in **Figure 9** (b). He also experimented with a focusing ring, as depicted in **Figure 28**. In later versions a bell-shaped cathode focused the electrons, see **Figure 29**. Siemens used such a form as well for their first laboratory model of a rotating anode tube, as depicted above in **Figure 16**.

The introduction of line focal spots led to a rectangular shape of the focusing cup, as demonstrated for a tube from C.H.F. Müller (later Philips) in **Figure 30**. The rectangular focal spot can clearly be identified by the erosion pattern on the stationary anode. The classic form emerged by the introduction of larger focusing electrodes to improve the definition of the focal spot even when changing the tube current and tube voltage. Space charge effects, and focal spot “blooming” became apparent, when the anodes allowed for higher tube currents. **Figure 31** shows a tube from the Philips production plant in Eindhoven, The Netherlands, which served to supply the Dutch market during World-War II and shortly after. The cathode head was integrated in a large cathode plate,which shielded the glass insulator from bombardment by backscattered electrons.

Figure 31 Hidden cathode in a Philips tube from the production plant in Eindhoven, The Netherlands. (Picture taken at the Medizinhistorisches Museum Hamburg, Germany,UKE.)

Figure 32 Close-up view of the thermionic cathode for superimposed focal spots of a Philips SRO^{TM} 33 100 tube.

Figure 32 depicts a typical modern dual focal spot cathode for an 80 kW rotating anode tube for radiography. Coiled tungsten wires of 250 µm diameter are mounted into a cathode head which shapes the electric field in such a way that electrons are focused into the focal spot on the anode. The back of its edge can be seen blurred in the front of the picture. On the other hand, space charge effects are electron optically taken into account during design in a such way that the focal spot dimension would not substantially change with tube current and tube voltage. **Figure 52** illustrates the electric field distribution for a single emitter tube, which leads to a well focused electron beam. Other than with magnetic focusing, electrostatic focusing largely benefits from invariance of the electron trajectories from tube voltage, when the tube current is small and space charge can be ignored. But, due to the relatively high tube current density, space charge effects cannot totally be avoided. In 1998 Siemens introduced a flat tungsten sheet emitter for the Pantix P40 tube for mammography, in 2003 for the Straton™ CT tube, see [25] and [9], and in the Gigalix™ tube series in 2013, see **Figure 54**. Flat emitters improve the starting conditions of electrons, and enable enhancing the electric field, which helps reducing space charge limitations of the emission current. Philips introduced this technology for the iMRC™ CT tube in 2007.

Figure 33 Ball bearing system for Philips SRO™ tube series tube with 90 mm target diameter.

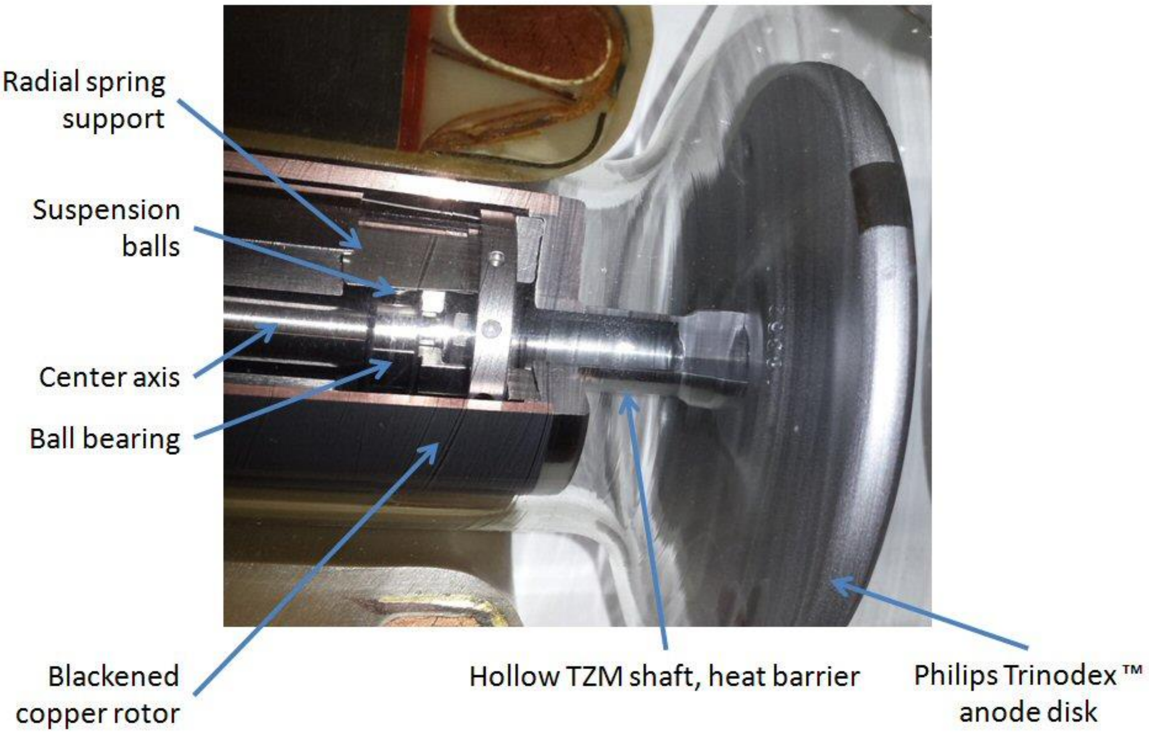

Figure 34 Low noise radial spring supported ball bearing system in a Philips glass tube.

8.3. Bearings and rotor systems

Ball bearing tubes have seen major improvements as well. **Figure 33**shows a ball bearing system for a standard radiographic X-ray tube like the Philips SRO 33100. Since the 1940's, Philips has coated balls and raceways with lead, from 1980 on with silverfor selected tube types. Initially until the middle of the 1990's, lead was rolled-in using a suspension of lead particulates in Vaseline^{TM}. Silver was coated galvanic since 1980 for the Super Rotalix Ceramic^{TM} tube, SRC 120, see **Figure 51**. In the 1990's Varian, Salt lake City, USA (now Varex), introduced ion coating, which has become the current standard coating technology.

Philips tackled rotor noise and vibration by implementing a radial spring suspension of one of the individual bearings, which enables the anode rotor to spin nearly force-free about its intrinsic axial axis of inertia, see **Figure 34**. The same principle applied to the straddle-type bearing of the SRC tube shown in **Figure 51**. The center of gravity was suspended between two bearings to even-out the radial load. This concept was later adapted by Siemens for the Akron^{TM} tube series from Siemens in the 1990's, by GE for the Performix CT tube series and by Varian, now Varex, for the MCS 70xx CT tube series.

Still, the rotor life of ball bearing tubes is limited to several hundred hours rotation time. It is therefore essential to stop the rotation after each exposure. **Figure 22** shows the focal spot track of a rotating anode with its typical erosion pattern from thermal cycling. Two melting marks indicate that the tube was damaged by a failure of the rotation system. As an alternative, major vendors, Philips, Siemens and GE tried magnetic bearings. But, controlof the magnetic suspension, and current transfer turned out to be difficult.

Another challenge of all ball and magnetic bearing based concepts is the residual enthalpy, which remains in the anode when the temperature drops and the visible glow of the anode ceases after a patient has been X-rayed, see **Figure 19**. In 1989 Philips returned to the roots of Bouwers and introduced a gallium-indium-tin lubricated spiral groove bearing to keep the rotor cool. This heat conducting liquid metal lubricant allows combining the benefits of great heat conduction of stationary anodes and its flat characteristics of heat dissipation, which is proportional to the temperature difference with ambient, and heat radiation. The invention of the liquid metal bearing for X-ray tubes dates back to the 1970’s in the Philips Research laboratory in Eindhoven, The Netherlands. Its market introduction in the Maximus Rotalix Ceramic™ tube (MRC) in 1989 was a quantum leap, see [27]. **Figure 35** shows the assembly process of its bearing system. Cardiology and angiography application benefitted first, before the platform concept has also been introduced for CT. Wait times for the rotor to speed up could be skipped, as the liquid bearing has virtually infinite life time. It may spin all day. Its great heat conduction has accelerated the clinical workflow. Large anodes with high momentum of inertia can be used. The tube runs without any audible noise. **Figure 36**shows a cut-out picture of the first product. In 1987, the author was project manager and R&D manager of Philips’ “Röntgenmüller” laboratory in Hamburg, Germany, and the team was frustrated. During tests of the first prototype tube, two years before planned market introduction, the device did not show any sign of generating X-rays at all. The nested liquid bearing was soaked with gas. High voltage could not even be switched on. Eventually, those problems were solved. The MRC™ platform has featured unprecedented durability and continues to be the basis of new developments. Toshiba, Siemens, and GE followed.

Figure 35 Final assembly of a liquid metal bearing system for the Philips MRC™ 200 angiography tube series.

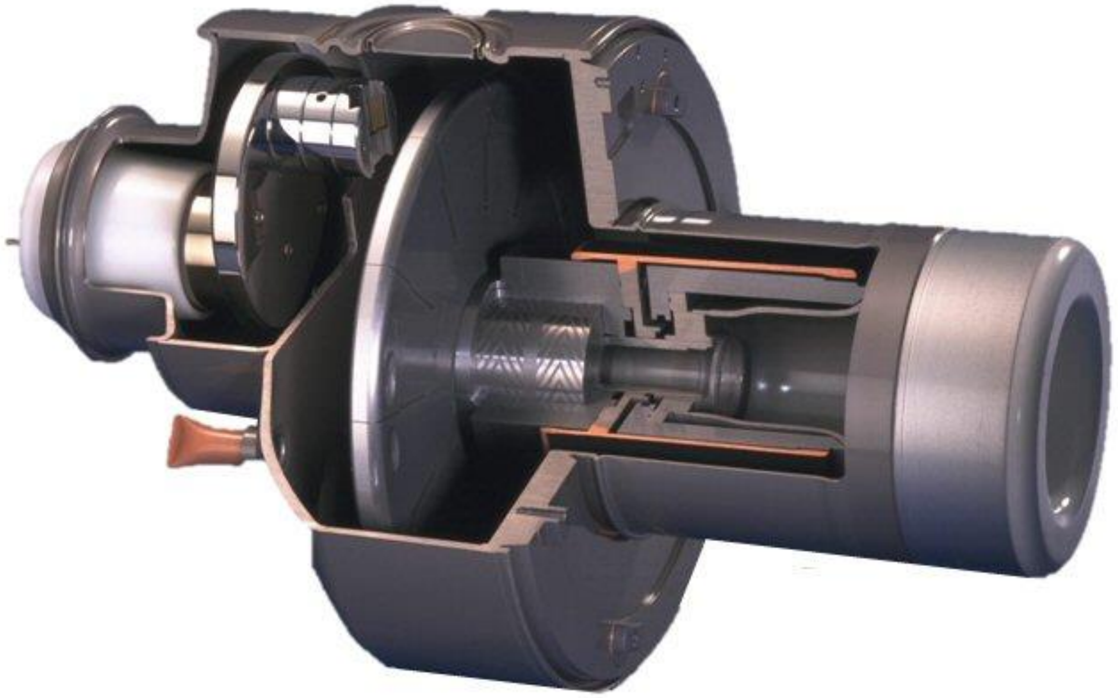

Figure 36 First rotating anode tube with liquid bearing and 200 mm anode disk, Philips MRC^{TM} 200 series for cardiology and angiography.

8.4. Tube frame

i. Glass

Glass envelopes have remained standard technology for low and medium performance diagnostic tubes. **Figure 37** illustratesthe blowing of a glass frame and the tempering process. **Figure 38**is a close-up picture of the X-ray window portion of a conventional glass tube for radiography and fluoroscopy. The near focal spot apertureis visible, which limits off focal radiation and the built-in X-ray filter. Issues with glass insulation arise from the ill-controlled charging by electron and ion impact and coating by metal from the thermionic cathode or from the anode. **Figure 39** illustrates the blue glow of the glass wall caused by electron and ion impact. Some vendors introduced roughened (“frosted”) glass to improve this. **Figure 40** shows a CTtube from Dunlee, Aurora IL, USA, a Philips subsidiary. A special assembly for surgery C-arm systems manufactured by Varian (now Varex), which comprises a glass tube, is shown in **Figure 41**.

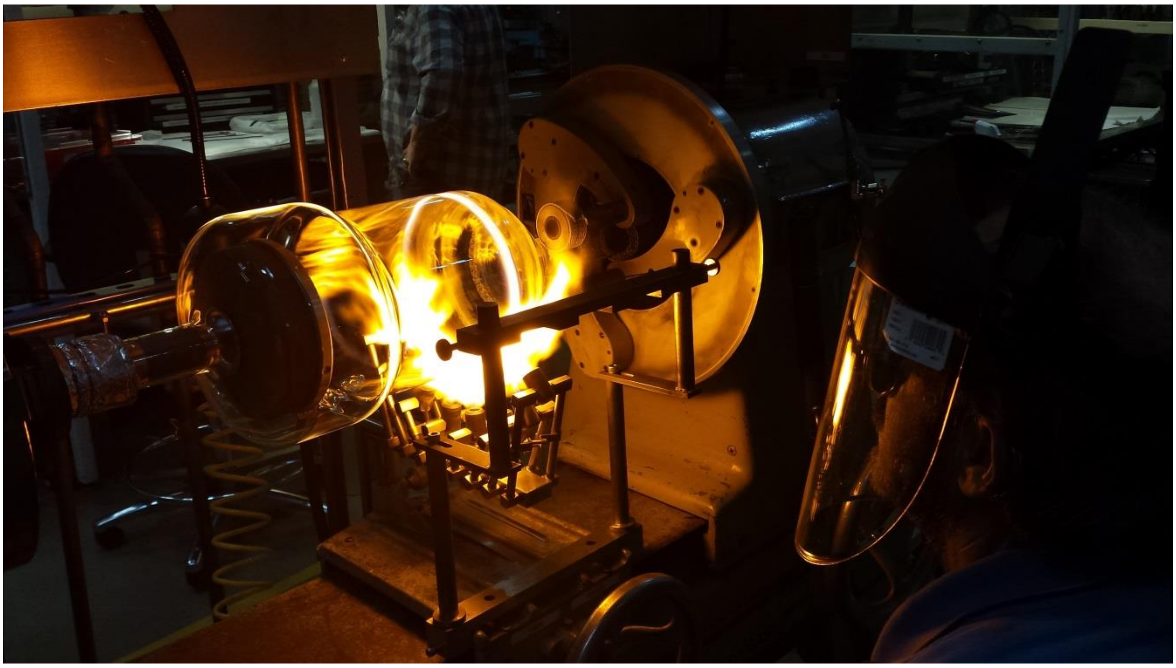

Figure 37 Glass blower at Dunlee, Aurora IL, a Philips company.

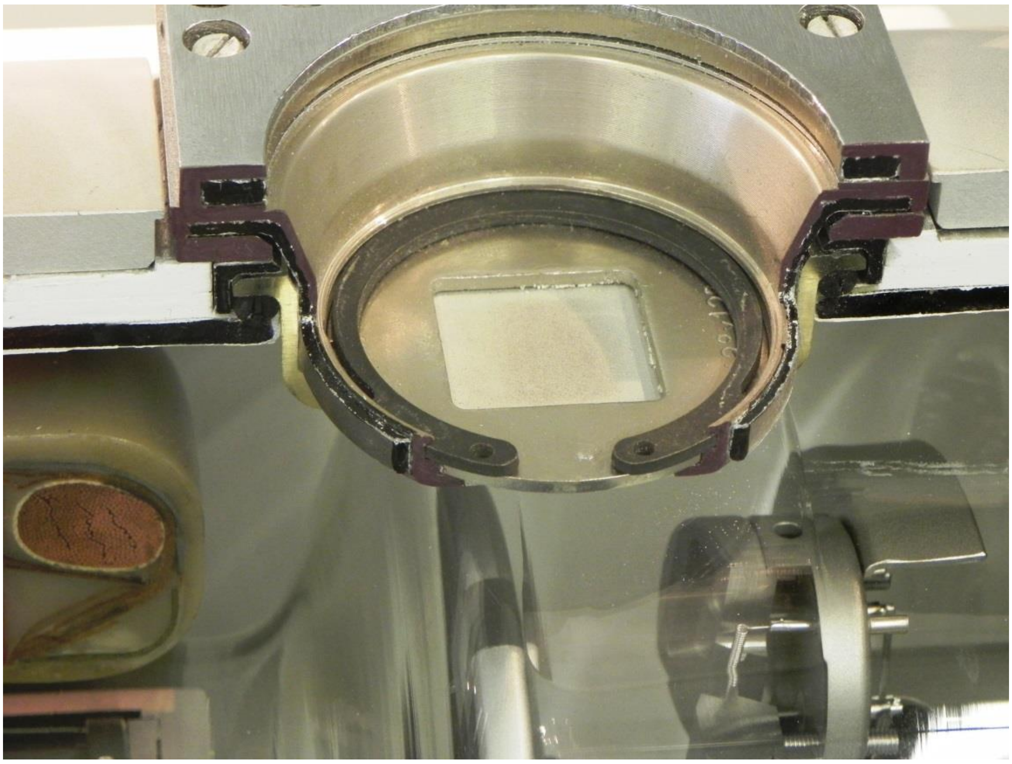

Figure 38 Close-up view of the radiation port of a Philips tube housing assembly for radiography and angiography with exchangeable near focal spot apertureagainst off-focal radiation and intrinsic radiation filter.

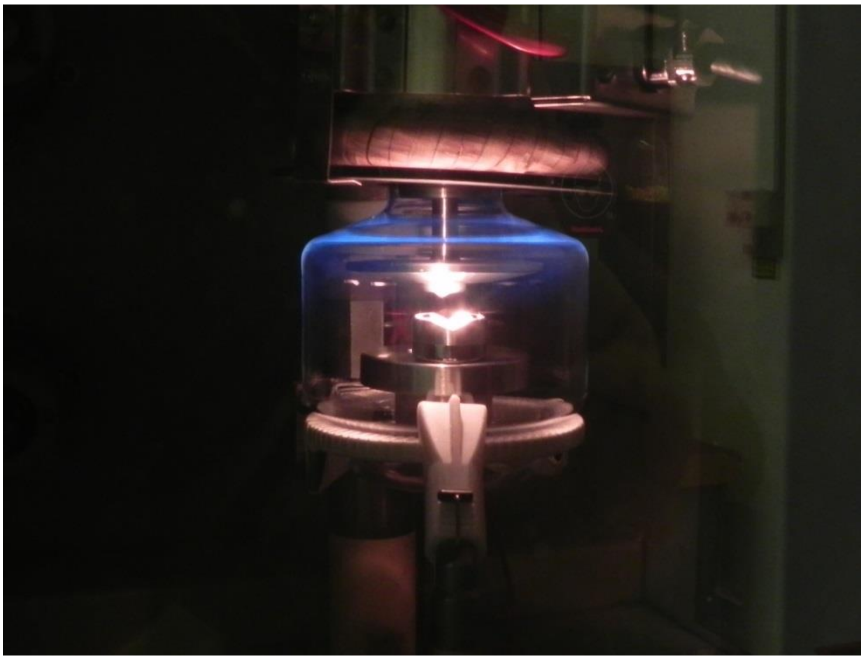

Figure 39 Photo of a glass tube during the exhaust process with electron bombardment of the anode. The blue glow at the inner glass wall (top, about the cathode region) signalscontinued impact of backscattered electrons and ionson the glass.

Figure 40 Frosted glass wall of a tube from Dunlee, Aurora, IL, USA, subsidiary of Philips, to improve the electrical stability under bombardment by backscattered electrons.

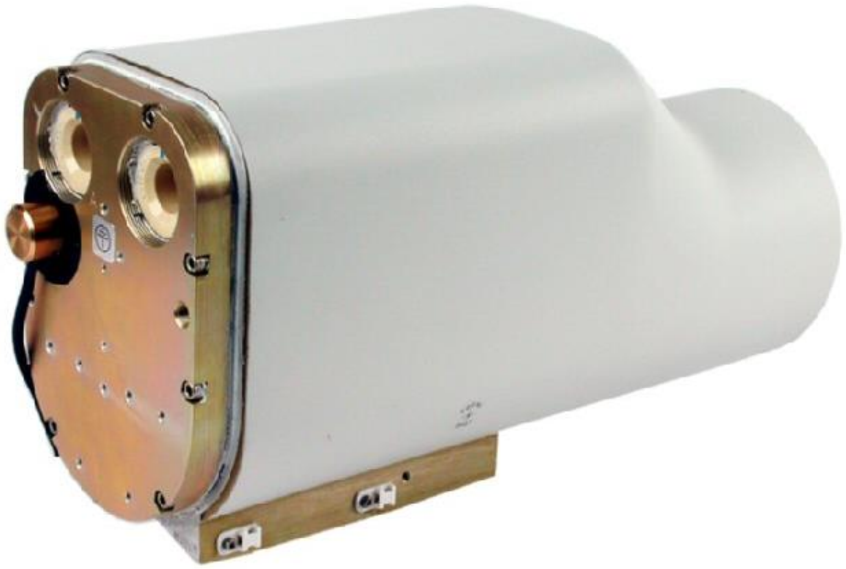

Figure 41 Varex tube OR-III tube assembly with RAD-99 glass insert for surgical C-arm systems. (Picture courtesy of Varex.)

ii. Metal center section

Bouwers from Philips had already implemented a metal center section in a stationary anode tube Metalix™ in the 1920’s, and re-used this X-ray shielding and protection technology for the first rotating anode tube Rotalix™ in 1929, see **Figure 12 (d)** and **Figure 12 (e)** above.**Figure 42**shows a GE tube MX-125 for angiography from 1972; and **Figure 43** depicts the details of glass-metal joints and the beryllium X-ray window of the Philips Super Rotalix Metal$^{\text{TM}}$ tube series, launched in the late 1970’s. As the metal center section of a bi-polar tube is subject to bombardment of scattered electrons from the focal spot, special attention has to be payed to thermal management of the X-ray window area and the unbalance between cathode and anode current. **Figure 44** illustrates the thermal fingerprint at the X-ray port of bi-polar angiography tube. Cooling oil cracked where temperatures of the frame (from of impact of backscattered electrons) exceeded ca. 200°C during operation.

In the 1950’s, glass tubes for non-destructive testing had become available for tube voltages of more than 250 kV. The assemblies were bulky and difficult to handle. Starting in the late 1970’s, Philips Hamburg, Germany succeeded replacing glass for high performance stationary anode tubes by compact metal frames with ceramics insulators, see [28]. A cut-out model of the first metal-ceramics tube on the market, the Philips Super Rotalix Ceramic SRC$^{\text{TM}}$ 120 0612, is depicted in **Figure 51**. This design initially caused severe problems by effects of surface flashover and puncture of the ceramics insulators when high currents were applied. Vacuum ultraviolet radiation, X-rays, ions and scattered electrons destabilized the isolating capabilities. Proper shielding of electrical triple points, improved processing and better ceramics solved the issues. Typical traces of tube arcing in a metal center section tube are well visible in **Figure 45**. Despite of these rough conditions the metal electrodes survive. Eventually, a novel robust technology of all metal ceramics tubes emerged, which is well received, notably in the US market.

In addition to the tube housing, metal center section technology also enables a high degree of recycling of vacuum components. The SRC^{TM} tube and its successors, notably the Philips MRC^{TM} tube series with liquid bearing, see **Figure 36**, can be disassembled and re-sealed multiple times. Begining with the SRC tube, metal ceramics technology has been introduced by all major vendors of high-performance tubes.

Figure 42 GE MX-125 metal center section tube for the emerging angiography application, introduced in 1972. (Photo courtesy of GE.)

Figure 43 Philips metal center section tube technology with steel frame, alumina coated beryllium X-ray window and glass-metal joints.

Figure 44 Carbonized beryllium X-ray window after impact of electrons backscattered from the focal spot of a bi-polar angiography tube.

Figure 45 Traces of arcing between metal electrodes of a metal center section tube for angiography. A glass wall would have imploded under such severe arcing.

9. Special applications and features

9.1. Dental X-ray

In dental systems, the small distance between X-ray source and image receiver allows for low tube voltages and low power ratings in single-shot dental application. **Figure 46** depicts a simple stationary tube for 50 kV tube voltage. **Figure 47**shows a cut-off picture of a Philips Oralix^{TM} dental tube housing assembly including high voltage transformer and rectifying circuitry. The tube comprised a kind of Wehnelt electrode, which consists of a cathode plate which is isolated from the electron emitter coil. Tube current and focal spot size were stabilized using self-controlled resistive biasing. The tube current is being fed into the electron emitter by means of a resistor, whereas the focusing electrode is directly connected to the negative high voltage terminal This produces negative bias (with respect to the electron emitter) at the focusing electrode. As a result, the focal spot width is reduced and the electron emission self-stabilized.

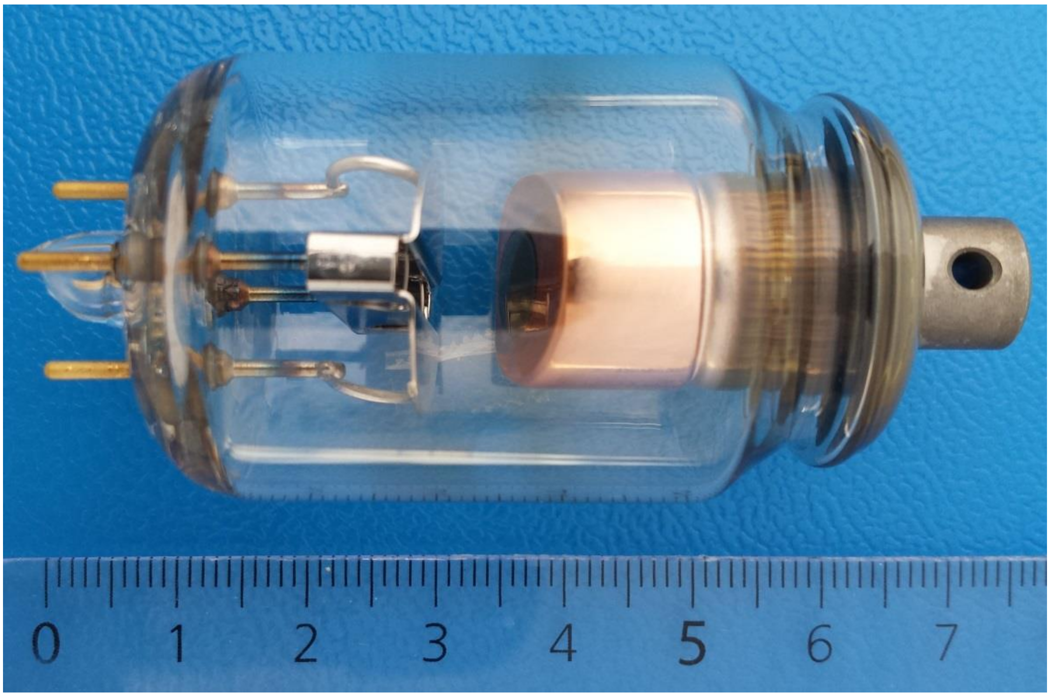

Figure 46 Philips dental tube FO12 for the Oralix^{TM} tube head, shown in Figure 36b, and centimeter ruler.

Figure 47 Cut-off picture of a Philips Oralix^{TM}dental tube head. Tube current and focal spot size were stabilized with a Wehnelt electrode and self-controlled resistive biasing. (Picture taken at the Medizinhistorisches Museum Hamburg, Germany,UKE.)

9.2. Mammography

Despite of being more costly than all-glass frame technology, metal center sections, which employed an X-ray window from beryllium, helped reducing X-ray attenuation and filter strength for the soft radiation required for mammography application. **Figure 48** depicts a cathode-grounded mammography tube, produced between 1980 and 1991 by VEB Röhrenwerk, Rudolstadt (Rörix), GDR, now Siemens. Although glass technology served well from a thermal and high voltage perspective for tube voltages between 18 kV and 50 kV, a glass frame causes undesired hard X-ray filtration. In the beginning of mammography glass tubes were indeed being used. But, it became clear very soon, that softer radiation was required for an optimal contrast-to-noise ratio in the images of soft tissue with potentially embedded malign calcifications. First, X-ray windows from beryllium were attached to the glass frame, and molybdenum or rhodium k-edge filters were added. **Figure 48**shows a better solution. Except for the necessary insulation by glass, the entire tube frame was made of metal. A beryllium window with low attenuation and X-ray filtration was brazed-in. The cathode of the tube was grounded. This simplifies “biasing”the cathode to minimize the focal spot width. Instead, CGR, France, a GE company, introduced an anode grounded solution in 1992.**Figure 49**shows a cut-out model of the tube housing assembly with the Statorix 52.2 (DMR) tube, produced from 1992. The tube has two comparatively large focal tracks, coated with rhodium and molybdenum, and positioned on the perimeter of the anode. It delivers minimal off-focal radiation and allows for convenient patient positioning.

According to the records of Varex, Salt Lake City, UT, USA, mammography tubes were the first X-ray sources which the predecessor company Varian produced, see **Figure 50**.

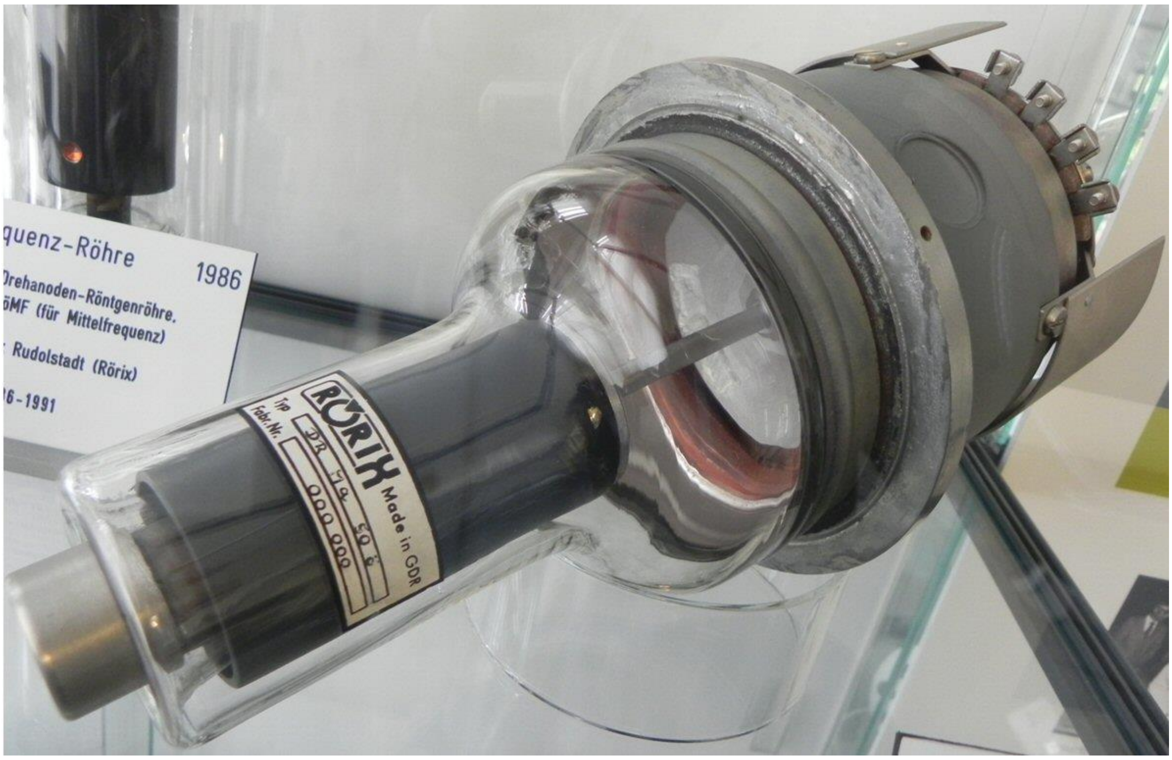

Figure 48 Mammography tube with metal center section, cathode grounded, produced between 1980 and 1991 by VEB Rudolstadt (Rörix, later Siemens), Rudolstadt, GDR.(Photo taken in the Siemens X-ray tube museum Rudolstadt, Germany.)

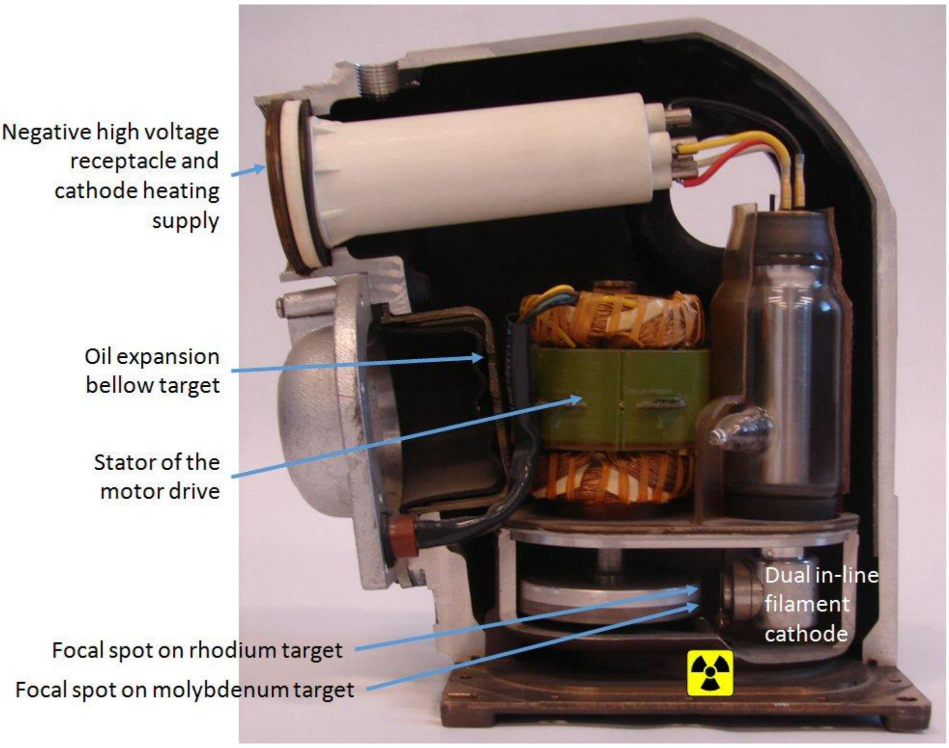

Figure 49 GE DMR mammography tube assembly. X-ray focal spots on molybdenum and rhodium targets positioned at the perimeter of the anode. (Photo courtesy of GE.)

Figure 50 The first tube produced by Varian, Salt Lake City, UT, USA (later Varex), the mammography tube B113 with metal center section, cathode grounded. (Picture courtesy of Varex.)

9.3. Angiography / cardiology application

Increasing fluoroscopy application in the 1970’s, and the necessityto record sequences of images in cardiology and angiography procedures (instead of single exposures), exceeded the technical capability of the glass tubes at the time. Tube life was inacceptable; the limited thermal energy per patient, which the tubes could sustain, was inappropriate and hampered the image quality and the work flow. The introduction of a graphite target by GE, see **Figure 25**, at least minimized the starting time and improved the durability of the balls bearings during long runs of an angiographic procedure.

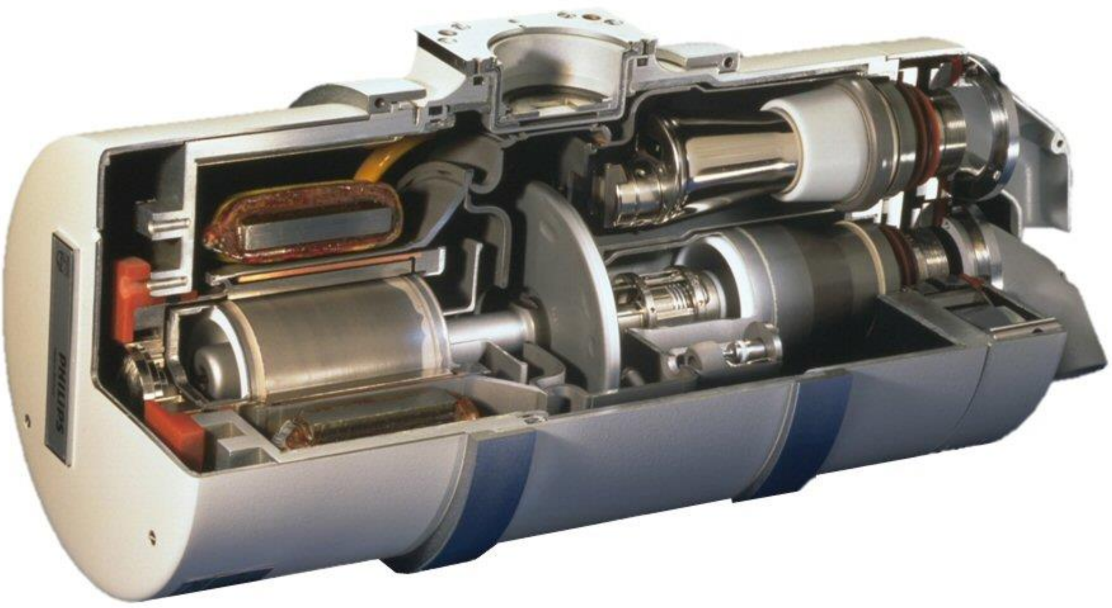

Figure 51 First all-metal-ceramics rotating anode tube in the market, introduced in 1980 by Philips, pioneering all high performance tubes of major vendors. ThisSRC ^{TM}tube series featureda comparatively large high temperature Trinodex^{TM} anode (at that time), compact design, scattered electron trap, rotating anode insulator to minimize the air-gap of the motor for short start-up time, silver-coated straddle ball bearing system with radial spring bearing suspension and axial pre-load thrust spring.

Philips improved the situation by introducing the full metal ceramic tube Super Rotalix Ceramic™ tube SRC 120 0610, see **Figure 51**, which featured a relatively large anode, suspended on a radially spring-supported straddle bearing system with a rotating ceramics insulator to maximize the efficiency of the motor. High patient and staff dose associated with angiographic diagnostics and therapy on site demanded for counter measures. One of them is enhancing X-ray filtration to narrow the spectrum. A powerful tube like the MRC^{TM} is required to benefit from hard filtration without introducing image noise and waiting times for cooling.

Another major step forward was the introduction of a tube current switch that operated without changing the tube voltage. Philips introduced it for angiography and cardiology tubes of the MRC^{TM} series in 1992, in 1996 with the MRM^{TM} tube series, and later also with SRM^{TM} metal center section tubes in radiography/fluoroscopy systems as grid controlled fluoroscopy GCF™. Already in 1937, Siemens had introduced grid control of the electron emission, similar to the current modulation in radio valves.

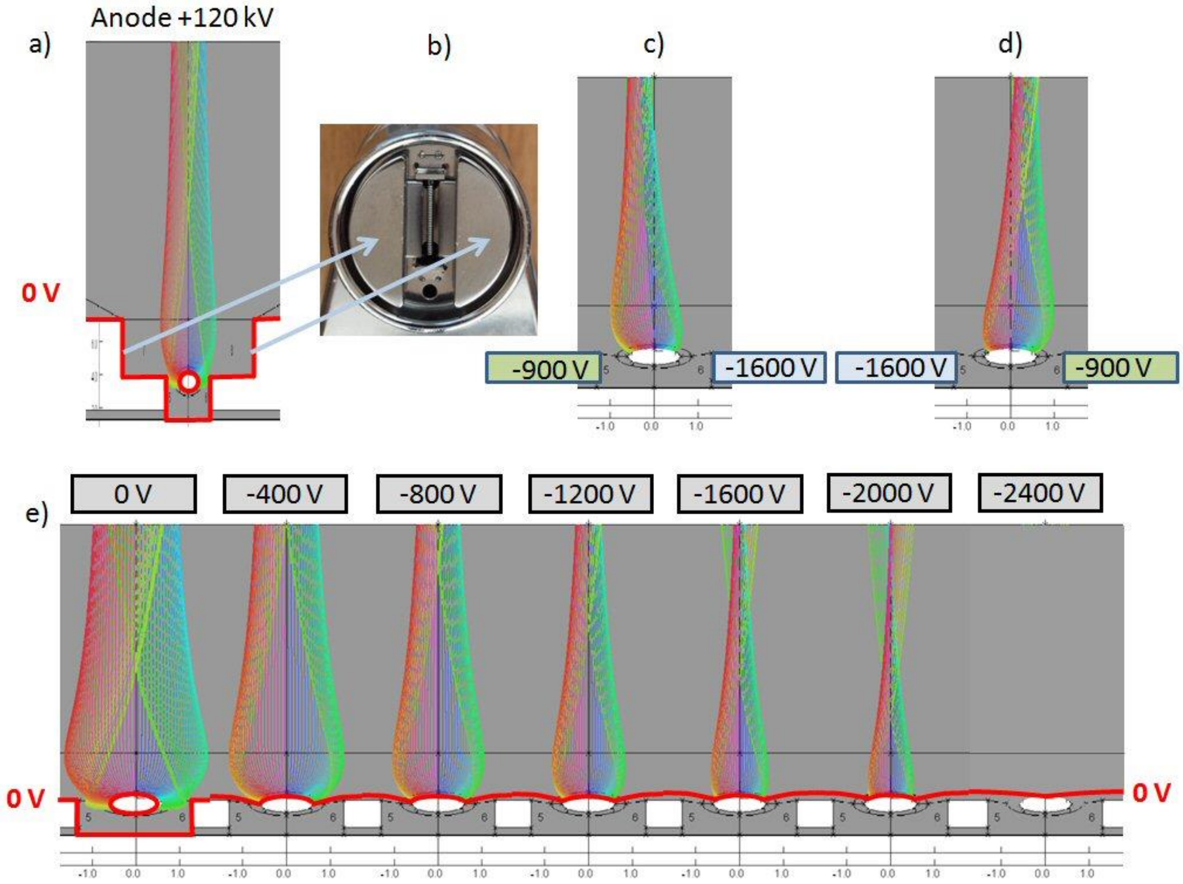

Figure 52 Ray tracing of electrons. Planar cross section through the emitter coil. Biasing of the control electrodes allow for focal spot deflection, as used in CT application, and also for switching the electron beam off.

Figure 52 demonstrates the basic principle of electron beam focusing, biasing and switching off the emission of electrons. Charging the electrodes, which surround the thermionic emitter,with a negative cut-off potential quenches the electron emission. The electron emitter is isolated from the rest of the cathode head. Upon application of the negative bias, the equipotential line, which represents the potential of the electron emitter, shifts allowing only electrons which still experience a pulling electric field (and which emerge from areas close to the center of the cathode coil) to escape. At cut-off the entire emitter is “covered” by a repelling field. Usually, the focal spot size shrinks with growing absolute bias, which allows for controlling the image resolution electronically. Further, in **Figure 52,** a means for deflection of the electron beam is shown, as used in many X-ray sources for CT. **Figure 53**shows the grid switch box, which Philips has been integrating in similar form into the tube housing assembly of the MRC tube series for angiography and cardiology from 1993 onwards. Other manufacturers have at least temporarily realized this feature with bias supply from the high-voltage generator, like Toshiba, and Siemens with early Megalix™ tubes and the latest angiography tube series Gigalix™. This tube, shown in **Figure 54**,comes with “gridded” flat electron emitters and a liquid bearing.

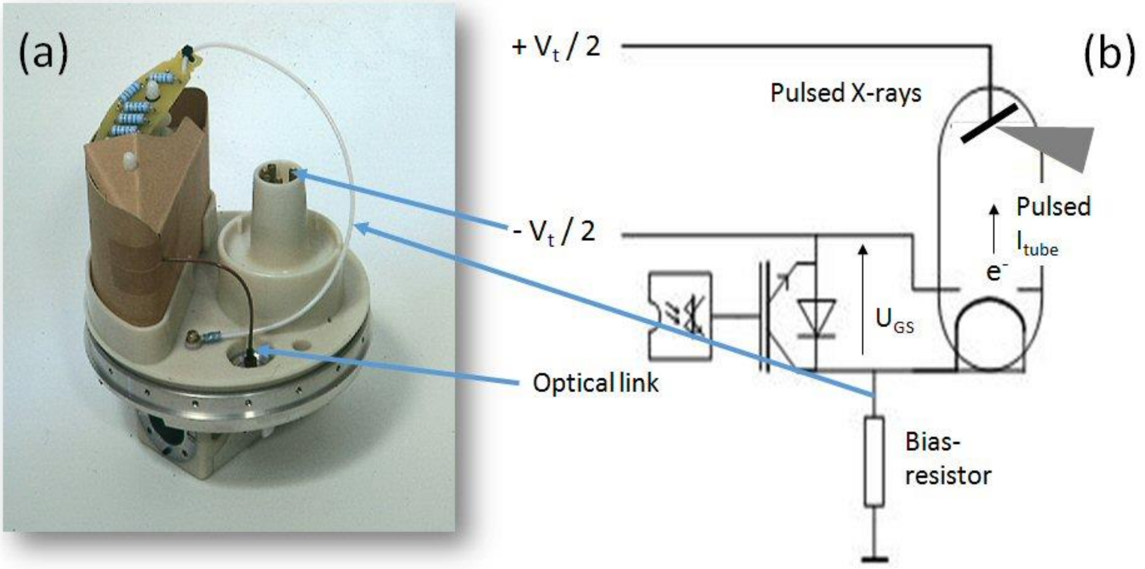

Figure 53 (a) Grid switching electronics for Philips angiography tubes, integrated in the tube housing assembly of the MRC™tube line, see **Figure 28**. (b) Electric schematics: The tube voltage remains unchanged when, upon an optical signal, the tube current I_{tube} is stalled by applying a negative voltage U_{GS} of several kilovolts between isolated cathode head and tungsten emitter. As the spectrum does not change, this “gridding” avoids unwanted soft photons during pulsing of the X-ray flux.

Figure 54 Siemens angiography tube of the Gigalix™series, launched 2013, with grid switchable flat electron emitter and liquid bearing. (Picture courtesy of Siemens.)

9.4. Compactness in radiography

The quest for compactness, versatility and scalability has inspired Varex, Salt Lake City, UT, USA to offer a series of single polar “anode end grounded” (AEG) tubes since 2010. **Figure 55 s**hows the drawing of a mammography tube type from patent literature. Rotating anode and X-ray focal spot are on ground potential, positioned proximal to one end of the tube housing assembly. The cathode is charged with negative high voltage potential. A stationary electron trap collects back-scattered electrons from the focal spot and reduces the electrical power supplied to the rotating anode. The small insulating gap keeps the efficiency of the motor drive up. Its magnetic stator is positioned parallel with the cathode.

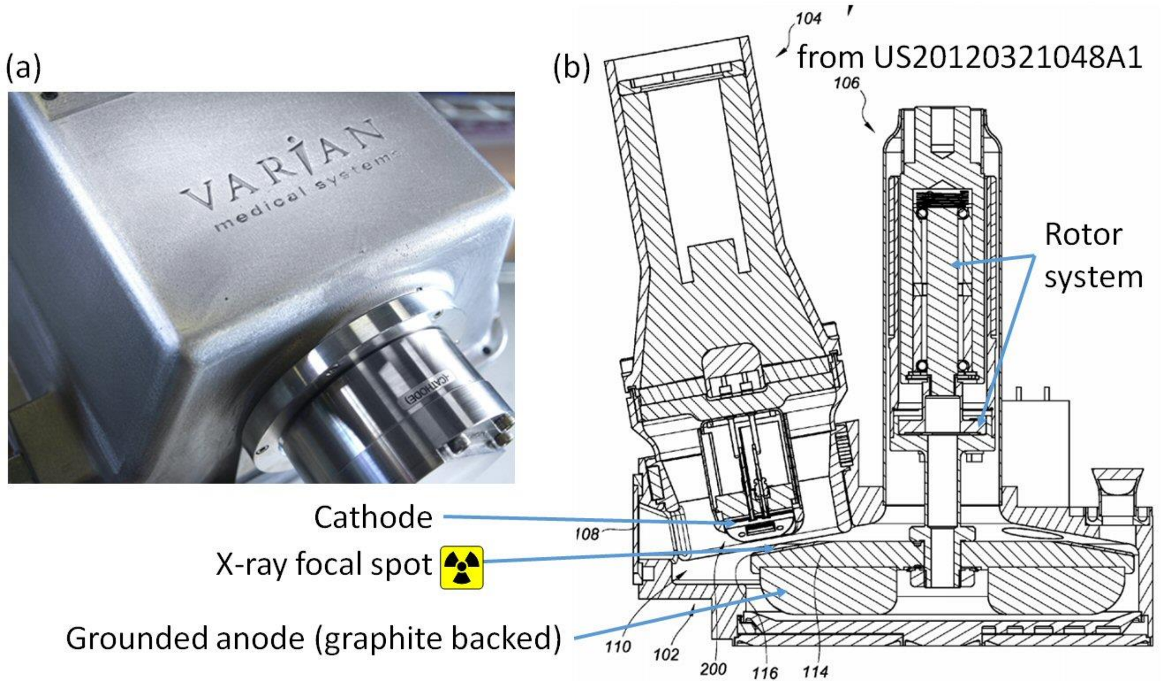

Figure 55 (a) Logo on one of the first anode end grounded (AEG) tubes developed by Varian, now Varex, Salt Lake City, UT, USA. (b) Drawing of an AEG tube frompatent application US20120321048A1. (Picture (a) courtesy of Varex.)

10. Production

Electrical stability and mechanical precision of X-ray tubes under high voltage of up to 150 kV and temperatures of up to 3300°C in the focal spot can only be guaranteed by well-controlled and clean production. Over decades, production yield at major manufacturers were in the range of 50% to 90%. Meanwhile, stringent process improvement and high quality material supply, rugged design, and high investment in production technology resulted in reduction of the scrap rates by at least an order of magnitude. **Figure 56** illustrates the evolution of production environment over nearly a century.

The development of the X-ray tubes continues, as an essential component of medical diagnostic imaging.

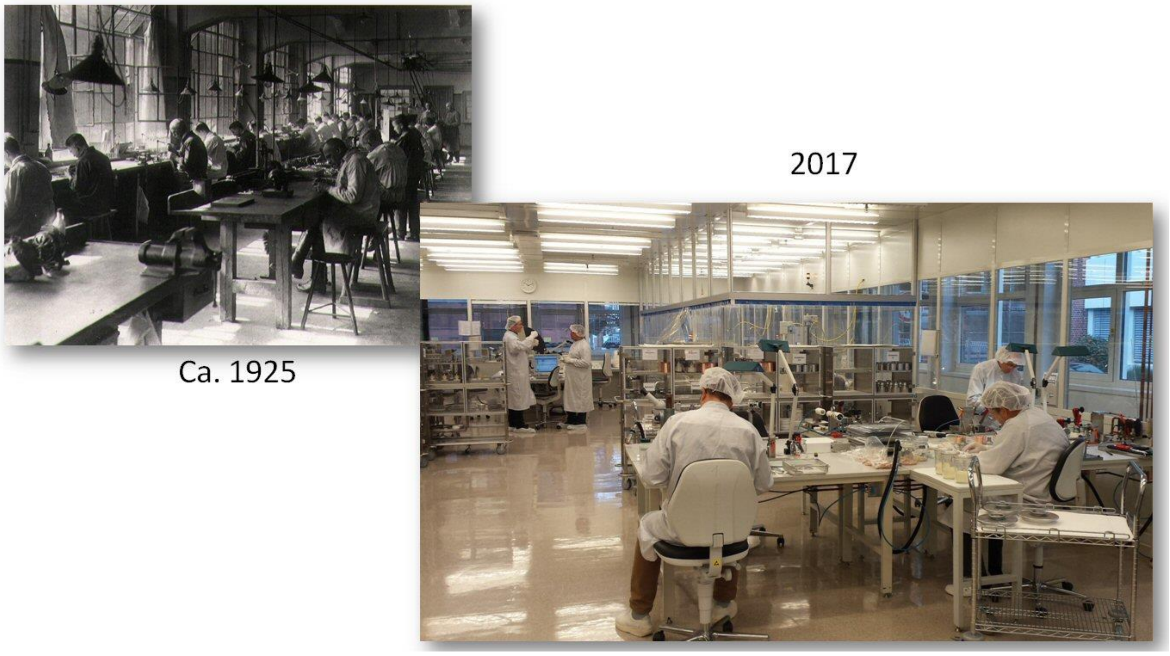

Figure 56 Assembly rooms at C.H.F. Müller, Hamburg, Germany, later Philips, around the year 1925, andin 2017 at the PhilipsX-ray tube plant in Hamburg. (Picture courtesy of Philips.)

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