Physical assessment
of a novel concept for computed tomography
with a stationary source ring of fixed X-ray anodes
for medical imaging

Physikalische Bewertung
eines neuartigen Konzepts für die Computertomographie
mit einem stationären Quellring aus Röntgen-Stehanoden
für die medizinische Bildgebung

Der Medizinischen Fakultät
der Friedrich-Alexander-Universität
Erlangen-Nürnberg
zur
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Zusammenfassung

Hintergrund und Ziele
Die potentielle Leistungsfähigkeit eines aktuellen Computertomographen (CT) ist im Wesentlichen durch die thermische Belastbarkeit der Röntgenanode begrenzt. Zusätzlich ist die Gantry-Umlaufzeit limitiert, da mit wachsender Zentrifugalkraft eine destruktive Wirkung einhergeht. Mit Blick auf die thermische Belastbarkeit ist in dieser Arbeit ein neuartiges CT mit Festanoden (engl.: Fixed Anodes Computed Tomography: FACT) vorgestellt worden, was vom grundlegenden Konzept aus keine mechanische Einschränkung aufweist. Zum Vergleich wurde ein gängiges klinisches CT als Referenz-CT herangezogen.

Material und Methoden
Mithilfe der freien Softwarekombination GAMOS/GEANT4 wurden Monte-Carlo-Simulationen durchgeführt, um die Energiedeposition von beschleunigten Elektronen in dem sogenannten thermischen Brennfleck einer Röntgenanode zu bestimmen. Die so erhaltene thermische Energie diente zur Ermittlung der Temperaturverteilung unter Anwendung der Finite–Elemente–Methode, wobei die kommerzielle Software COMSOL Multiphysics zum Einsatz kam. Basierend auf typische Abmessungen für Anoden wurde ein grundlegendes Simulationsmodell für Festanoden, die aus einer dünnen Wolframschicht, eingebettet in einen Kupferblock, aufgebaut sind, entwickelt und zum Vergleich auf ein Modell zur Drehanode übertragen. Die Betriebstemperatur des Röntgenanodenbrennflecks im Wolframtarget wurde auf eine maximal zulässige Temperatur von 2500 K festgelegt. Zur Kühlung wurde ein Wärmepad mit 300 K am entfernten Kupferblockende definiert. Simulationen zum Festanodenmodell wurden unter der Annahme einer kurzen bis in den Beginn einer langen thermischen Belastung (1 µs – 1 s) bei der jeweiligen maximalen thermischen Brennfleckleistung durchgeführt. Im Anschluss wurden zahlreiche Parameter zum thermischen Studienmodell der Festanode verändert, um die Modellierung auf seine Gültigkeit untersuchen zu können. Die Langzeitbelastung einer einzelnen Festanode wurde hinsichtlich eines kontinuierlichen Impulsbetriebs bei einem FACT untersucht. Es wurde ein virtuelles Modell zur FACT erstellt, um verschiedene zeitliche Abläufe im Röntgenquellring, der eine kreisförmige Anordnung von 1160 einzelnen Festanoden bildet, analysieren zu können. Unter der Annahme von bekannten Detektoreigenschaften, die auf die deutlich kleineren Integrationszeiten beim FACT übertragen worden sind, wurde die Bildqualität mithilfe der CT-
Bildrekonstruktionsbibliothek ROTLib aus dem Institut für Medizinische Physik in Erlangen, Deutschland, ermittelt. Mit der Definition einer *Relative Performance* (*RP*) wurde ein Bezug zum Referenz-CT hergestellt.

**Ergebnisse**

Simulationsstudien mit den definierten Anodenmodellen zur thermischen Brennfleck-Leistungsdichte (*P*ₜₜ/ₐ) waren in guter Übereinstimmung in den absoluten Werten sowie deren Trends zu Literatur- und Hersteller-Angaben. Studien zum kontinuierlichen Impulsbetriebs zeigten, dass mit Festanoden das FACT prinziell unbegrenzt betrieben werden kann. Aus dem virtuellen Modell zum FACT ging hervor, dass rund 60 Gantry-Umläufe pro Sekunde erforderlich sind, um die Röntgenleistung (bei *RP* = 1) entsprechend dem Referenz-CT zu erreichen. Unter dieser Bedingung konnte eine äquivalente Bildqualität beim FACT durch Superposition erzielt werden. Die optimale Projektionsdauer aus jeder Projektionsrichtung lag bei 10 µs. Mit einer Strahl-Pause von 1 µs zwischen den Projektionen waren 78,4 Umläufe pro Sekunde bei aufeinander folgenden Röntgen-Quellenaktivitäten möglich, was in einer *RP* von 1,3 resultierte bei gleicher Brennfleckabmessung im Vergleich zum Referenz-CT.

**Schlussfolgerungen**

Als stationäres System mit Festanoden zeigt FACT keine Brennfleck-Verschmierung während der Projektion. Mit einer *RP* > 1 kann eine kürzere Aufnahmezeit erreicht werden, bei gewöhnlicher Strahlenexposition und Bildqualität. Basierend auf der hohen Anzahl von Umläufen bei jeweils niedriger Dosis kann mit einem FACT eine hohe Bildwiederholungsrate und sehr dünne Bildschichten erzielt werden, was für ein breites Spektrum von medizinisch-diagnostischen sowie technischen Anwendungen einen deutlichen Fortschritt darstellen könnte.
Summary

Background and Aims
The potential performance of current technology for computed tomography (CT) is basically limited by the thermal load capacity of the X-ray anode. In addition, the gantry rotation time is limited, because the centrifugal force can become destructive. Focusing primarily on the thermal load capacity, this work intends to show a novel CT with fixed anodes (Fixed Anodes Computed Tomography: FACT), which has basically no mechanical constraints. For comparison, a common clinical CT was used as Reference CT.

Material and Methods
Monte Carlo simulations, with the free software combination GAMOS/GEANT4, were used to determine the energy deposition of accelerated electrons in the so-called thermal focal spot of an X-ray anode. The thermal energy thus obtained was used to determine the temperature distribution, using the finite element method, where the commercial software COMSOL Multiphysics was used. Based on the typical sizes of the anode, a basic simulation model has been developed for fixed anodes, which comprises a thin tungsten layer embedded in a copper block, and is transmitted for comparison to a model for a rotating anode. The operating temperature of the X-ray focal spot in the tungsten target of the anode was set at a maximum permissible temperature of 2500 K. For cooling, a heat bath at 300 K has been defined at the distal copper block end. Simulations for the fixed anode model were performed under the assumption of a short thermal load till up to the beginning of long thermal load (1 µs – 1 s) at the respective performances of the maximum thermal focal spots. Subsequently, numerous parameters were changed for carrying out the studies of the thermal model of the fixed anode in order to investigate the validity of modelling. Long-term exposure of a single fixed anode was examined for continuous pulse operation at any FACT. A virtual model for FACT has been created in order to analyse different temporal sequences in the X-ray source ring, forming a circular array of 1160 single fixed anodes. Under the assumption of known detector characteristics, which have been transferred to the much lower integration times at FACT, the image quality was determined using the CT image reconstruction library ROTLib at the Institute of Medical Physics in Erlangen, Germany. With the definition of a Relative Performance (RP), the relation to the Reference CT was made.
Results
Simulations for thermal focal spot power density ($P_{th}/A$) of anodes were in good agreement with literature results and vendor data with regard to their absolute values and trends. Studies on continuous pulse operation showed that with fixed anodes, the FACT can be operated, in principle, in an unlimited manner. The virtual model for FACT showed that around 60 gantry rotations per second are required to achieve the reference CT, according to the X-ray power (at $RP = 1$). Under this condition, an equivalent image quality in FACT can be obtained by superposition. The optimal duration of each projection direction was 10 µs. With a beam pause of 1 µs between the projections 78.4 rounds per second at successive X-ray source activities were possible, resulting in an $RP$ of 1.3 at the same focal spot size, in comparison with the Reference CT.

Conclusions
As a stationary system with fixed anodes, FACT has no focal spot blurring of the X-ray source during projection. With an $RP > 1$, a shorter scan time can be achieved, while maintaining radiation exposure and image quality. Based on the high number of rounds at each low dose, we can conclude that FACT can support a high image frame rate and very thin slices, which could be of significant advantage in a wide range of medical diagnostic as well as technical applications.
1. Introduction

,"Dass ich erkenne, was die Welt im Inneren zusammenhält.,"

Faust. Der Tragödie erster Teil, J. W. Goethe, 1808.

Every third-generation computed tomography (CT) scanner incorporates an X-ray tube and a detector arrangement that mechanically rotate around the patient. Current clinical CT scanners and most industrial CT scanners operate on this principle.

In recent decades, volumetric CT imaging has advanced with the advent of spiral acquisition [23, 42, 7], and has progressed to multidetector row CT (MDCT) scanners [29, 19]. During the continuous movement of their couches, these systems acquire sufficient information in a helical path for reconstructing images from raw projection data. An increased number of detector rows provides the advantages of thinner slices, shorter scan times, and reduced motion artefacts.

In particular, because of the rapid increase in the number of installed detector rows, there is a desire to obtain sufficient volume coverage in the axial direction during a single round. However, a wide X-ray beam has a number of drawbacks, such as increased scattering, over-scanning, and cone-beam artefacts at large cone angles. Various approaches and novel concepts have been proposed to address different issues [39, 31, 20, 41, 28, 11, 24, 37]. Besides, the approaches of the fourth-generation CT and the electron beam CT (EBCT) [4] are not much in demand these days.

Recently, an inverse-geometry CT (IGCT) system was proposed for achieving a scanned volume during a single gantry rotation that was essentially free of cone-beam artefacts [9, 10, 18, 44].

Scanning a volume during a single rotation is limited by the gantry rotation time, since the centrifugal force can become destructive. If this mechanical restriction is taken out of a system, the maximum temperature at the focal spot of an X-ray anode poses a serious limitation for the scanning time. In this study, we described a concept for CT based on a ring of stationary X-ray sources, as proposed by Foster and Müller [15, 16, 14].

The investigations into possible achievable image frame rates were closely related to potential performance. In general, a number of medical applications would benefit from a high image frame rate for a volume, including cardiac imaging, CT angiography, perfusion studies, and other de-
manding imaging applications. The potential performance of a conventional CT is primarily limited by the thermal load capacity of the X-ray anode. Hence, we began with studies on the thermal load capacities of anode focal spots. For these studies, a CT concept was outlined that had no mechanical restrictions caused by gantry movements and that allowed for a high image frame rate, which was coupled with rounds of the X-ray source ring at doses normally used for patients. The aim of the study is to provide a conceptual theoretical framework for CT with fixed anodes based on the feasibility of thermal load capacity. However, this study does not cover technical feasibility of the source ring and does not consider detector performance or efficiency. Since detectors need to be developed in accordance with their specific requirements, we used as a benchmark today’s acquisition of X-ray attenuation without an adaptation to the novel concept. Furthermore, the detection properties of the currently used integration times are extrapolated linearly to small time ranges. This means that the same total energy and photon fluence per projection yields identical image quality.

**Basic concept for the novel concept**

The basic concept of a CT with fixed anodes (FACT) is illustrated in Figure 1.1.

*Figure 1.1:* Concept for FACT. (a) 3D design of a compact FACT with a single source ring and a detector ring mounted on a robotic arm. (b) Geometric relationships. (c) Helical source path of FACT compared to that of a multi-slice spiral CT. (d) Image reconstruction based on the multi-slice spiral CT determined by pre-processing. Alternatively, the information for the reconstructed images could be combined during post-processing, as employed in Section 4.4.3.

The generation of a primary X-ray beam from an X-ray tube follows the same principle that has
been known for over a century. A rotating anode X-ray tube, which conventionally revolves in
a gantry around an object, is replaced in FACT by a stationary source ring of fixed anodes. In
the current study, 1160 fixed X-ray anodes were used, analogous to the Reference CT specified in
Table 1.1.

For carrying out a theoretical analysis, the beam at a single fixed anode is allowed to be switched
on and off at any frequency. The fixed anodes in the source ring were used in sequential operation.
Owing to the restricted exposure time for each direction, the required number of projections for
typical image information was acquired using multiple gantry rounds ($\approx 20$). Projection data
were combined during pre- or post-processing to acquire equivalent information analogous to
the principle used in the Reference CT. Throughout these studies, we chose parameters of our
design in accordance with the Reference CT, which was also used as a benchmark to determine
the performance of our novel concept. The operating data for this Reference CT (see Table 1.1)
were based on SOMATOM Definition, Siemens Medical Solutions, Forchheim, Germany.

**Table 1.1:** Specifications used for FACT and Reference CT

<table>
<thead>
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<th>Symbol</th>
<th>Specification</th>
<th>FACT</th>
<th>Reference CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{el}$</td>
<td>Electrical X-ray tube power</td>
<td>depending on $(P_{th}/A)_{max}$</td>
<td>100 kW</td>
</tr>
<tr>
<td>$U$</td>
<td>X-ray tube voltage</td>
<td>120 kV</td>
<td>120 kV</td>
</tr>
<tr>
<td>$t_{round}$</td>
<td>Gantry round time of the source</td>
<td>up to 300 ms</td>
<td>300 ms</td>
</tr>
<tr>
<td>$N$</td>
<td>Source positions per round</td>
<td>1160</td>
<td>1160</td>
</tr>
<tr>
<td>$SID$</td>
<td>Source-to-isocenter distance</td>
<td>60 cm</td>
<td>60 cm (rounded)</td>
</tr>
<tr>
<td>$OFS$</td>
<td>Optical focal spot</td>
<td>$0.7 \times 0.9 \text{ mm}^2$</td>
<td>$0.7 \times 0.9 \text{ mm}^2$</td>
</tr>
<tr>
<td>$A$</td>
<td>Thermal focal spot area</td>
<td>$6 \text{ mm}^2$</td>
<td>$6 \text{ mm}^2$</td>
</tr>
<tr>
<td>$(P_{th}/A)$</td>
<td>Thermal focal spot power density</td>
<td>$(P_{th}/A)_{max}$ is shown in Figure 4.4 (a)</td>
<td>$(P_{th}/A)_{const} = 8.6 \text{ kW/mm}^2$</td>
</tr>
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2. Technical and physical aspects of the thermal load capacity of X-ray tubes

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2.1. Basics of X-ray systems

In order to form an X-ray image, the object (i.e. the patient) must be positioned between the X-ray tube and the imaging system. Typically, an X-ray system consists of an unit that comprises the basic system, the generator, the tube and the image acquisition system. In line with the radiological requirement, the patient is typically positioned on a fixed basic system and one or more X-ray projection images are taken of the relevant anatomical region. Exceptions to this include non-floor-mounted systems, such as the mobile surgical C-arm or mobile radiography systems, which
can be moved towards the operating table or patient bed.

The X-ray generator is the “heart” of the diagnostic system. It converts the current supplied by the network to the required energy as an adjustable tube and expose voltage $U$ and the corresponding high-voltage waveform for generating X-rays (see also the use of waveform factor $w$ in Equation 2.4).

An X-ray tube (see Figure 2.1) is the “extended arm” of the X-ray generator connected via high-voltage cables. The X-ray tube and the envelope housing form a single unit, which is referred to as the X-ray tube or just the tube [17].

![Figure 2.1: Sketch of a fixed anode X-ray tube: 1: envelope housing, 2: cathode (electron source), 3: beam of focused electrons ($e^{-}$), 4: fixed anode made of copper (Cu), 5: tungsten (W) target and focal spot](image)

The X-ray tube is a relatively simple electrical device, which typically contains two units: A cathode and an anode. The cathode is the source of the electrons; it releases electrons from the current conductor. A typical construction represents a coiled tungsten wire, which is also known as a spiral-wound filament. Significant heating of the tungsten wire releases a number of electrons. The heating output determines the amount of tube current $I$ and, consequently, the quantity (dose rate) of radiation. A cylindrical cap on the cathode, called Wehnelt cylinder, forms a focusing potential to direct the electron flow to the desired focal spot on the anode. The potential difference causes an uptake of kinetic energy $E_{kin}$ for the free electrons, in accor-
dance with the applied X-ray tube voltage $U$:

$$E_{\text{kin}} = \frac{m}{2} \cdot \nu^2 = e \cdot U. \quad (2.1)$$

$m$: Mass of electron, $\nu$: Velocity of electron, $U$: Voltage between anode and cathode,

$e = 1.6 \cdot 10^{-19}$ As: Electron charge

As the electron penetrates the anode, it loses its energy. An anode of the X-ray tube can be stationary/fixed (see Section 2.3.1) or rotating (see Section 2.3.2 and 2.3.3). The anode is the component in which the X-ray radiation is generated. It is typically a piece of metal with a high melting point, on which the positive potential of the tube circuit is present. The primary functions of an X-ray anode are conversion of the kinetic energy into X-ray radiation as effectively as possible and dissipation of the heat generated in the interaction process as rapidly as possible. The material for the anode is selected to enhance these functions (see Section 2.6).

A look at the efficiency of X-ray production shows a relatively small fraction of the energy delivered to the anode by the accelerated electrons is converted into X-radiation; most of the energy is absorbed by the anode and converted into heat. The equation 2.2 for efficiency shows the dependence of the material of the anode target (with atomic number $Z$) and the tube voltage $U$. It is considered a classical approximation:

$$\eta = \frac{\text{radiation power}}{\text{electrical tube power}} = k \cdot Z \cdot U \quad (2.2)$$

$k$: Proportionality factor, $Z$: Atomic number of the target medium (Z of Wolfram is 74),

$U$: Voltage between anode and cathode

wherein $k = 1.1 \cdot 10^{-9}$ [V$^{-1}$] represents a typical experimentally determined constant of an X-ray tube [27].

For an anode target, material made of tungsten ($Z = 74$) and a tube voltage $U$ of 120 kV results in an efficiency $\eta$ of only 0.98%, but which is much lower in practice because of filtering and collimating. This miniscule percentage has not been surpassed in any way till now. The contrast effect in the image essentially depends on the energy of the X-rays used. Therefore, the optimum anode voltage (typically in the range of 20 keV to 150 keV) is determined for most of the diagnostic questions. Hence, such low efficiency has to be accepted.

Thus, the potential performance of an X-ray tube is, in principle, determined by an effective heat dissipation. Appropriately, the application of technical artifices has resulted in a variety of X-ray tube designs.
2.2. Forms of interaction

The accelerated electrons lose their energy as they penetrate the anode. Here, two types of interactions are well known. (Figure 2.2 shows an outline of interactions.) The first and more important form of interaction results from the electron’s collision with the atoms in the anode material. The atoms are ionized or raised to a higher energy level. Excited atoms then fall back to their equilibrium state via emission of the so-called characteristic radiation or via radiationless processes. Characteristic radiation may leave the anode (as plotted in Figure 4.5 a)) or the atoms may release their energy by further interaction with the matter. Finally, the energy that is transferred as a result of collisions is converted to lattice vibration – i.e. it leads to an increase in thermal energy. Overall, more than 99% of the kinetic energy is converted in this way by electron collisions. It has no value in radiography and has to be dissipated in applied X-ray diagnostics.

The second form of interaction involves the deceleration of electrons colliding in the electric field of the atomic nuclei. This results in the emission of radiation as so-called bremsstrahlung. The probability of radiation or a collision depends on the electron’s kinetic energy and the atomic density of the material. In the energy range that is relevant for medical diagnostics, less than 1% is converted into X-ray energy [36].

![Figure 2.2: Outline of the interactions due to e⁻ bombardment of high Z target](image)

2.3. X-ray tube designs

As mentioned in the previous section, more than 99% of the power applied is converted into heat. One of the greatest challenges in the development of high power X-ray tubes is efficient heat dissipation. When the function and service life of an X-ray tube are considered as a whole, the
anode is usually the key object of the design [36, 27].

Owing to their characteristic anode design, three categories of X-ray tubes are differentiated for use in medicine:

- Tubes with stationary/fixed anodes (see Section 2.3.1)
- Tubes with rotating anodes (see Section 2.3.2)
- Rotating envelope tubes (see Section 2.3.3)

### 2.3.1. Tubes with stationary/fixed anodes

![Figure 2.3: Fixed anode](image)

Figure 2.3: Fixed anode: a) tungsten rhenium target, b) focal spot, c) copper block, d) copper block socket (stem), e) vacuum-tight connection between tube envelope and copper block. For some applications, channels for the circulation of cooling agents are drilled into the copper block [36]

Figure 2.3 illustrates a typical stationary anode. It is also known as a fixed anode. The base body is made of a copper block. A tungsten target is inserted only in the area of the focal spot. The copper block has the task of buffering the deposited thermal energy and carrying it away from the heated focal spot via thermal conduction through the copper block towards its stem and, hence, to the outside of the tube. The copper block is, therefore, designed to be voluminous. If the heat capacity of the copper is insufficient, then the stored thermal energy must be dissipated by external cooling. This typically occurs by convection, either via air flow or cooling fluid.

The copper block is placed in the tube envelope and isolated by a vacuum-tight. The anode is often outfitted with a cup-shaped electron capture hood (see Figure 2.4). A field-free space is
thereby created in close proximity to the target surface. The example shows how such a design element can effectively stop reflected electrons from falling back on the anode surface and thereby help reduce undesired extra-focal radiation (see also Section 2.4.2).

Fixed anodes are characterized by their relatively small design and can only be loaded to approximately 2 kW. For applications in medicine with low power, the fixed anode is primarily used in dental radiology (see Figure 2.5 (a)), in orthovoltage therapies for the treatment of chronic inflammatory and degenerative diseases of the musculoskeletal soft tissues (see Figure 2.5 (b)), for interventional radiotherapy (see Figure 2.5 (c)) and as special designs, to find out hollow organs for carrying out radiotherapy on them (see Figure 2.5 (d)).

2.3.2. Tubes with rotating anodes

The expensive and technologically demanding rotating anodes have become the standard design for medical diagnostics. Thanks to their rotation, they allow a thermal power load of up to 100 kW, which is the factor of 50 more in comparison to the fixed anode.

The essential component is a rotating anode disk, which may have a diameter of around 15 cm and a mass of up to 1 kg. Compared to a fixed anode, a rotating anode offers the advantage of enabling distribution of the thermal energy that is deposited in the focal spot across the large surface of the focal ring. It typically consists of tungsten or tungsten-rhenium alloy and has a thickness in the range of 0.5 mm to 1.3 mm [17]. The rotating anode body has to be more thermally resistant than the fixed anode with its copper block. The supporting disk (disk body) is usually made of molybdenum (Mo) and may be of different thicknesses (one supporting disk: 4 mm to 19 mm), depending on the design. This disk increases heat capacity (heat storage capacity) and decreases crack formation on the anode. Owing to the design, rotating anodes are to be cooled only by thermal radiation, because the anode disk cannot be brought into direct contact with a cooling medium. In order to increase the emissivity, an additional graphite layer is usually attached on the rear of modern anodes. Since, in most technical designs, the tube voltage is applied to the anode, the distance of the rotating anode to the tube housing must be kept sufficiently large in order to
Siemens Panoramic Dental Tube: 20 cm long and 6.2 cm in diameter, oil-immersed, single focus of 0.8 mm, fitted with a hooded anode and a beryllium window, and with a large external aluminium heat sink fixed to the anode end of the tube, 50 – 80 kV, 10 – 15 mA, and exposures of 10 – 15 seconds. [12]

Siemens Deep Therapy Tube: 40 cm long, oil-immersed, line focus, deep hooded anode with a deep-seated tungsten target and a beryllium window, ground glass X-ray output port, anode cooling by forced oil circulation inside the hollow anode body, 250 – 300 kV. [12]

Mini X-ray Tube for Electronic Brachytherapy System: 2.25 mm diameter of tube, maximum peak voltage: 50 kV, maximum beam current: 0.3 mA, source power: 15 W. The X-ray tube is designed as a replacement for brachytherapy isotopes Ir-192. [43]

Cold Cathode Field Emission X-Ray Tube (for Flash): 20 cm long and 2.5 cm diameter, pulse duration: 0.03 ms, applied voltage: up to 350 kV, maximum current at maximum voltage: 1400 A, peak power: 147 MW, X-ray source diameter: 1.5 mm, anode material: tungsten. Emission of electrons from cold cathodes consisting of one or more sharp needle-points, the so-called field emission, has been known for many years. In the Fifties and early Sixties, it was demonstrated that X-ray tubes with field emission cathodes, obviously remarkably simple in construction in comparison to the hot filament cathodes, could be made to generate X-ray beams of very high intensities with output currents of hundreds of amperes as a series of pulses controlled by suitably designed highly efficient pulsers, which are useful in flash radiography and stop motion pictures of high speed events. [12]

Figure 2.5: Typical fixed anode X-ray tubes: (a) and (b) with a (thermionic) filament cathode and, for comparison, (c) a mini X-ray tube with Carbon Nanotubes (CNT) field-emission electron source and (d) a Cold Cathode Field Emission X-ray tube used for pulsed operation.
avoid voltage flashovers. A workaround would be anode designs in which the anode is at ground potential, since closer spacing between the anode disk and the tube housing, and, thus, the coolant can be allowed [36].

Figure 2.6 shows a typical rotating anode X-ray tube glass envelope, as available for purchase from the manufacturer Plansee.\footnote{http://www.plansee.com/}

![Figure 2.6: Images of rotating anodes and accessories, as offered by the manufacturer Plansee](image)

(a) Example of a rotating X-ray tube for high-resolution devices used in general X-ray applications, mammography, angiography and computed tomography

(b) Examples of different metal- and graphite-backed anodes

### 2.3.3. Rotating envelope tubes

The latest development represents the design of the so-called rotating envelope tube. It allows direct liquid cooling for the rear of the rotating anode, thus combining the advantages of fixed and rotating anodes. Under the trademark of Stratton [40], Siemens developed a rotating envelope tube for use in computed tomography and angiography, where extreme performance requirements are needed. Figure 2.7 shows the schematics of the Stratton tube with the anode that is directly attached to the tube envelope.

According to the manufacturer’s information regarding the X-ray tube Stratton, a power of 100 kW is applied directly to the focal spot by the generator. The temperature at the focal spot reaches 2500°C, and the temperature on the focal track hits 2000°C. Because of the direct cooling, the back of the anode has a temperature of only 200°C, which results in a temperature gradient of more than 1800°C/cm. The tube rotation frequency is 160 Hz. With the additional scanner rotations, the Stratton tube has to grapple with 40 times the gravity (40 g).

Figure 2.8 compares the Stratton rotating envelope tubes to the conventional design of a rotating anode, both of which are used by Siemens for CT.
Figure 2.7.: Schematics of the Straton tube from Siemens [40], showing the anode and the planar cathode within a rotating vacuum enclosure. The bearings are mounted outside the vacuum enclosure. Deflection coils magnetically direct the electron beam to specific areas on the target. Circulating oil rapidly removes excess heat from the anode.

Figure 2.8.: Size comparison of tube designs offered by Siemens: Straton tube (left) compared to the conventional rotating anode tube (right).

2.4. The target area

2.4.1. The focal spot and the principle behind the line focus

Because of geometric imaging properties, the ideal X-ray source would be a point source. When the accelerated electrons penetrate the anode, their kinetic energy is mainly converted into heat energy, which is measured as temperature increases. For sharp and low noise images, a small spot
size and high power density are needed. But the amount and spatial density of power deposited onto the anode surface limits the anode’s service life. High heat densities cause thermomechanical stress in the anode, which can result in the destruction of material structures. To overcome these conflicting demands, Götze (the story of this is given in [13]) introduced the line focus in as early as 1918. This concept is still in use in almost every X-ray tube manufactured today [36]. Figure 2.9 (a) shows a sketch of the principle behind the line focus. The length relationship between optical focal spot ($F_{op}$), thermal focal spot ($F_{th}$) and the anode angle ($\alpha$) is illustrated in figure 2.9 (b) and given in Equation 2.3.

\[
\sin \alpha = \frac{F_{op}}{F_{th}} \quad \text{und} \quad \tan \alpha = \frac{F_{op}}{HF}
\]  

\[ (2.3) \]

$\alpha$: Anode angle, $F_{op}$: Length of optical focal spot, $F_{th}$: Length of thermal focal spot, $HF$: Length of heating filament (here without focusing)

The size of a focal spot influences the achievable image sharpness. The larger the focal spot, the greater the load capacity, but also the greater the geometric unsharpness. Focal spot sizes can be found standardized according to DIN EN 60336 [32]. An extract is provided in Table 2.1.
Table 2.1.: Extract of the nominal values of focal spots and the corresponding size (DIN EN 60336).

<table>
<thead>
<tr>
<th>Focal spot nominal value $f$</th>
<th>Dimensions of optical focal spot, maximum allowed values in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>width</td>
</tr>
<tr>
<td>0.1</td>
<td>0.15</td>
</tr>
<tr>
<td>0.3</td>
<td>0.45</td>
</tr>
<tr>
<td>0.5</td>
<td>0.75</td>
</tr>
<tr>
<td>1.0</td>
<td>1.40</td>
</tr>
<tr>
<td>1.5</td>
<td>2.00</td>
</tr>
<tr>
<td>2.0</td>
<td>2.60</td>
</tr>
<tr>
<td>3.0</td>
<td>3.90</td>
</tr>
</tbody>
</table>

The measurement of a tube’s focal spot size, using a slit or pinhole camera, is also specified in DIN EN 60336 [32]. Figure 2.10 shows the actual size of the focal spot, which must be determined from the corresponding line spread function based on 15% of the measured peak value. The dashed (red) line indicates the idealized focal spot size, which is used in this study.

![Figure 2.10: Example of a line spread function from DIN EN 60336.](image)

2.4.2. Off-focal radiation

In a diagnostic X-ray tube, around 50% of the incident energy of the accelerated electrons leaves the anode surface, either after elastic or inelastic interactions, or after the trigger of secondary electrons. The energy of the scattered primary or secondary electrons is reduced by an average of around 20% relative to the primary energy. [26, 30]

As they are attracted from the positive electrical potential, we meet the escaping electrons for a second time in the close or distant surroundings of the focal spot on the anode (or housing) (see Figure 2.11). An assessment of the off-focal radiation was also made during preliminary considerations for the parametric studies (see Section 4.2).

Since the X-ray radiation is generated outside the focal spot, it is called off-focal radiation. The greatest proportion of off-focal radiation constitutes the X-ray quanta generated from electrons that are reflected several times between the anode and housing [17]. Depending on the actual
design of the X-ray tube, it is possible to influence the heat distribution to some degree, such as through electrical fields for deflecting, via use of a grounded aperture, for absorbing the emitted electrons, or by using absorbent surfaces in the tube housing. However, a special design solution is not the subject of this study and, therefore, the tube housing with its large heat capacity (typically over one million Heat Units (HU), see also Section 2.5) is therefore not considered further.

Figure 2.11.: Principle of the generation of off-focal radiation on a rotating anode by electrons leaving the anode surface. Backscattered electrons are reaccelerated to the anode outside the focal spot. This causes a low-intensity, widespread radiation distribution pattern. Hotspots outside the focal spot indicate areas where the electrons are more likely to interact. [5]

2.5. The determining physical quantities of heat production and heat capacity

Thermal energy in the focal spot is produced through interaction of the accelerated electrons with the anode medium. Since only a small fraction of the electronic energy is converted in X-radiation, it is ignored in the heat calculations. Assuming that all of the electrical X-ray tube power is converted into heat, in a single exposure, the quantity of heat in Heat Unit (HU) produced in the focal spot is given by Equation 2.4:

\[
\text{Heat Unit} = w \cdot U_{\text{peak}} \cdot I \cdot t
\]  

(2.4)

\(w\): Waveform factor, \(U_{\text{peak}}\): Peak value of \(U\), \(I\): Tube current, \(t\): Operating time

where the product of tube current (\(I\)) and operating time (\(t\)) constitutes the so-called tube current-scantime product (\(Q\)). \(U\) is the effective voltage and \(U_{\text{peak}}\) is the peak value of \(U\). In this relationship, \(w\) is the waveform factor (with the value of 0.71 for single-phase, 0.96 for three-phase current six-pulse and 0.99 for three-phase current 12-pulse); its value is determined by the waveform of the voltage applied to the X-ray tube. Nowadays, the generator for CT systems usually provides a very good constant potential, so that a \(w = 1.0\) can be accepted, as was done throughout this study.
Figure 2.12: Factors that determine the amount of heat production and the three regions of an X-ray tube having specific heat capacities. The figure represents an X-ray therapy tube [27].

The thermal energy generated in the focal spot can be stored temporarily due to the heat capacity of the anode material, because the heat dissipation by external cooling is comparatively slow. In accordance with the operating time and the power demand on the anode, therefore, a sufficient heat capacity must be available.

In science and engineering, it is more convenient to use heat capacity in relation to a unit of mass as specific heat capacity ($c$):

$$c = \frac{E_{th}}{m \cdot \Delta T}$$

(2.5)

\(\Delta E_{th}\): Thermal Energy, \(m\): Mass, \(\Delta T\): Temperature change

In the case of fixed anodes, copper offers itself as the anode support material with the highest specific heat capacity (see Figure 3.3 or Table 3.1). Fixed anodes can also be easily brought into contact with an external cooling medium. This facilitates the transport of heat in the external cooling medium.

In the case of rotating anodes, however, the mass of the anode disc is typically increased to enhance the local heat storage capacity. Nevertheless, in order to prevent a heat-overload on the focal track and preclude the melting of the anode surface as well as prevent vaporization of the anode material, rotating anode tubes are thermally monitored by measuring the radiated temperature (after Equation 2.6) and are temporarily locked for operation on reaching the maximum load. However, the high anode mass restricts the rotational speed in the gantry of modern CT scanners.

The resulting centrifugal forces thereby restrict the rotational speed of the X-ray tube in the gantry. Increasing the local heat storage capacity involves a common procedure – i.e. the increase of the
mass of the rotating anode disc. Another approach provides the design of the rotating envelope tube (see Section 2.3.3), in which the anode disc is directly connected to the metallic tube body. The quantity of heat in this case is transported over the entire surface of the envelope by heat conduction (see also Section 2.7.2). It is directly in contact with the coolant for a rapid transport of heat energy. Since high heat storage is largely unnecessary, it allows a compact and lightweight design of a rotating anode, which benefits the requirements of the CT system with respect to the mechanical stability.

As also indicated in Figure 2.12, in general, one can identify three different regions in the X-ray tubes having different heat capacities. The region with the lowest heat capacity represents the focal spot area. The resulting heat energy flows from there to the anode body or directly via electromagnetic radiation to the surrounding tube envelope, from which an applied cooling system emits the heat energy to the atmosphere. Figure 2.13 illustrates these transport mechanisms (see also Section 2.7) between the heat capacity regions, which are indicated as different-sized containers filled with thermal power $P_{th}$.

![Diagram of heat energy distribution in X-ray tubes](image)

**Figure 2.13.** Schematic illustration of the three critical areas in X-ray tubes with a different mechanism of heat dissipation. When the tube is in operation, heat generally flows into and out of the areas shown. Damage can occur if the heat content of any area exceeds its maximum heat capacity.

### 2.6. Target material

For efficient X-ray generation, a target material of a high atomic number $Z$ is preferred. Owing to the very low absolute efficiency (see Equation 2.2), the thermal properties are of equal impor-
tance. Therefore, a high melting point, along with good thermal conductivity $\lambda$ and high specific heat capacity $c$ are the additional requirements for a target material.

The optimal choice of materials can be shown in the case of a fixed anode for long loading times (see also Section 2.8). There, the value of $Z \cdot \vartheta_{\text{max}} \cdot \lambda$ needs to be as high as possible (with $\vartheta_{\text{max}}$: maximum permissible temperature). In the case of short loading times, it is necessary to maximize the value of $Z \cdot \vartheta_{\text{max}} \cdot \sqrt{\lambda \cdot \rho \cdot c}$.

To prevent degradation of the vacuum tube, the $\vartheta_{\text{max}}$ value is based on a maximum vapour pressure of $1.3 \cdot 10^{-2}$ Pa. As a rule, the maximum permissible temperature in the focal spot should be around 30% lower than the melting point of the target material.

As indicated in Table 2.2, tungsten proves to be the first choice for both short and long loading times. This is because of its high atomic number, its high melting point and its good thermal properties in comparison to other materials with high melting points. However, because of the high thermal conductivity and heat specific capacity of copper, even better performance can be achieved by embedding the tungsten target of an optimized thickness into copper designed in accordance with the thermal performance requirements.

**Table 2.2:** Anodes materials for fixed and rotating anodes [36]

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic number</th>
<th>Permissible temperature $\vartheta_{\text{max}}$ at $1.3 \cdot 10^{-2}$ Pa (K)</th>
<th>Thermal conductivity $\lambda$ (W/cm·K)</th>
<th>Fixed anodes $Z \cdot \vartheta_{\text{max}} \cdot \lambda$</th>
<th>Order of suitability</th>
<th>Rotating anodes $Z \cdot \vartheta_{\text{max}} \cdot \sqrt{\lambda \cdot \rho \cdot c}$</th>
<th>Order of suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>29</td>
<td>1032</td>
<td>3.98</td>
<td>119113</td>
<td>8</td>
<td>3.68</td>
<td>110135</td>
</tr>
<tr>
<td>Mo</td>
<td>42</td>
<td>2167</td>
<td>1.38</td>
<td>125599</td>
<td>7</td>
<td>1.88</td>
<td>171106</td>
</tr>
<tr>
<td>Ag</td>
<td>47</td>
<td>832</td>
<td>4.18</td>
<td>163450</td>
<td>4</td>
<td>3.18</td>
<td>124350</td>
</tr>
<tr>
<td>Ta</td>
<td>73</td>
<td>2587</td>
<td>0.55</td>
<td>103868</td>
<td>9</td>
<td>1.13</td>
<td>213402</td>
</tr>
<tr>
<td>W</td>
<td>74</td>
<td>2757</td>
<td>1.3</td>
<td>265223</td>
<td>1</td>
<td>1.81</td>
<td>369273</td>
</tr>
<tr>
<td>Re</td>
<td>75</td>
<td>2557</td>
<td>0.71</td>
<td>136160</td>
<td>6</td>
<td>1.38</td>
<td>264650</td>
</tr>
<tr>
<td>Os</td>
<td>76</td>
<td>2280</td>
<td>0.87</td>
<td>150754</td>
<td>5</td>
<td>1.77</td>
<td>306706</td>
</tr>
<tr>
<td>Ir</td>
<td>77</td>
<td>2220</td>
<td>1.46</td>
<td>249572</td>
<td>3</td>
<td>2.06</td>
<td>352136</td>
</tr>
<tr>
<td>Pt</td>
<td>78</td>
<td>1742</td>
<td>0.71</td>
<td>96472</td>
<td>10</td>
<td>1.41</td>
<td>191585</td>
</tr>
<tr>
<td>Au</td>
<td>79</td>
<td>(1063)</td>
<td>3.14</td>
<td>263687</td>
<td>2</td>
<td>2.81</td>
<td>235975</td>
</tr>
<tr>
<td>U</td>
<td>92</td>
<td>(1132)</td>
<td>0.25</td>
<td>26036</td>
<td>11</td>
<td>0.75</td>
<td>78108</td>
</tr>
</tbody>
</table>

### 2.7. Heat dissipation

Nearly all the energy applied to the X-ray generation must be released via the tube envelope to the environment in the form of heat. X-ray tubes are typically designed in accordance with the user's specific requirements. High performance X-ray tubes rely on the capacity of all tube envelope
materials to deliver high heat conductivity and a high absorption coefficient for thermal radiation.

2.7.1. Thermal radiation

The transfer of heat is most rapid through thermal radiation in the form of electromagnetic radiation in the infrared and visible light region. The emitted power \( P_{\text{rad}} \) increases with the fourth power of the difference between the temperatures of the anode and the surrounding area (see Equation 2.6). Therefore, thermal radiation is particularly effective in high anode temperatures. Moreover, it is extremely fast, because infrared radiation is emitted at the speed of light. But this transport mechanism fails at low anode temperatures because, in addition to the decrease in radiated power with temperature, the emissivity \( \epsilon(T) \) of the anode surface decreases.

\[
P_{\text{rad}} = A \cdot \sigma_0 \cdot \epsilon(T) \cdot (T_A^4 - T_E^4) \propto (T_A^4 - T_E^4)
\]

\( A \): Radiating surface, \( \sigma_0 \): Stefan Boltzmann constant \( (5.67032 \cdot 10^{-8} \, \text{W} \, \text{m}^{-2} \, \text{K}^{-4}) \),
\( \epsilon(T) \): Emissivity, \( T_A \): Anode temperature, \( T_E \): Environmental temperature

The condition for effective radiation cooling as per Equation 2.6 is a high emissivity \( \epsilon(T) \), a large radiating surface \( A \), a high anode temperature \( T_A \) and a low environmental temperature \( T_E \).

The emission value \( \epsilon(T) \) of pure tungsten anodes is from 0.35 to 0.40. In modern composite rotating anodes, graphite with \( \epsilon(T) = 0.8\ldots0.9 \) is used in the rear. However, a precondition for effective cooling of the anode body is a sufficient heat transfer from the focal spot, and respectively from the focal track, through to the radiating rear end of the anode. [27]

2.7.2. Heat conduction and convection

Heat dissipation in the case of directly cooled tubes (fixed anodes and rotating envelope tubes) is dominated by heat conduction through the solid envelope material. For cooling the focal spot, an effective transport of heat energy into the volume of the anode is necessary. Since substances having a high electric conductivity also have high thermal conductivity, copper serves as a suitable heat transfer medium (see Table 2.2). However, copper has a relatively low melting point as well as insufficient radiation efficiency applied to imaging. Therefore, especially in the target area of fixed anodes, a flat piece of high melting material with good efficiency for the beam production, such as tungsten or molybdenum, is pressed into the surface. In the case of rotating anodes, because of the high mechanical stress of the anode body, the more dimensionally stable molybdenum is also used instead of copper.

The dissipated heat energy per unit of time, power of heat conduction \( P_{\text{cond}} \), at the interface between two substances is proportional to the heat transfer coefficient \( (\alpha) \), the area of contact \( (A) \) and the temperature difference between anode temperature \( (T_A) \) and the temperature of the
environment or coolant \((T_S)\), according to Equation 2.7. In particular, the high heat transfer coefficient and the resulting high cooling capacities can be reached through turbulent coolant flow to the surface of the object that has to be cooled.

\[
P_{\text{cond}} = \alpha \cdot A \cdot (T_A - T_S) \propto (T_A - T_S) \tag{2.7}
\]

\(\alpha\): Heat transfer coefficient, \(A\): Area of contact, \(T_A\): Anode temperature, \(T_S\): Temperature of environment or coolant

Heat convection takes place through the net displacement of a fluid that transports the heat content with its velocity. Convection (especially convective cooling and convective heating) also refers to the heat dissipation from a solid surface to a fluid, which is typically described by the heat transfer coefficient \((\alpha)\), as shown in Equation 2.7. [27]

### 2.8. Analytical description for the thermal load capacity of an X-ray tube anode

The temperature of the focal spot is significantly higher than the temperature of the anode disc. The analytical description of the thermal capacity of X-ray anodes can be attributed mainly to the works of Osterkamp [34, 35] from the year 1948. A clear summary can be found, for example, in Krestel [25] and Morneburg [33]. For orientation purposes, only the most important results of their works should be followed.

#### 2.8.1. Load capacity of stationary/fixed anodes

From the theory for short loading times \((\Delta t < 0.05 \text{ s} \text{ for standard focal spot dimensions})\), the rise in temperature \((\Delta T_{\text{Focus}})\) can be approximated by

\[
\Delta T_{\text{Focus}} = \frac{2 \cdot P_{\text{th}}}{A} \sqrt{\frac{\Delta t}{\pi \cdot \lambda \cdot \rho \cdot c}} \tag{2.8}
\]

\(P_{\text{th}}\): Thermal focal spot power (input), \(A (= 2 \cdot \delta \cdot l)\): Thermal focal spot area, \(\Delta t\): Projection duration, \(\lambda\): Thermal conductivity, \(\rho\): Density, \(c\): Specific heat capacity

The values used in this study for this equation are given in Table 1.1 and Table 3.1. The projection duration \((\Delta t)\) describes the exposure time, in which an initial temperature increase \((\Delta T)\) is expected at a constant thermal power density \((P_{\text{th}})\).

In the case of long loading times, the rise can be approximated by

\[
\Delta T_{\text{Focus}}^* = \frac{P_{\text{th}}}{A} \cdot \frac{D}{\lambda} \tag{2.9}
\]
$P_{th}$: Thermal focal spot power (input), $A (= 2 \cdot \delta \cdot l)$: Thermal focal spot area,
D: Smallest dimension of the focal spot, $\lambda$: Thermal conductivity

In real conditions, especially during very long loading times, the maximum permitted temperature is limited by the tolerable temperature at the boundary between the anode tungsten and copper as well as by the anode’s thermal capacity and the heat dissipation to the surrounding cooling (see also Section 2.7). Furthermore, this description does not take into account the amount of heat that accumulates, as may be the case for a short cooling phase between repetitions. For the comprehensive assessment of a concept, in which, for example, a time-dependent heat transport and cooling capacity should be considered, this analytical description does not seem adequate. This led us to comprehensive computer simulations (see Section 3).

### 2.8.2. Load capacity of rotating anode

In a rotating anode, the thermal energy generated in the focal spot is distributed because of the rotation to the focal track. Figure 2.14 shows the typical geometries of a rotating anode with its thermal areas.

![Figure 2.14: Typical geometries of a rotating anode with an illustration of the focal spot and focal track [36]](image)

While in the case of fixed anodes, the time duration ($\Delta t$) in Equation 2.8 corresponds to the period during which the load is applied, it is necessary to replace this duration in the case of rotating anodes by the time interval of the impacting electron beam in the area of focal spot at one revolution:

$$\Delta t = \frac{2 \cdot \delta}{v} = \frac{\delta}{\pi \cdot f \cdot R} \quad \text{(2.10)}$$

$\delta$: Focal spot half width, $v$: Velocity, $\pi$: Pi, $f$: Anode rotating frequency,
$R$: Focal track radius
The temperature rise at the focal spot for a rotating anode is thus approximated by

\[ \Delta T_{\text{Focus}} = 2 \cdot \frac{P_{\text{th}}}{A} \sqrt{\frac{\delta}{\pi^2 \cdot \lambda \cdot \rho \cdot c \cdot f \cdot R}} \]  

\[ (2.11) \]

\( P_{\text{th}} \): Thermal focal spot power (input), \( A = 2 \cdot \delta \cdot l \): Thermal focal spot area, \( \delta \):
Focal spot half width, \( \pi \): Pi, \( \lambda \): Thermal conductivity, \( \rho \): Density, \( c \): Specific heat capacity, \( f \): Anode rotating frequency, \( R \): Focal track radius

The focal track on the anode target is formed by heating the focal spot area during the rotation. The focal spot area is visible on used targets as a highly roughened circle (see Figure 2.14). The focal track temperature \( T_{\text{Track}} \) increases with the number of revolutions \( n \):

\[ \Delta T_{\text{Track}} = k \cdot T_{\text{Focus}} \cdot \sqrt{\frac{\delta \cdot (n + 1)}{\pi \cdot R}} \]  

\[ (2.12) \]

\( k \): Anode design-dependent factor, \( T_{\text{Focus}} \): Focal spot temperature, \( \delta \): Focal spot half width, \( n \): Number of revolutions during time \( t \), \( \pi \): Pi, \( R \): Focal track radius

The absolute temperature in the focal spot \( (\theta_{\text{Focus}}) \) results from the sum as follows:

\[ \theta_{\text{Focus}} = \theta_{\text{Anode}} + \Delta T_{\text{Track}} + \Delta T_{\text{Focus}} \]  

\[ (2.13) \]

\( \theta_{\text{Anode}} \): Initial temperature of the anode (basic temperature), \( \Delta T_{\text{Track}} \): Focal track temperature (relative), \( \Delta T_{\text{Focus}} \): Focal spot temperature (relative)

The rise in temperature in the focal spot takes place within milliseconds; the temperature equalization between disk and focal track takes the same amount of time. Each of the three quoted temperatures is subject to specific limitations related to the materials and processes used. [36]

Figure 2.15 shows a schematic representation of temperature profile of different rotating anode designs with respect to their operation time.
Figure 2.15: Schematic representation of the temperature profile of a cooled rotating anode of conventional design that is cooled exclusively via radiation cooling compared to the convection cooling (turbulent oil cooling) at a rotating envelope tube, where at sufficient cooling, the focal spot temperature remains even during continuous operation below the critical loading limit for material destruction [27]
3. Material and methods

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3.1. Simulation model of the thermal loads for single anodes

3.1.1. The default 3D simulation model for fixed and rotating anodes

The default simulation model for a single fixed anode in the source ring of FACT is based on the
typical construction of a fixed anode in an X-ray tube (see also Section 2.3.1) and it is modelled
as a sandwich consisting of two materials with high atomic number at the target area and with
high thermal conductivity as the basic function of the body. Towards the focal spot, a tungsten
(W) target layer of 0.5 mm thickness was adjoined, without thermal contact resistance, to a copper
(Cu) square body with a base area of 25 mm by 3.2 mm and a height of 20 mm. At the end of the
copper body height, a heat bath was defined at 300 K for cooling. Away from the heat bath and for
the worst case scenario, a thermal insulation was chosen for all other boundary conditions for the
outer surfaces (see also Figure 3.1 and 3.2).

This fixed anode model was extended to a rotating anode model, analogous to the principle used
for the Reference CT (see Table 1.1). Our model of a rotating anode with a radius of 60 mm had the same sandwich configuration as the fixed anode defined above. The non-conventional use of copper as a base for a rotating disc was considered a usable approximation for theoretical investigations during a short operation time. Using copper for a rotating anode model with its outstanding material property of thermal conductivity also leads to the worst case scenario for FACT, when compared with conventional clinical CTs.

The default simulation models are defined with the optical focal spot \((OFS)\) of 0.7 x 0.9 mm\(^2\). For extensive simulation studies for the fixed anode (see Section 3.3), this was assumed our worst case for the thermal load by choosing the relatively large focal spot for CT at a nominal value \((f)\) of 1.0 (see Table 2.1), which was performed under the designation heat transfer study model. The independence of the focal spot size - as is given in the Osterkamp formulas for fixed anodes (see Section 2.8.1) - was considered in the context of parametric simulation studies (see Section 3.3).

### 3.1.2. Different simulation space dimensions of the heat transfer study model

Generally, the heat transfer study model was used in three dimensions in this study (see Section 3.1.1) in order to stay as close as possible to the real object characteristics. Since the defined fixed anode model is constructed with axial symmetry, the question arises after simulations with reduced dimensions, in order to significantly reduce the degrees of freedom for solving the FEM simulations (see Section 3.1.4) and thereby reduce the computational time.

The computer hardware for simulations consisted of an HP Workstation Z800 with 12 dual core CPU, a clock frequency of 3.3 GHz, and a random-access memory size of 24 Gigabytes. In the heat transfer simulation (see Section 3.1.4) in three dimensions (3D), the solver treated up to 1.5 million degrees of freedom available in simulation time of up to two hours for an investigated projection period. Limits were achieved in this case, the available memory was completely utilised, and the solver did not find a result in every case. From a reduced simulation space dimension, the solver treated reliably in 2D up to 400 thousand degrees of freedom in a simulation time of up to 10 minutes. For only one dimension, it was up to 150 thousand degrees of freedom in less than one minute for an investigated projection period.

For this purpose, the quadratic 3D model for fixed anode was reduced around its height axis to two dimensions (2D) and to one dimension (1D). Figure 3.1 compares the different dimensions of the heat transfer study model for fixed anodes.
Figure 3.1: Comparison of the different dimensions of the heat transfer study model for fixed anodes. The given layer heights of tungsten and copper are each the same. In the one-dimensional (1D) case, the deposited heat energy can only flow in one direction from the focal spot to the heat bath. In the two-dimensional (2D) case, the thermal flow may be considered with a further degree of freedom in the heat transfer simulations (see Section 3.1.4). The anode width is determined by the possible section width for an anode in the X-ray source ring so that the defined number of these fixed anodes can be arranged (see Section 1. Basic concept for FACT). In the three-dimensional (3D) case, the complete three spatial directions are given for the flow of heat. In each case the basic specifications were applied to the focal spot size and cooling.
3.1.3. Energy deposition

The energy deposition of accelerated electrons in the so-called thermal focal spot was determined on the basis of the latest research on particle interactions included in the Monte Carlo simulation GEANT4 [2]. Within the GAMOS framework, rapid access to verified programming routines is provided [1]. All simulations were performed using GAMOS 3.0 by accessing GEANT 4.9.4.p01 (see the basic user code for GAMOS/GEANT4 in Appendix A). The physics of low-energy interactions was described by the Livermore models [6] (also known as EEDL [38] - EPDL [8] models) and tracks were followed down to the production cut length of 10 nm or energy of 1 eV, including rest energy deposition, below which the particles were placed under split in terms of probability. Energy was collected in 1 nm voxels. These voxels were averaged in the lateral extension to have a representative 1D distribution of energy along a relevant penetration depth, which is printed in Figure 4.1 along with its criteria. Thus, a small effect of scattering on field boundaries was eliminated when used only in the central area with half the focal spot width. Preliminary investigations showed that a deeper penetration depth of 8 µm at 80 keV and 12 µm at 120 keV did not give significantly different results in the subsequent FEM applications, although the calculation time increased dramatically.

The trajectories and energy of the emitted particles were registered on the target surface with a so-called PhaseSpace\(^1\) element in the GAMOS/GEANT4 simulation. Based on the differences between the primary energy of the incident electron beam and the energy of the emitted electrons and photons, the relative proportions of deposited energy in the thermal focal spot was calculated (see the basic user code for MATLAB in Appendix B)).

Overall, the deposition of energy in the thermal focal spot on the tungsten target results in an increase in temperature, which can be determined from the solutions of partial differential equations as described in the following section.

3.1.4. Heat transfer

Applying partial differential equations to describe the temperature profile in the X-ray anode from the deposited energy, the finite element method (FEM) was used. The commercial software COMSOL Multiphysics (version 4.3) was applied with the Heat Transfer module for solid interfaces. For FEM simulations, the corresponding temperature-dependent data of material properties given in Table 3.1 were used from the Material Library of COMSOL Multiphysics, which was based on the Material Property Database (MPDB) from JAHM Software\(^2\), and plotted temperature-dependent in Figure 3.3.

The acquired depth energy distribution (see Section 3.1.3) was evenly applied over the thermal

---

\(^1\)https://www-nds.iaea.org/phsp/

\(^2\)http://www.jahm.com
Figure 3.2: 3D simulation model with representation of incident electron beam (e⁻): (a) at the fixed anode model in short intervals with a given projection duration and (b) at the rotating anode model with continuous long-lasting beam. The fixed anode, designed as a square body, was made of copper (Cu) with a base area of 25 mm by 3.2 mm and a height of 20 mm. The tungsten (W) target layer had a material thickness of 0.5 mm. The rotating model used the same construction, but as a cylindrical body with a rotational frequency of 150 Hz and a radius of 60 mm. The thermal focal spot area (A) on the anode surface is formed by the entering electrons of equally distributed intensity. For cooling, a heat bath of 300 K has been defined. The surfaces, except for the heat bath, were considered thermally insulated.

focal spot area (A) and scaled using the relative proportion of deposited energy. Based on a number of simulations, values for the maximum thermal power density \((P_{th}/A)_{max}\) were obtained. This caused an increase in temperature from 300 K to 2500 K within a certain period, which we called the projection duration \((\Delta t)\). Krieger [27] indicated that, due to the vapour pressure of anode material, the favorable operating temperature of an anode is around 70% of its melting temperature (cf. Table 3.1) to obtain a service life at an usual expectation. This led us to the absolute upper temperature limit of 2500 K for the tungsten target layer. According to the printed Table 2.2 is even the permissible temperature at 2757 K for tungsten (W).

Bouwers [3] and Osterkamp [34, 35] carried out fundamental work on the load capacities of X-ray tubes while in operation. We used formulas based on simple modelling assumptions (see Section 2.8) for comparisons with our simulation results. In addition to the initial temperature, which could be estimated from values in the literature, we were interested in heat transport under various conditions in terms of both temporal and spatial resolution. First we considered the default 3D simulation model with an atomic interaction region in the thermal focal spot and with macroscopic dimensions with respect to the basic copper block. The kinetic energy of electrons is mainly deposited in a penetration depth of a few micrometres after entering the target medium of tungsten (see Section 3.1.3). Specifically, a grid of finite elements was adopted for the sampling theorem to restrict the degrees of freedom to a relatively low number when finding a solution.
Figure 3.3: Illustration of the temperature-independent material properties in dashed lines (used for Osterkamp formulas, described in Section 2.8, and Monte Carlo simulations, given in Table 3.1) and temperature-dependent material properties in continuous lines (used for FEM simulations to heat transfer, given in Material Property Database (MPDB) from JAHM Software). The properties of the materials considered, tungsten (W) and copper (Cu), includes (a) thermal conductivity $\lambda$, (b) density $\rho$ and (c) specific heat capacity $c$. 
Table 3.1: Material properties used for Monte Carlo simulations and Osterkamp formulas

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Specification</th>
<th>Tungsten (W)</th>
<th>Copper (Cu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ</td>
<td>Thermal conductivity</td>
<td>170 W m(^{-1})K(^{-1})</td>
<td>400 W m(^{-1})K(^{-1})</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>19.25 g cm(^{-3})</td>
<td>8.92 g cm(^{-3})</td>
</tr>
<tr>
<td>c</td>
<td>Specific heat capacity</td>
<td>138 J kg(^{-1})K(^{-1})</td>
<td>385 J kg(^{-1})K(^{-1})</td>
</tr>
</tbody>
</table>

Melting point of W is used for 3695 K and of Cu is used for 1358 K

3.2. Off-focal charged particle tracing

To assess the significance of the charged particles (e\(^-\)) escaping over the anode surface into the vacuum space, these particles were tracked under the influence of an electrostatic field. For this purpose, the COMSOL module Charged Particle Tracing was used for simulation.

The initial values for the escaping electrons constitute the three-dimensional velocity vector (including the direction and energy) taken from the PhaceSpace container in the Monte Carlo simulation (see Section 3.1.3). The counteracted electromagnetic field, which is applied within an X-ray tube that is operated to accelerate the electrons between the cathode and anode, is modelled in this study as a simple cylindrical structure based on possible X-ray tube distances. Since we do not commit ourselves to an exact tube design in this study, we consider only the first trajectory in a simple electrostatic field between the cathode and anode. Thus, this has neglected the influence of a focusing potential field and the presence of a cup-shaped electron capture hood (see Section 2.3.1).

The following specifications for this analysis were determined:

- Definition of the simulation structure: An electrostatic field was created between two rounded electrodes with a radius of 100 mm and distance of 60 mm between the parallel plane surfaces with a potential difference of 80 keV or 120 keV. The medium in between is defined as air at a temperature of 300 K and a pressure of 1.3E-2 Pa.

- Definition of the electrons: Charge number \(Z = -1\), relativistic electron mass and a number of 10,000 representative particles that initially started equidistant to each other from a thermal focal spot area with the nominal value \(f\) of 1.0 (see Table 2.1) localized centrally at the round anode plate surface.

The mathematical interface of COMSOL makes it possible to solve arbitrary ordinary differential equations. The particle position is always computed using Newton’s second law: \(\frac{d}{dt}(m \cdot v) = F\). A report for the prepared user program can be found in Appendix C.
3.3. Parametric simulation studies for thermal loads of single fixed anodes

To identify influences on the choice of modelling parameters and possibilities for optimization, a parameter study was performed for the single fixed anode. The default model was represented by the heat transfer study model. The following model parameters were considered in the range that appeared technically feasible:

- **Height of copper body**: The default model used 20 mm. To investigate mainly the impact of lower heat storage capacity, the following material thicknesses were also used: 10 mm, 5.0 mm, 2.0 mm. An extension of this study was conducted by a distinction between the tube voltages of 80 kV and 120 kV, as well as the simulation space dimensions 1D, 2D and 3D.

With priority on the thermal feasibility of a novel CT with Fixed Anodes (FACT), the following parametric simulation studies were carried out only for electrons that are incident at an acceleration of 120 kV. In addition, the volume of data and the simulation times in this study were reduced to an attractive level by a restriction to the simulation of two dimensions:

- **Height of tungsten target**: The default model uses 0.5 mm. In order to evaluate the influence that different manufacturers have, the target layer thickness was varied in both directions: 0.1 mm, 1.0 mm and 2.0 mm.

- **Focal spot size**: Starting from the relatively large focal spot size for CT with the nominal value \( f \) (see Table 2.1) of 1.0 (used in the default model), a reduction in spatial extent was implemented. In addition to \( f \) of 0.5 and 0.1, the above-defined \( OFS \) of 0.7 x 0.9 mm\(^2\) (see Table 1.1) was studied and applied for comparing the CT concepts.

- **Material property**: A visualization of the specified material properties can be found in Figure 3.3. As can be seen from the Osterkamp formula (see Equation 2.8), a slight irregularity in the material composition can be simulated by a variation of different material parameters. Based on this, similar relation with +10% or -10% were chosen for each of the three given material parameters by the factor \( dM \) of 1.1 and 0.9, no matter whether it was temperature-independent or temperature-dependent: \( dM \cdot \rho(T) \), \( dM \cdot \lambda(T) \) and \( dM \cdot c(T) \).

- **Cooling mechanism**: Standard conditions were the thermal isolated boundaries that form the outer surface of the fixed-anodes model and the constant head bath of 300 K at the distal end of the copper block. On the one hand, this simple model has been extended to a natural thermal radiation on the target surface to a constant ambient temperature of 300 K to observe
the influence of additional heat dissipation. On the other hand, starting from the standard condition, the defined heat bath was replaced by the mathematical approach for convection cooling using a coolant with a temperature of 300 K and a relatively slow flow rate of 1 m/s to observe the worst heat outflow condition.

3.4. The virtual model with fixed anodes for computed tomography (FACT)

The basic concept for CT with fixed anodes (FACT) was introduced in Section 1. At the beginning of this section, there is a description of the simulation model and the studies of the thermal loads for fixed anodes, which can serve as an independent module for a source ring for the FACT. A virtual model was created to estimate the potential performance of a FACT from the thermal study model. For this purpose, a comparison with the previously introduced Reference CT is performed.

3.4.1. Power and timing for a single anode and the X-ray source ring

![Graph showing operating times for a single fixed anode and for a source ring with 1160 fixed anodes.](image)

Figure 3.4.: Operating times for a single fixed anode and for a source ring with 1160 fixed anodes. \((P_{th}/A)_{max}\) was determined by the power factor \((\eta)\), see Equation 3.5). (a) Illustration showing a projection duration \((\Delta t)\) of 10 µs. The repetition frequency is 78.4 Hz. (b) Each fixed anode in the source ring operates with the same given repetition frequency i.e. the gantry rounds amount to 78.41/s. In this case, a beam pause \((t')\) of 1 µs was used between the projections of different single anodes of the X-ray source ring in which no source activity is present.

During the cooling phase for a single thermally isolated fixed anode, the other identical anodes in the source ring operate equally in succession. The electron beam cannot be instantaneously
switched between anodes. To qualitatively incorporate technically required operations—such as rise and fall phases during the pulsed operation of X-ray sources—a beam pause \((t')\) was incorporated, which can be introduced between two projections. The simulation environment for a single anode was also used to study the performance of an entire ring of anodes, as required with FACT.

Based on intermediate results, we considered various beam pauses \((t')\) of 0 µs, 1 µs, 3 µs, and 5 µs. Figure 3.4 (b) presents an example of the operating time for a source ring with 1160 fixed anodes. The indicated projection duration \((\Delta t)\) for each single fixed anode was 10 µs. With a beam pause \((t')\) of 1 µs, the temporally possible repetition frequency at a single fixed anode (i.e. gantry rounds per second) was 78.4 Hz.

To achieve the expected image quality within a typical scanning time, the question arose whether FACT could provide the necessary number of superpositions for a projection direction. Superpositions were necessary, because the projection duration \((\Delta t)\) of FACT was approximately only 1/20 as compared with that of the Reference CT. With about the same \((P_{th}/A)_{\text{max}}\), an equal amount of total energy was emitted after 20 projections for the same direction, as with the Reference CT. Thus, it was possible to acquire the same information on the detector to obtain equivalent image quality. Therefore, we concluded that a fixed detector ring could acquire equivalent information relative to the detector of a third-generation CT. In this theoretical approach, it was assumed that detection is independent of the readout rate.

Under identical conditions, the photon spectra and fluence \((\Psi_{ph})\) for both fixed and rotating anode technologies were equal in the first approximation and proportional to the deposited thermal energy \((E_{th})\):

\[
\Psi_{ph} \propto E_{th} \quad (3.1)
\]

Assuming a known deposition of energy, it was thus possible to determine image quality, provided that only the nature of the energy deposition differs between systems. As a reference, we used a conventional CT with a constant \((P_{th}/A)_{\text{const}}\) (see Table 1.1) for an unlimited operation time \((t_{operation})\). The thermal energy in the FACT source ring for a single round was determined by the number of rectangular pulses \((N)\) with a fixed projection duration \((\Delta t)\). The following definition of \(n_{\text{min}}\) gives the theoretical minimum number of rounds from the ratio of the thermal focal spot energies within any operation time \((t_{operation} = N \cdot (\Delta t + t'))\) under the assumption of a 300 K initial anode temperature at FACT:

\[
n_{\text{min}} = \frac{[(P_{th}/A)_{\text{const}} \cdot t_{operation}]_{\text{CT}}}{[(P_{th}/A)_{\text{max}} \cdot \Delta t \cdot N]_{\text{FACT}}} \quad (3.2)
\]

A possible remaining residual heat from previous pulses in a single anode is not taken into account in Equation (3.2). Thus, mathematically, an infinite cooling phase for FACT is assumed between
source activities after each round. For exact consideration of finite cooling phases between the source activities at a possible round frequency, \((P_{th}/A)_{max}\) is reduced, as a result of the residual heat in the anode.

For this, we investigated the potential order of temporal sequences \((\Delta t + t')\) for the source ring operating in pulsed mode. Values for the round frequency \(f_{\text{possible}}\) of successively active sources in the source ring were determined for various possible timings using the following equation:

\[
f_{\text{possible}} = \frac{1}{N \cdot (\Delta t + t')}
\] (3.3)

In addition to such theoretical investigations, we considered technical feasibility, exploring the maximum operating frequencies achievable for a limited range of realizable specifications. We determined the limited round frequency \(f_{\text{limited}}\) to be restricted to a maximum operating frequency \(\kappa\):

\[
f_{\text{limited}} = \begin{cases} \kappa, & \text{for } f_{\text{possible}} > \kappa \\ f_{\text{possible}}, & \text{else} \end{cases}
\] (3.4)

Based on our intermediate results, we suggest 60 Hz as a lower limit for the operating frequency – i.e., \(\kappa_1 = 60\) Hz – and a further limit of \(\kappa_2 = 100\) Hz with respect to the high dataflow from the detector ring to a CPU (cf. Figure 5.2).

During a pulsed operation, the maximum temperature of Cu (cf. Figure 4.14) can increase as a function of the duration of the cooling phase. To account for a finite cooling phase, during which the temperature of the anode does not reach 300 K, we defined the scaling factor \(\eta\) for \((P_{th}/A)_{max}\) to prevent the maximum temperature of 2500 K in the tungsten target layer during a long-time operation in pulsed mode (cf. Section 4.4.1):

\[
\left[\left(P'_{th}/A\right)_{max}\right]_{\text{FACT}} = \left[\eta \cdot \left(P_{th}/A\right)_{max}\right]_{\text{FACT}}
\] (3.5)

### 3.4.2. Relative Performance (RP) of FACT with regard to a Reference CT representing a typical clinical CT

With the ratio between the thermal loads of FACT and the Reference CT was introduced an assessment factor, Relative Performance (RP), as follows:

\[
RP = \frac{\left[P'_{th}/A\right]_{max} \cdot \Delta t \cdot N \cdot f}{\left[(P_{th}/A)_{\text{const}}\right]_{CT}}
\] (3.6)

with reference to Equations 3.2 – 3.5 and \((P'_{th}/A)_{max}\) (see Equation 3.5) for pulsed operation at a given round frequency \(f\).
3.4.3. Medical Imaging

Image reconstruction using FACT is based on the same fundamentals used in conventional CT [21]. While using a spiral scan, it is known that spatial resolution and image quality are determined by z-filtering/z-interpolation during pre-processing. Alternatively, this information can be combined during post-processing by interpolating the reconstructed images (cf. Figure 1.1 (d)). As previously indicated, the FACT concept uses the principle of superposition, which can be illustrated with a CT image reconstruction (see Figure 4.18). For this purpose, permission was obtained to use the reconstruction library of the Institute of Medical Physics, University Erlangen-Nürnberg, Germany. The parameters for simulation were closely linked to SOMATOM Definitions, Siemens Medical Solutions, Forchheim, Germany, which formed the basis for the defined Reference CT (see Table 1.1) in this study.

The dependence of image quality was discussed in a previous paper, in which a dose-weighted contrast-to-noise ratio (CNRD) [22] was chosen as the criterion for image quality optimization. The standard deviation ($SD$) in the image plane was used as a surrogate for what the signal noise would be for $n$ number of rounds:

$$SD = \sqrt{\frac{1}{M-1} \sum_{i=1}^{M} (\xi_i - \bar{\xi})^2} \propto \frac{1}{\sqrt{Q}} = \frac{1}{\sqrt{I \cdot N \cdot \Delta t \cdot n}} \quad (3.7)$$

$SD$ was determined from $M$ pixel values ($\xi_i$) in a region of interest (ROI) in a homogeneous image section with respect to their mean value ($\bar{\xi}$). Equation 3.7 gives the well-known proportion to the tube current-scan time product ($Q$).

The question of a quantitative improvement in image sharpness due to a sharp focus on a fixed anode is not answered in this work. The same extension of focal spot width in relation to the blurred focus in CT is included in the following boundary value analysis.

3.4.4. Boundary value analysis of operating times

In contrast to conventional CT using rotating X-ray tubes, no blurring of the optical focal spot ($OFS$, see Table 1.1) occurs with FACT, which is an advantage for image sharpness. In practice with conventional CT with specifications used for the Reference CT, due to rotational movement during scanning, the $OFS$ blurs to a factor of 4.6 ($= \text{integration over blurred focal spot width/focal spot width} = 3.2 \, \text{mm} / 0.7 \, \text{mm}$) in each integrated projection direction. If one follows this expansion with FACT, the result is an $OFS^+$ and an $A^+$. These values are listed in Table 3.2.

This application of boundary value analysis corresponds to a successive distribution of the thermal load on an entire body source ring.
Table 3.2: Further specifications used for FACT and the Reference CT

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Specification</th>
<th>FACT</th>
<th>Reference CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$OFS^+$ (represents a modified OFS)</td>
<td>$OFS$ including blurring</td>
<td>$3.2^a \times 0.9 \text{ mm}^2$</td>
<td>$3.2^b \times 0.9 \text{ mm}^2$</td>
</tr>
<tr>
<td>$A^+$ (represents a modified A)</td>
<td>$A$ corresponding to blurring</td>
<td>$27.6 \text{ mm}^2$</td>
<td>$6 \text{ mm}^2$</td>
</tr>
</tbody>
</table>

$^a$ Focal spot width corresponding to blurring

$^b$ Blurring assumed from the rotational movement during the detection
4. Results

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4.1. Simulation model of the thermal loads for single anodes

Applying the 3D simulation model described in Section 3.1.1, Monte Carlo simulations (see Section 3.1.3) were used with an incident electron beam within the thermal focal spot area (A) defined in Table 1.1. Simulations used for heat transfer in the X-ray target are described in Section 3.1.4. The results of the energy deposition in a focal spot, and the quality and quantity of the emitted photons and electrons, are shown in the following sections.
4.1.1. Energy deposition

With use of Monte Carlo simulation, the energy deposition in the tungsten target could be determined. Section 2.2 provides a common description of the forms of interactions of charged particles with matter. The frame description of the Monte Carlo routines is given in Section 3.1.3. The basic user code for GAMOS/GEANT4 is printed in the Appendix A.

In addition to the defined material properties (see Table 3.1), the density of tungsten and copper in the Monte Carlo simulation has also been multiplied by a factor of 0.9 and 1.1 as preliminary work for parametric simulation studies (introduced in Section 3.3). In addition to the simulations for electron energies of 120 keV, these were also performed for 80 keV.

Figure 4.1 shows the deposited energy in the central area of the focal spot. The basic user code for MATLAB for the evaluation of the deposited energy with the PhaseSpace container out of the Monte Carlo simulation is printed in Appendix B. As an exit condition for the registration of the maximum depth, the drop under 0.1 percent of maximum deposited energy ($E_{max}$) was used. For the initial electron energy at 80 keV, it resulted in a maximum depth of 8 nm and at 120 keV it resulted in a maximum depth of 12 nm. The maximum of the energy deposition at 80 keV is $1.4E+16 \, \text{W/m}^3$ and for 120 keV it is $7.9E+15 \, \text{W/m}^3$. In all cases, no relevant difference between the various material densities was found in regard to the use as initial values for FEM simulations.

The results from the parametric simulation studies regarding the material properties are shown in Section 4.3.4.

In addition to the energy deposition, an escape of energy over the anode surface is observed.

For this purpose, the PhaseSpace container has been read and evaluated. Further results for the energy deposition in the target and the energy carried out with their proportions in the escaped particles can be found in Table 4.1.
Table 4.1: GAMOS results out of $10^6$ particles in the Monte Carlo simulation

<table>
<thead>
<tr>
<th>$E_{\text{Primary}}$ of $e^-$ (keV)</th>
<th>Target</th>
<th>$E_{\text{PhaseSpace}}$ of $E_{\text{Primary}}$ (%)</th>
<th>$E_{e^-}$ of $E_{\text{PhaseSpace}}$ (%)</th>
<th>$E_{\text{ph}}$ of $E_{\text{PhaseSpace}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>0.9</td>
<td>-0.434</td>
<td>50.3</td>
<td>99.6</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>-0.414</td>
<td>49.2</td>
<td>99.6</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>-0.404</td>
<td>49.0</td>
<td>99.6</td>
</tr>
<tr>
<td>120</td>
<td>0.9</td>
<td>-0.775</td>
<td>51.3</td>
<td>99.6</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>-0.755</td>
<td>50.8</td>
<td>99.6</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>-0.705</td>
<td>49.6</td>
<td>99.6</td>
</tr>
</tbody>
</table>

The evaluation was made for the primary electron energies ($E_{\text{Primary}}$) of 80 keV and 120 keV. Table 4.1 shows the amount of energy detected at the anode surface. This was around 50% in relation to $E_{\text{Primary}}$. The escaped energy dominates with a proportion of 99.6% by electrons. An estimate of the electrons that are falling back, with impact on the focal spot performance, is carried out in the following Section 4.2. The carried energy of the X-ray photons with a percentage of 0.2% in relation to the primary energy ($E_{\text{Primary}}$) is used in this study as a negligible quantity for the physical assessment of the thermal load capacity of a X-ray tube. Since the remaining energy in the anode does not contribute, it was considered as if it is completely responsible for the temperature increase in the focal spot referred to as thermal energy ($E_{\text{th}}$).

Following this reasoning, Equation 4.1 gives the approximative relationship that applies to thermal focal spot power ($P_{th}$), and electrical X-ray tube power ($P_{el}$) as primary power of the accelerated electrons:

$$P_{th} = \frac{P_{el}}{2} \quad (4.1)$$

$P_{el}$: Electrical X-ray tube power, $P_{th}$: Thermal focal spot power

Loehr’s work [30] agrees with the Equation 4.1 for an impact angle close to the right angle to the target surface, as considered in this study at 84°, which represents an anode angle of 6°.

4.1.2. Heat transfer

In Figure 3.1, the heat transfer study model was presented in each simulation space dimension (1D, 2D and 3D) with its geometry and focal spot size. Figure 4.2 shows, in relation to this, the temperature distribution as an example for a projection period of 10 µs.

In addition to the actual observations for a fixed anode, simulations were also performed for the rotating anode to explain the thermal load capacity of different anode designs. Figure 4.3 shows
the different 3D simulation models (see Figure 3.1.4) and typical trajectories of the particles as well as the simulation results for temperature distribution after ten seconds of operation. The maximum temperature in the copper block of the fixed anode did not reach 500 K, whereas, in the rotating anode, a temperature of 1000 K has been exceeded. The value of the heat content shows that the rotating anode is charged 1000 times higher than a fixed anode at the given operating point within the concept of FACT.

Figure 4.2.: Temperature distributions for the different simulation space dimension (1D, 2D and 3D) for fixed anodes as an example for a projection period of 10 µs

Figure 4.3.: 3D simulation model of (a) fixed anode and (b) rotating anode along with the temperature distribution after ten seconds of operation using the maximum possible electrical X-ray tube power ($P_{el}$) which was set for each projection. Both models are also described in Figure 3.2. The trajectories of the emitted charged electrons ($e^-$) are indicated based on simulation results in conjunction with a static electromagnetic field between the cathode and the anode. For reasons of comparability, an exact tube design was not pursued. However, a study of these trajectories (with COMSOL Multiphysics) showed that the reflected electrons directed their energy away from the thermal focal spot in a first approximation after multiple uniform reflections over the relatively large interior surfaces of the X-ray vacuum tube. The re-entry energy was neglected in our simulations, as this would have resulted in a small increase in background temperature.

Figure 4.4 (a) shows values of the thermal focal spot power density ($P_{th}/A$) for various projection...
durations for the 3D fixed anode model and independent of time for the 3D rotating anode model as well as for the Reference CT. From the FEM simulations result the \((P_{th}/A)_{max}\), which caused a temperature increase from 300 K to 2500 K at the fixed anode in a given projection duration \((\Delta t)\) from 0.001 ms to 1000 ms. In comparison, the results from the Osterkamp formulas (Equation 2.8 and Equation 2.9) were plotted using Table 1.1 and the material properties from Table 3.1. The value from the FEM simulations of the rotating anode with a load limit at ten seconds of 8 kW/mm\(^2\) and the value of the Reference CT, \((P_{th}/A)_{const} = 8.6\) kW/mm\(^2\), were projected, independent of time, onto this figure to facilitate direct comparisons, especially with \((P_{th}/A)_{max}\) from a 3D fixed anode model.

Figure 4.4 (b) shows the relative deviation of the thermal focal spot power density \((P_{th}/A)\) at the fixed anode between FEM simulation and the Osterkamp formulas. It shows a relatively good correlation, particularly near the projection duration \((\Delta t)\) of 10 \(\mu\)s. This projection duration value is also highlighted in the following sections, as it represents the optimum operating range for FACT, particularly with regard to \(RP\) (cf. Figure 4.17).

![Figure 4.4: (a) Thermal focal spot power density \((P_{th}/A)\) of various projection durations for the 3D fixed anode model and independent of time for the 3D rotating anode model as well as for the Reference CT. (b) Relative deviation of \(P_{th}/A\) at the fixed anode between FEM simulation and the Osterkamp formulas.](image-url)
4.2. Off-focal charged particle tracing

Figure 4.5: Graphical representation of the detected particle properties in the Monte Carlo simulation when exiting the surface of the anode. The left column shows the photons and the right column the electrons in each case with a primary energy of 80 keV and 120 keV of the incident electrons. Graphics (c) and (d) show the relative energy of the escaped particles with respect to the angle to the surface normal for the anode angle of 6°. The graphs in (e) and (f) for the angle about the direction of the surface normal in each case shows a random distribution of energy, as expected.

In relation to the primary energy of the accelerated electrons, the photons barely carry the energy from the anode surface (see also Table 4.1) and the trajectory is not influenced by the electromagnetic field between cathode and anode. Hence, they usually interact at large distances from the focal spot. If their energy is again incident on the focal spot after reflection or via generation of secondary electrons, this is more in the negligible range for the assessment of the load capacity of FACT, especially in direct comparison with the Reference CT, basically at the same conditions for its rotating anode (see also Figure 4.3).

Figure 4.5 shows the particle properties in the Monte Carlo simulation that are detected when exiting the surface of the anode. Besides, from the literature, it is well-known that energy (a) and
directional distribution (c) of the X-ray photons with no preferred direction in the radial orientation (e) were right-sided compared in the figure depicting the electrons (b,c,f). It can be seen from the spectral energy distribution of the electrons (b) that the large part is close to the primary energy of the incident electrons. The direction distribution (d) shows that a large proportion of the electron energy starts from the surface normal at an angle between 30° and 55°, with no preferred direction in the radial orientation (f).

The tracing of the trajectory of charged particles with electron properties and the electron energy, representative for the focal spot location (see Section 3.2), provides the following kinetic energy distribution of the electrons when they drop back to the anode. Figure 4.6 shows in a first approximation a linear increase in energy with increasing radius up to the edge of the circular anode surface (with radius of 100 mm). Other interactions caused by these incident electrons are not followed up, especially because the design of the anode has an influence on the result, which was not covered by this study. Based on discussions with developers of X-ray tubes, it can be assumed that there is a uniform energy deposition in the enveloped tube in a first approximation. The influence of the electrons flying around to the temperature in the focal spot is thus scaled by the ratio of the focal spot area on to the internal impact tube surface, provided there is a sufficiently high cooling efficiency. Owing to the undetermined tube design in this study, an investigation into the energy deposition for multiple scattering (“ping-pong” simulation) has been omitted.

![Figure 4.6:](image)

**Figure 4.6:** Kinetic energy distribution after racing the first flight of the emitted electrons, which are dropping back to the anode inside the electro-magnetic field. For this purpose, a simple model described in Section 3.2 is used.

### 4.3. Parametric simulation studies for thermal loads of single fixed anodes

Figure 4.4 shows $(P_{th}/A)_{max}$ from the heat transfer study in 3D compared to the result from the applied Osterkamp formula (see Section 2.8) for projection durations from 0.001 ms to 1000 ms. In the following subsections, the results of the parametric simulation studies were plotted with the
definition of the parameters, which can be found in Section 3.3. For this purpose, the different projection durations were considered from 0.001 ms to 50 ms, which facilitates comparison with the Osterkamp formula for short loading times (see Equation 2.8). This was of interest with regard to the novel concept of CT and was shown in relative deviation (in %) from Figures 4.7 to 4.12.

### 4.3.1. Different heights of the copper body at 120 kV and 80 kV and at different simulation space dimensions (3D, 2D, 1D)

Figures 4.7 (a)-(f) show the relative deviation for different heights of the copper (Cu) body with differentiation in the tube voltage (U) of 120 kV (left) and of 80 kV (right) as well in the simulation space dimension of 3D (bottom), 2D (middle) and 1D (top). Slight differences were seen due to the tube voltage in simplified description below a projection time of 0.01 ms and above 10 ms. A summary of the simulation space dimensions from Figure 4.7 was presented in the following Figure 4.8 for the basic heat transfer study model. The 3D simulations showed between 2D and 1D a deviation at projection durations of less than 0.1 ms. This deviation could be explained by a difference in the internal modelling of COMSOL between space dimensions. Using symmetric conditions (for 2D and 1D) apparently reduced the lateral heat capacity of the focal spot volume at short loads. When using symmetric conditions for 2D and 1D, the degrees of freedom are reduced. Thereby, apparently, the heat capacity of the focal spot volume was poorly represented in short loads. A comparable phenomenon was seen in longer projection durations ($\Delta t > 1$ ms) for the 1D model. Here, only one direction of the heat flow is available and lateral pathways cannot be considered. In the middle range ($0.1$ ms < $\Delta t < 1$ ms) for short loading times, however, a good match with each other was found for the different simulation space dimensions.

### 4.3.2. Different heights of the tungsten target layer at 120 kV and 2D

This and the following studies were carried out only for a tube voltage of 120 kV and for 2D. Analogous to the modification of the copper (Cu) body height (cf. Section 4.3.1), the height of the tungsten (W) target layer was also modified. Figure 4.9 shows the relative deviation with respect to the Osterkamp formula for the default heat transfer study model (W:0.5 mm) for an extremely thin (W:0.1 mm) and two thicker layers (W:1.0 mm and W:2.0 mm). At low projection durations, no clear difference could be seen based on the thickness of the layer. From a projection duration of $\Delta t > 0.1$ ms, differences became apparent due to the reduction of heat accumulation: the thinner the tungsten (W) layer, the higher the $(P_{th}/A)_{max}$. 
Figure 4.7: Relative deviation with respect to the Osterkamp formula for different heights of the copper (Cu) body with differentiation in the tube voltage (left) of 120 kV and (right) of 80 kV as well as in the simulation space dimension of 1D (a and b), 2D (c and d) and 3D (e and f).
4.3.3. Different sizes of the focal spot at 120 kV and 2D

The results from the above consideration of different target layers showed a similar pattern in the relative deviation, as in Figure 4.10 at different focal spot sizes. At low projection durations of $\Delta t < 0.1$ ms, no difference on the basis of the focal spot size could be seen. It was only here that the independence of the focal spot size ($A$) in the Osterkamp formula (see Equation 2.8 – 2.11) could be confirmed. From a projection duration of $\Delta t > 0.1$ ms, differences became apparent due to the reduction of heat accumulation: the smaller the focal spot size, the higher the $(P_{th}/A)_{max}$.

4.3.4. Variation in the material properties at 120 kV and 2D

To obtain an impression of material errors or irregularities in the composition, as they might occur in reality, the three material parameters (shown in Figure 3.3) for the tungsten (W) target layer were changed for the worst case of the combination. For this purpose, the respective material parameters were all adjusted in the same sense upwards by the factor $dM$ of 1.1 or downwards.
Figure 4.10.: Relative deviation with respect to the Osterkamp formula for different sizes of the focal spot by the factor $dM$ of 0.9. Figure 4.11 shows the relative deviations from the Osterkamp formula. The Osterkamp formula with $dM = 1.1$ and with $dM = 0.9$ shows a 14% higher and a 16% lower values for $(P_{th}/A)_{max}$ as at $dM = 1.0$. The results for simulations showed similar deviations to each other as for the Osterkamp formulas.

Figure 4.11.: Relative deviation for the Osterkamp formula and for the heat transfer study model with variation in the material properties using the factor $dM$ of 0.9, 1.0 and 1.1

4.3.5. Different boundary condition/cooling mechanism at 120 kV and at 2D

In addition to the basic heat transfer study model with its defined isolation and cooling via heat bath at 300 K, two more complex simulations were carried out to ensure the real conditions in further details. The results of this are compared in Figure 4.12. The results showed no relevant difference to the assumptions of the basic heat transfer study model for the considered short loading times.
**Figure 4.12.**: Relative deviation with respect to the Osterkamp formula for the basic heat transfer study model and with changes in the cooling mechanism

### 4.3.6. Summary of parametric simulation studies

The parametric simulation studies were carried out in an interactive forward direction at high simulation volume. Due to the comparable results out from the differentiation of typical tube voltages ($U$ of 80 kV and 120 kV, see Section 4.3.1) for CT, no significant differences were expected in the further parametric simulation studies. Thus, the following simulations were reduced to $U$ of 120 kV, which is often used in clinical operation for CT. Moreover, since the 2D simulations reflect the character of this study, to take the worst case especially for low projection durations, it was also possible to rely on simulations with significantly fewer degrees of freedom while maintaining the lateral heat flow, particularly for higher projection durations of the short loading times. In the wide range from $\Delta t > 0.004$ ms to $\Delta t < 6$ ms were the values for $(P_{th}/A)_{max}$ from the simulations below the values calculated from the Osterkamp formula for short loading time. The simulations showed therein an overestimation of up to 17% in the calculations resulting from the Osterkamp formula.

In summary, Figure 4.13 showed the minimum and maximum curves that will provide the above-mentioned parametric simulation studies with the range of results for the maximum thermal focal spot power density $(P_{th}/A)_{max}$. In addition to the result range from the simulations, the result from then Osterkamp formula for short loading times were shown. In addition, the line from the Osterkamp formula for short loading times were shown. It can be seen that the results from the parametric simulation studies encompass the expectations from the literature.

Osterkamp’s formulas can be found even as an analytical description for the thermal load capacity in X-ray tube anodes (see also Section 2.8). Modern computer systems, however, enable studying complex configurations and operating procedures. The simulation modelling was also verified to be sufficiently considered based on data from the literature for short loading times. In the following consideration for the FACT, the proven study model was used unchanged. A parameter variation
was omitted here, since it is assumed that equivalent conditions exist in direct comparison with a common CT.

![Graph](image_url)

**Figure 4.13.** The range of results from parametric simulation studies for maximum thermal focal spot power density \((P_{th}/A)_{max}\) that caused a temperature increase from 300 K to 2500 K during a certain projection duration \((\Delta t)\). In addition to the maximum and minimum overall simulation results, the lines from the Osterkamp formula for short loading times were shown.

### 4.4. The virtual model with fixed anodes for computed tomography (FACT)

#### 4.4.1. Power and timing for a single anode and the X-ray source ring

The simulations performed above for the heat transfer study model of fixed anodes described one target module of the source ring of FACT without neighbourhood influence. Studies of repeated pulsed loads showed that, at fixed anodes, a pulsed operation could have an unlimited time frame.

As representative results of our simulations at projection durations of 1 µs, Figure 4.14 showed the FEM simulation results for the maximum temperatures in the anode medium resulting from pulsed long-time operations with a repetition frequency of 78.4 Hz (see Figure 3.4). Here, after a pulsed operation time of around six seconds, the maximum temperature in the tungsten target reached a plateau of 2500 K (± 0.5 %), whereas the maximum temperature in the adjoining copper block did not exceed 500 K (see Figure 4.15 (b)). The constant power factor, \(\eta\), had a value of 0.915 (see Figure 4.15 (a)).

Figure 4.15 showed the simulation results for (a) the power factor \(\eta\) and (b) the maximum temperature of the copper block using various projection durations \((\Delta t)\). The power factor \(\eta\) was close to 1 at low gantry rounds because sufficient time passes to the next activity at each single anode. In this case, the copper block could hardly accumulate heat energy due to the relatively small thermal focal spot power \((P_{th}, \text{see Figure 4.4})\) per pulse as well as the long cooling phase between the
Figure 4.14.: Example of a temperature profile during pulsed operation of a fixed anode. The maximum temperature in the tungsten (W) target was 2500 K (± 0.5 %). In the copper (Cu) block, the maximum temperature did not reach 500 K. A time-unlimited operation was assumed, based on the plateau for the maximum temperatures in the medium of a fixed anode.

The shorter the projection durations the higher was $P_{th}$ and the initial temperature in the anode increased due to accumulated heat energy from previous pulses. The different cases of various beam pauses ($t'$) and the restriction to a maximum operating frequency ($\kappa$) became apparent at projection durations of $\Delta t < 0.8$ ms. The corresponding gantry rounds per second are plotted in Figure 4.16.

Figure 4.15.: Operating results for (a) power factor $\eta$ and (b) maximum temperature of a copper block. The gantry rounds correspond to the possible, and possible but limited, gantry rounds from Figure 4.16. For the allowed temperature of copper (Cu) 1032 K could be used, as given in Table 2.2.

The feature of time-unlimited operation at one fixed anode was transferred to a circular array of fixed anodes, which are addressed in succession below. This led to the concept of FACT. These results are described below.

The results from Equations 3.2 – 3.4 are plotted in Figure 4.16 for the given beam pauses ($t'$) using three different settings of round frequency (no limitation, limitation at 100 Hz and at 60 Hz). For comparisons, reference gantry rounds of 3.33 1/s are projected independent of $\Delta t$. A duration
of 0.26 ms from a projection direction of the Reference CT is marked. \( f_{\text{possible}}(\Delta t = 10 \mu s) \) is indicated by an arrow.

**4.4.2. Relative Performance (RP) of FACT with regard to a Reference CT**

represents a typical clinical CT.

In Equation 3.6, Relative Performance \((RP)\) was defined to show the relationship between FACT and the Reference CT from the perspective of possible source performance.

Figure 4.17 showed the \( RP \) curves for the given projection durations \((\Delta t)\) and the beam pauses \((t')\). As a reminder, the purpose for preparing these figures was to find the operating range for FACT with an \( RP \) of \( \geq 1 \). In this study, it is not considered \( t' > 5 \mu s \), because the source performance for the Reference CT may have been difficult to achieve (see Figure 4.17 (a)). The FACT operating range for \( RP \geq 1 \) is displayed as a time bar. The typical operating range of a CT was shown to the right, with a time bar from 0.2 ms to 1 ms for comparison.

Limiting the gantry rounds to the round frequency at 100 Hz restricted the lower projection time range for FACT to about 4 \( \mu s \), as shown in Figure 4.17 (b). A maximum round frequency at 60 Hz reduced the operating range to an operating point around 10 \( \mu s \), which is shown in a short time bar in Figure 4.17 (c).

A brief example of the relationship of projection duration, beam pause, gantry rounds and beam power is given in the following section.

**4.4.3. Medical Imaging**

Using the operating point highlighted above \((\Delta t = 10 \mu s, t' = 1 \mu s)\), the applied superposition with FACT required validation. Figure 1.1 (c) and (d) illustrates the principle of data acquisition with FACT in comparison to a conventional CT. Figure 4.18 (a, b) showed the simulation results for post-processing, which can be applied using FACT. In the circular region of interest (ROI), the \( SD \) in Hounsfield units (HU) of the image voxels was determined. After interpolating 18 images with FACT \((18 \cdot 13.9 \text{ mAs})\), the determined \( SD \) was equal to that of the Reference CT. After one round, the ratio of tube current-scan time product \((Q_{CT}/Q_{FACT})^{-0.5}\) is 0.24 and reflects the standard deviation ratio \( SD_{CT}/SD_{FACT} \) of 0.24 according to the relation in Equation 3.7. The scan time for the same image quality using FACT was less by a factor of 1.3. For comparison, simulated imaging after one round with the Reference CT was shown in Figure 4.18 (c). Under the assumption of the same detector conditions, the criterion for image quality optimization (CNRD) is not affected further, because the same operating conditions for X-ray sources are provided.
Figure 4.16: Minimum, possible, and possible but limited gantry rounds defined in Equations 3.2 – 3.4.

The different figures showed the results for the given beam pauses, \( t' \): (a) without beam pause, (b) \( t' = 1 \mu s \), (c) \( t' = 3 \mu s \) and (d) \( t' = 5 \mu s \). The minimal values were determined according to Equation 3.2 at infinite cooling phases between the pulses – i.e. without any residual thermal energy from a previous pulse, in a single anode from the source ring. The possible gantry rounds, however, note residual heat with the above-introduced power factor \( \eta \), which ensured compliance with the thermal load limit at 2500 K.
Figure 4.17: $RP$ for a given beam pause, $t'$, (a) at no frequency limit, (b) at a limit of 100 Hz, and (c) at a limit of 60 Hz
Figure 4.18: Example of FACT application for post-processing reconstructed images and comparison with the Reference CT. Based on 100 kW at 120 kV, the tube current - scan time product, $Q$, with (a) FACT in one of 18 rounds was 13.9 mAs and with (c) the Reference CT in one round was 250 mAs. (b) After interpolating 18 images with FACT (18 x 13.9 mAs), the measured SD was equal to that of the Reference CT. The scan time for the same image quality with FACT was less by a factor of 1.3.

4.4.4. Boundary value analysis of operating times

Figure 4.19 showed the results of the approach defined above (see Sec. 3.4.4) for a boundary value analysis transferred from focal spot blurring with a conventional CT. With a focal spot size of $A^+$, the right side of the operating range for FACT shifted towards the operating range for a conventional CT. At the transition to the CT operating range, $RP \rightarrow 1$. This can demonstrate the smooth transition between the novel FACT concept and the conventional CT.

At the highlighted operating point ($\Delta t = 10 \, \mu s$, $t' = 1 \, \mu s$ in Figure 4.19 (a), the minimum number of rounds has been reduced from 55 to 12. At the same point, the $RP$ increased from 1.3 (see Figure 4.17 (b)) to 6 (see Figure 4.19 (b)). This reflected the focal spot broadening by a factor of 4.6.
Figure 4.19: Illustrations of boundary value analysis. The operating range for FACT, shown with a dark grey time bar, was made available to the operating time of the Reference CT. The light grey time bar marks the range for the FACT with a broadened focal spot area.
5. Discussion

Our results for a source ring of fixed anodes showed that it should be thermally possible to achieve a novel concept for CT, the performance of which is equal to or even better than that of conventional CT. The necessary energy fluence for a beam projection for a typical image quality is theoretically achievable, as the number of rounds was sufficient for the principle of superposition to be used within a typical scan time. With FACT, at least 60 gantry rounds per second were necessary to achieve the same performance as the Reference CT with an X-ray tube power of 100 kW. In this case, the operating point for a projection was in the range of 10 µs. If 50 kW is sufficient, then FACT could be operated at 30 rounds per second, or a projection duration in the range of 60 µs could be used, which is about one-fourth of the typical integration time for CT detectors. Thus, a significant advantage of a fixed CT system is that the optical focal spot is not blurred, which would enhance the sharpness of a reconstructed image. The resulting high image frame rate would be possible with a typical X-ray exposure to a patient. This would be beneficial for different applications, such as in cardiac imaging, CT angiography, perfusion studies, and other demanding imaging applications.

Figure 5.1 showed a spot diagram of the respective typical and common operating ranges based on the electrical X-ray tube and source ring power ($P_{el}$). When the focal spot size is increased, which occurs with current CT technology as a result of movement, FACT showed an enhanced

**Figure 5.1.** Spot diagram. $P_{el}$ is used as a scale for X-ray outputs of the respective concepts. The heat content illustrates the resulting heat transfer to an anode, which must be dissipated by cooling. Since the fixed anodes of the source ring reach a temperature plateau, a time-unlimited operation is assumed with FACT.
performance by a factor of about six. This superior performance could be used to scan more rapidly or to increase image quality. Another advantage should be noted: By ensuring sufficient direct cooling of the fixed anodes, FACT provides for time-unlimited operation.

Based on the frequency rounds, our calculations for the volume of data (around 8 GB/s for 64 slices) from the detector ring showed that only interfaces currently under development could transfer this accumulating data in real time. Even from this perspective, developing FACT would be in keeping with the current zeitgeist. Figure 5.2 showed the relative dataflow with FACT as compared to that with the Reference CT.

![Relative dataflow with FACT as compared to that with the Reference CT](image)

**Figure 5.2:** Relative dataflow with FACT as compared to that with the Reference CT

In parallel to the investigated source ring, a fixed detector ring is defined. Thus, projections from each anode element on the detector occur obliquely to the reconstructed transverse plane. In conjunction with the detector elements, we will not discuss further the lack of collimation of the scattered X-rays. In this context, the development of fast detectors is desirable for capturing the direction of incidence.

Before the FACT can replace the third-generation CT, we see that a number of technical developments have to be made, on the source side such as supplying a focused electron beam at the anode positions in the source ring, providing sharp edges at the rectangular pulses or on the detector side such as improving the read-out speed and efficiency for small quantum numbers and the distinction between primary X-ray beam and X-ray scatter during the detection. All of these developments present additional challenges that need even more detailed investigations.

A distinct advantage over conventional CT could be considered by setting a second source ring on the other side of the detector. Figure 5.3 showed a schematic for this advanced concept. This provides a rectangular beam field in the z-direction and does away with over-scanning, which could result in reducing unnecessary exposure of patients, without any additional complex technology.

Such a dual-source FACT would theoretically provide for a doubling of the Relative Performance (RP) of the FACT concept introduced above.
Figure 5.3: Schematic of a dual-source FACT and illustration showing how to do away with over-scanning
6. Conclusions

FACT, a new CT concept relying on fixed anodes was proposed. The design was compared with a known conventional CT to evaluate the thermal load capacity and medical imaging possibilities. Although concerned primarily with physical assessment, we have also considered it necessary to dwell on the technical limits of FACT.

The simulations showed that FACT is thermally feasible. Image data are acquired in multiple gantry rounds using the principle of superposition yielding high image frame rates at very thin slices, which can be beneficial for numerous medical applications. As an example, at the same radiation exposure for the patient, the much thinner layers (at high axial spatial resolution) of FACT are indeed noisy, but at high contrast, via use of contrast agents for CT angiography or at calcification in the breast, the branching of blood vessels or the size assessment could be improved.

The thermal load capacity allows a time-unlimited operation that could have an application in industrial use as well as in safety and security. As a fixed system, FACT has no blurring of the optical focal spot during projection. In comparison to the third-generation CT, the Relative Performance ($RP$) of 1.3 was determined at a given thermal focal spot area. With an $RP > 1$ can be achieved a shorter scan time while maintaining radiation exposure and image quality as defined above.
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3.1. Comparison of the different dimensions of the heat transfer study model for fixed anodes. The given layer heights of tungsten and copper are each the same. In the one-dimensional (1D) case, the deposited heat energy can only flow in one direction from the focal spot to the heat bath. In the two-dimensional (2D) case, the thermal flow may be considered with a further degree of freedom in the heat transfer simulations (see Section 3.1.4). The anode width is determined by the possible section width for an anode in the X-ray source ring so that the defined number of these fixed anodes can be arranged (see Section 1. Basic concept for FACT). In the three-dimensional (3D) case, the complete three spatial directions are given for the flow of heat. In each case the basic specifications were applied to the focal spot size and cooling.

3.2. 3D simulation model with representation of incident electron beam (\(e^-\)): (a) at the fixed anode model in short intervals with a given projection duration and (b) at the rotating anode model with continuous long-lasting beam. The fixed anode, designed as a square body, was made of copper (Cu) with a base area of 25 mm by 3.2 mm and a height of 20 mm. The tungsten (W) target layer had a material thickness of 0.5 mm. The rotating model used the same construction, but as a cylindrical body with a rotational frequency of 150 Hz and a radius of 60 mm. The thermal focal spot area (A) on the anode surface is formed by the entering electrons of equally distributed intensity. For cooling, a heat bath of 300 K has been defined. The surfaces, except for the heat bath, were considered thermally insulated.

3.3. Illustration of the temperature-independent material properties in dashed lines (used for Osterkamp formulas, described in Section 2.8, and Monte Carlo simulations, given in Table 3.1) and temperature-dependent material properties in continuous lines (used for FEM simulations to heat transfer, given in Material Property Database (MPDB) from JAHM Software). The properties of the materials considered, tungsten (W) and copper (Cu), includes (a) thermal conductivity \(\lambda\), (b) density \(\rho\) and (c) specific heat capacity \(c\).

3.4. Operating times for a single fixed anode and for a source ring with 1160 fixed anodes. \((P_{th}/A)_{max}\) was determined by the power factor (\(\eta\), see Equation 3.5). (a) Illustration showing a projection duration (\(\Delta t\)) of 10 \(\mu s\). The repetition frequency is 78.4 Hz. (b) Each fixed anode in the source ring operates with the same given repetition frequency i.e. the gantry rounds amount to 78.4 l/s. In this case, a beam pause (\(t'\)) of 1 \(\mu s\) was used between the projections of different single anodes of the X-ray source ring in which no source activity is present.
4.1. Deposed energy along the depth in the central area of the focal spot. The value for the given material density for tungsten in Table 3.1 is shown by the factor 1.0. A variation of this temperature-independent density of 10% up and down is represented by the factor of 0.9 and 1.1 to the given material density for tungsten.

4.2. Temperature distributions for the different simulation space dimension (1D, 2D and 3D) for fixed anodes as an example for a projection period of 10 µs.

4.3. 3D simulation model of (a) fixed anode and (b) rotating anode along with the temperature distribution after ten seconds of operation using the maximum possible electrical X-ray tube power \( P_{el} \) which was set for each projection. Both models are also described in Figure 3.2. The trajectories of the emitted charged electrons \( (e^-) \) are indicated based on simulation results in conjunction with a static electromagnetic field between the cathode and the anode. For reasons of comparability, an exact tube design was not pursued. However, a study of these trajectories (with COMSOL Multiphysics) showed that the reflected electrons directed their energy away from the thermal focal spot in a first approximation after multiple uniform reflections over the relatively large interior surfaces of the X-ray vacuum tube. The re-entry energy was neglected in our simulations, as this would have resulted in a small increase in background temperature.

4.4. (a) Thermal focal spot power density \( P_{th}/A \) of various projection durations for the 3D fixed anode model and independent of time for the 3D rotating anode model as well as for the Reference CT. (b) Relative deviation of \( P_{th}/A \) at the fixed anode between FEM simulation and the Osterkamp formulas.

4.5. Graphical representation of the detected particle properties in the Monte Carlo simulation when exiting the surface of the anode. The left column shows the photons and the right column the electrons in each case with a primary energy of 80 keV and 120 keV of the incident electrons. Graphics (c) and (d) show the relative energy of the escaped particles with respect to the angle to the surface normal for the anode angle of 6°. The graphs in (e) and (f) for the angle about the direction of the surface normal in each case shows a random distribution of energy, as expected.

4.6. Kinetic energy distribution after racing the first flight of the emitted electrons, which are dropping back to the anode inside the electro-magnetic field. For this purpose, a simple model described in Section 3.2 is used.
4.7. Relative deviation with respect to the Osterkamp formula for different heights of the copper (Cu) body with differentiation in the tube voltage (left) of 120 kV and (right) of 80 kV as well as in the simulation space dimension of 1D (a and b), 2D (c and d) and 3D (e and f).

4.8. Summary of simulation space dimensions from Figure 4.7 for the basic heat transfer study model.

4.9. Relative deviation with respect to the Osterkamp formula for different heights of the tungsten (W) layer.

4.10. Relative deviation with respect to the Osterkamp formula for different sizes of the focal spot.

4.11. Relative deviation for the Osterkamp formula and for the heat transfer study model with variation in the material properties using the factor $dM$ of 0.9, 1.0 and 1.1.

4.12. Relative deviation with respect to the Osterkamp formula for the basic heat transfer study model and with changes in the cooling mechanism.

4.13. The range of results from parametric simulation studies for maximum thermal focal spot power density ($P_{th}/A_{max}$) that caused a temperature increase from 300 K to 2500 K during a certain projection duration ($\Delta t$). In addition to the maximum and minimum overall simulation results, the lines from the Osterkamp formula for short loading times were shown.

4.14. Example of a temperature profile during pulsed operation of a fixed anode. The maximum temperature in the tungsten (W) target was 2500 K ($\pm 0.5\%$). In the copper (Cu) block, the maximum temperature did not reach 500 K. A time-unlimited operation was assumed, based on the plateau for the maximum temperatures in the medium of a fixed anode.

4.15. Operating results for (a) power factor $\eta$ and (b) maximum temperature of a copper block. The gantry rounds correspond to the possible, and possible but limited, gantry rounds from Figure 4.16. For the allowed temperature of copper (Cu) 1032 K could be used, as given in Table 2.2.

4.16. Minimum, possible, and possible but limited gantry rounds defined in Equations 3.2 – 3.4. The different figures showed the results for the given beam pauses, $t'$: (a) without beam pause, (b) $t' = 1\mu$s, (c) $t' = 3\mu$s and (d) $t' = 5\mu$s. The minimal values were determined according to Equation 3.2 at infinite cooling phases between the pulses – i.e. without any residual thermal energy from a previous pulse, in a single anode from the source ring. The possible gantry rounds, however, note residual heat with the above-introduced power factor $\eta$, which ensured compliance with the thermal load limit at 2500 K.
4.17. $RP$ for a given beam pause, $t'$, (a) at no frequency limit, (b) at a limit of 100 Hz, and (c) at a limit of 60 Hz.

4.18. Example of FACT application for post-processing reconstructed images and comparison with the Reference CT. Based on 100 kW at 120 kV, the tube current - scan time product, $Q$, with (a) FACT in one of 18 rounds was 13.9 mAs and with (c) the Reference CT in one round was 250 mAs. (b) After interpolating 18 images with FACT ($18 \times 13.9$ mAs), the measured $SD$ was equal to that of the Reference CT. The scan time for the same image quality with FACT was less by a factor of 1.3.

4.19. Illustrations of boundary value analysis. The operating range for FACT, shown with a dark grey time bar, was made available to the operating time of the Reference CT. The light grey time bar marks the range for the FACT with a broadened focal spot area.

5.1. Spot diagram. $P_{el}$ is used as a scale for X-ray outputs of the respective concepts. The heat content illustrates the resulting heat transfer to an anode, which must be dissipated by cooling. Since the fixed anodes of the source ring reach a temperature plateau, a time-unlimited operation is assumed with FACT.

5.2. Relative dataflow with FACT as compared to that with the Reference CT.

5.3. Schematic of a dual-source FACT and illustration showing how to do away with over-scanning.
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Appendix

A. Basic user code for GAMOS/GEANT4: Monte Carlo simulation for energy deposition and detection of the emitted particles via PhaseSpace container

```plaintext
### Control&Verbosity ######
/run/verbose 1
/controls/verbose 1
/gamos/verbose GmBaseVerbosity = -1
/gamos/verbose GmSV2Verbosity = -1
/gamos/verbose GmSoringVerbosity = -1
/gamos/verbose GmUVVerbosity = -1
/gamos/verbose GmPhysicsVerbosity = -1
/gamos/verbose RTVerbosity = -1

### Geometry ######
/gamos/setParam GmReadPhantomGeometry: FileName \SimpleTube.geom
/gamos/setParam GmSimplePhantomGeometry: MaterialNames TungstenBody
/gamos/setParam GmSimplePhantomGeometry: MaterialDensities 19.3
/gamos/setParam GmSimplePhantomGeometry: NCells 1 1 1200
/gamos/setParam GmSimplePhantomGeometry: PhantomDims 1 mm 1 mm 1 mm 12 mm 0.0 mm 0.0 mm 12 mm 0.0 mm ### dZ=10nm
/gamos/setParam GmReadPhantomGeometry: InitialDisplacement 0.0 0.0 0.0
/gamos/setParam GmReadPhantomGeometry: InitialRotAngles 0.0 deg 0.0 0.0
/gamos/geometry GmSimplePhantomGeometry

### PhysicsList ######
/gamos/PhysicsList GmPhysics Livermore-Register LowE-EPDL processes for gammas
/gamos/GmPhysics/addPhysics gamma-lowerener Livermore-Register LowE-EPDL processes for electrons
/gamos/GmPhysics/addPhysics electron-lowerener
/gamos/setParam GmMultipleScattering: Model Electron GoudsmitSaunderson

### Generator ######
/gamos/generator GmGenerator

### PhaseSpace ######
/gamos/setParam RTPhaseSpaceUA: FileName \GAM-PhaseSpace.txt
/gamos/setParam RTPhaseSpaceUA: ZStops 10.0 mm
/gamos/setParam RTPhaseSpaceUA: KillAfterLastZStop TRUE
/gamos/setParam RTPhaseSpaceUA: StoreZ FALSE
/gamos/setParam RTPhaseSpaceHistos: Hadrons FALSE
/gamos/setParam RTPhaseSpaceHistos: Nbins 600
/gamos/setParam RTPhaseSpaceHistos: HisMax 150 keV
/gamos/userAction RTPhaseSpaceUA

### Miscellaeous ######
/gamos/physics/prodCutsEnergyLimits 1 eV 1 MeV
/gamos/geometry/createRegion TargetReg phantomContainer
/gamos/physics/setCuts TargetReg 1.0 mm 1.0 mm ### atom dimension: 0.1 nm = 1A
/gamos/physics/setCuts AnodeBodyReg 1.0 mm 1.0 mm
/gamos/setParam GmEnergySplitter: NIterations 5

### Visualisation ######
# /run/initialize
/gamos/random/setSeeds 1000 1001 ### Random seed numbers

### Source ######
/gamos/generator/addSingleParticleSource source GmGeneratorDist:PositionRectangle 1/2 mm 1/2 mm 0.0 0.0 5 mm
/gamos/generator/directionDist source GmGeneratorDist:DirectionConst 0 deg 0 deg 0 deg 0 deg 0 deg 0 deg 0 deg 0 deg

### Scoring ######
/gamos/scoring/createMFSelector doseEnergyDet phantom
/gamos/scoring/addScore2MFD energyScore GmG4PSEnergyDeposit doseEnergyDet
/gamos/scoring/scoreErrors energyScore FALSE
/gamos/scoring/addScore2MFD doseScore GmG4PSDoseDeposit doseEnergyDet
/gamos/scoring/scoreErrors doseScore FALSE
/gamos/scoring/addPrinter2Score RTPSPHoseHistos doseScore ### saving scores of dose in root histograms
/gamos/userAction GmGeneratorHistosUA ### Saving event generator in root histograms

### Numbers of Particles ######
/run/beamOn 100000000 ### (6.2415096516 x 10^18) corresponds to 1 Ampere
```
# GmPSPrinterXYZEnergy.hh

```cpp
#include "GmPSPrinterXYZEnergy.hh"
#include "G4Parameterisation.hh"
#include "GmScoringVerbosity.hh"
#include "G4Scoring.hh"
#include "G4Extension.hh"
#include "G4Analysis.hh"
#include "GmNumberOfEvent.hh"
#include "GmGeometry.hh"
#include "GmTouchable.hh"
#include "GmGeometryUtils.hh"
#include "GmParameterMgr.hh"
#include "GmAnalysisMgr.hh"
#include "Gm3ddoseHeader.hh"
#include "GmRegularParamUtils.hh"
#include "GmReadDICOM.hh"
#include "GmScoringVerbosity.hh"
#include "GmPSPrinterXYZEnergy.hh"
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#include "G4Analysis hh"
The text appears to be a code snippet related to a program, possibly in C++ or a similar language. The code seems to involve operations on geometric objects, such as touching a phantom volume, and calculations related to voxel limits and dose calculations. The code includes functions like `GmGeometryUtils`, `GmRegularParamUtils`, and variables such as `nx`, `ny`, and `nz` that likely represent dimensions or parameters of geometric objects. The syntax and structure suggest it's part of a larger program, possibly for simulating or analyzing physical phenomena.
#ifndef GmPSPrinterXYZEnergy.hh
#define GmPSPrinterXYZEnergy.hh

#include <vector>
#include "globals.hh"
#include "GamosCore/GamosScoring/Management/include/GmVPSPrinter.hh"
#include "GamosCore/GamosBase/Base/include/GmIOtextMgr.hh"

class G4PhantomParameterisation;

// class description:
// This class fill a dose file in 3ddose (DOXYZnc) format

class GmPSPrinterXYZEnergy : public GmVPSPrinter, GmIOtextMgr
{
public:// with description
    GmPSPrinterXYZEnergy(G4String);
    virtual ~GmPSPrinterXYZEnergy();
    virtual void DumpAll(G4THitsMap<G4double>*, GmVPrimitiveScorer*, theScorer);
    virtual void SetParameters(const std::vector<G4String>& param);

private:
    void WriteHeader();
    void WriteValues(G4THitsMap<G4double>*, GmVPrimitiveScorer*, theScorer);

private:
    G4double theUnit;
    G4String theUnitName;
    G4PhantomParameterisation* thePhantomParam;
};

#endif
B. Basic user code for MATLAB: Evaluation of the PhaseSpace container from of the Monte Carlo simulation

```matlab
function MC2HTEnergyCurve(Density, AnodeAngle, E_nom_keV, Color)
    %Import data from PhaseSpace11 and PhaseSpace22
    data0 = importdata(’GAM-PhaseSpace-Header.txt’);
    ParticleNumber=data0(1);
    NX=data0(2);
    NY=data0(3);
    NZ=data0(4);

    data2length1=NX*NY*NZ;
    VoxelX=data2(6)-data0(5);
    VoxelY=data2(5+NX+2)-data0(5+NX+1);
    VoxelZ=data2(5+NX+1+NY+2)-data0(5+NX+1+NY+1);
    VoxelVolumeMeter3=abs(VoxelX*VoxelY*VoxelZ);

    data1 = load(’GAM-PhaseSpace.txt’);
    data2length2=length(data2);

    E_Target=length1; % Energy of source
    E_TargetRel = E_Target/E_Quelle;

    data2(:,4) = data2(:,4)/max(data2(:,4)); % normalize to 1 kW/m³
    EnergyMAXTemp=find(data2(:,4)==max(data2(:,4)))
    EnergyMAX=data2(EnergyMAXTemp,3);
    EnergyMAXInterval99Temp=find(data2(:,4)>max(data2(:,4))*0.99);
    EnergyMAXInterval99=E_MAXInterval99Temp(end)-E_MAXInterval99Temp(1)+VoxelZ;
    dlmwrite(’MATXTOM-DepthEnergyCurve.txt’,
             data2(:,3:4),’precision’,’%d’,’newline’,’pc’);

    data3 = load(’/....//Statistic_Anode3D.txt’);
    data3 = [data3,....;
             Density, AnodeAngle, E_nom_keV, EnergyMAX, EnergyMAXInterval99, ParticleNumber, E_PhaseSpaceRelative, E_PhaseSpacePTyp11Rel, E_PhaseSpacePTyp22Rel, VoxelX, VoxelY, VoxelZ, VoxelVolumeMeter3, max(data2(:,4))];
    dlmwrite(’/....//Statistic_Anode3D.txt’,
             data3, ’precision’,’%d’,’newline’,’pc’);

figure(1)
hold on
pplot(data2(:,1),data2(:,4),’Color’,[Color Color 1],’LineWidth’,2); 98% blue
p99plot(data2(EnergyMAXInterval99Temp,3),data2(EnergyMAXInterval99Temp(1),4),’Color’,[1 Color Color],’LineWidth’,2); 98% red
clf
HeatSource1D(1), HeatSource2D(1); HeatSource2D(2), HeatSource2D(3)
```
C. COMSOL program report (extract): Tracing of particles influenced of an electromagnetic field

**Global Definitions**

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_field</td>
<td>80 [keV]</td>
<td>Acceleration energy between cathode and anode</td>
</tr>
<tr>
<td>E_0</td>
<td>0.51099892811 [MeV]</td>
<td>Rest energy of an electron</td>
</tr>
<tr>
<td>v2c_eBeam</td>
<td>sqrt(1 - E_0^2/(E_0 + E_field)^2)</td>
<td>Relativistic electron velocity</td>
</tr>
<tr>
<td>AbsolutePressure</td>
<td>1.3E-2 [Pa]</td>
<td>Absolute Pressure of vacuum</td>
</tr>
</tbody>
</table>

**Functions**

<table>
<thead>
<tr>
<th>Function name</th>
<th>Function type</th>
</tr>
</thead>
<tbody>
<tr>
<td>int1</td>
<td>Interpolation</td>
</tr>
</tbody>
</table>

Interpolation function (explicit for 80 keV)

**Model (mod1)**

Geometry 1

**Materials**

<table>
<thead>
<tr>
<th>Description for Air</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permeability</td>
<td>{1.0, 0, 0}, {0, 1.0, 0}, {0, 0, 1}</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>{1.0, 0, 0}, {0, 1.0, 0}, {0, 0, 1}</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>\rho(T[K]) [Pa*s]</td>
</tr>
<tr>
<td>Ratio of specific heats</td>
<td>{1}</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>{1.0[kW/(m<em>K)], 1.0[kW/(m</em>K)], 0.0, 0.0, 0.0}</td>
</tr>
<tr>
<td>Heat capacity at constant pressure</td>
<td>{C_p(T[K]) [J/(kg*K)]}</td>
</tr>
<tr>
<td>Density</td>
<td>{1000[kg/m^3]}, {1[kg/m^3]}</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>{1.0[kW/(m<em>K)], 1.0[kW/(m</em>K)], 0.0, 0.0, 0.0, 0.0, 0.0[kW/(m*K)]}</td>
</tr>
<tr>
<td>Speed of sound</td>
<td>{1.0[km/s]}</td>
</tr>
</tbody>
</table>
### Electrostatics (es)

#### Equations

\[
\nabla \cdot \mathbf{D} = \rho_v \\
\mathbf{E} = -\nabla V
\n\n\]

#### Settings

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Electric potential</td>
<td>Quadratic</td>
</tr>
<tr>
<td>Value type when using splitting of complex variables</td>
<td>Complex</td>
</tr>
<tr>
<td>Activate terminal sweep</td>
<td>Off</td>
</tr>
<tr>
<td>Reference impedance</td>
<td>50,\Omega</td>
</tr>
<tr>
<td>Parameter to export</td>
<td>Z</td>
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</table>

#### Variables

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Unit</th>
<th>Description</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>es.d</td>
<td>(d)</td>
<td></td>
<td>Contribution</td>
<td>Domains 1-2</td>
</tr>
<tr>
<td>es.ny</td>
<td>(dn_y)</td>
<td></td>
<td>Normal vector, y component</td>
<td>Boundaries 1-12</td>
</tr>
<tr>
<td>es.nz</td>
<td>(dn_z)</td>
<td></td>
<td>Normal vector, z component</td>
<td>Boundaries 1-12</td>
</tr>
<tr>
<td>es.unTex</td>
<td>(0)</td>
<td>Pa</td>
<td>Maxwell upward electric surface stress tensor, x component</td>
<td>Boundaries 1-12</td>
</tr>
<tr>
<td>es.unTey</td>
<td>(0)</td>
<td>Pa</td>
<td>Maxwell upward electric surface stress tensor, y component</td>
<td>Boundaries 1-12</td>
</tr>
<tr>
<td>es.unTez</td>
<td>(0)</td>
<td>Pa</td>
<td>Maxwell upward electric surface stress tensor, z component</td>
<td>Boundaries 1-12</td>
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<tr>
<td>es.dnTex</td>
<td>(0)</td>
<td>Pa</td>
<td>Maxwell downward electric surface stress tensor, x component</td>
<td>Boundaries 1-12</td>
</tr>
<tr>
<td>es.dnTey</td>
<td>(0)</td>
<td>Pa</td>
<td>Maxwell downward electric surface stress tensor, y component</td>
<td>Boundaries 1-12</td>
</tr>
<tr>
<td>es.dnTez</td>
<td>(0)</td>
<td>Pa</td>
<td>Maxwell downward electric surface stress tensor, z component</td>
<td>Boundaries 1-12</td>
</tr>
<tr>
<td>es.intWe</td>
<td>(es.\int \cdot W)</td>
<td>J</td>
<td>Total electric energy</td>
<td>Global</td>
</tr>
<tr>
<td>es.C11</td>
<td>(1/es.V_0)</td>
<td>F</td>
<td>Capacitance</td>
<td>Global</td>
</tr>
<tr>
<td>es.S11dB</td>
<td>(10\log_{10}(\text{Re}(es.C11)))</td>
<td>dB</td>
<td>S-parameter</td>
<td>Global</td>
</tr>
<tr>
<td>es.qref</td>
<td>50,\Omega</td>
<td></td>
<td>Reference impedance</td>
<td>Global</td>
</tr>
</tbody>
</table>

### Charged Particle Tracing (cpt)

#### Equations

\[
\frac{d(m\mathbf{v})}{dt} = \mathbf{F}_t
\]

#### Settings

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>Formulation</td>
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<tr>
<td>Relativistic correction</td>
<td>Off</td>
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<tr>
<td>Wall accuracy order</td>
<td>1</td>
</tr>
<tr>
<td>Maximum number of secondary particles</td>
<td>10000</td>
</tr>
<tr>
<td>Steer particle status data</td>
<td>Off</td>
</tr>
<tr>
<td>Release type</td>
<td>Transient</td>
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</tbody>
</table>

### Release from Grid 1

#### Equations

\[
\mathbf{q} = q_0 \\
\mathbf{v} = v_0
\]
### Settings

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Release times</td>
<td>0</td>
</tr>
<tr>
<td>x</td>
<td>range(-5.0e-4, 10e-4/1e3, 5.0e-4)</td>
</tr>
<tr>
<td>y</td>
<td>range(-5.0e-4, 10e-4/1e3, 5.0e-4)</td>
</tr>
<tr>
<td>z</td>
<td>0.001</td>
</tr>
</tbody>
</table>

**Initial velocity**

- Initial particle velocity: \(c \text{const*int1}(x, y, z)\)

### Variables

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Unit</th>
<th>Description</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>cpt.Ntf.g1[1]</td>
<td>noja(cpt.g1[1])</td>
<td>L</td>
<td>Total number of particles released by feature</td>
<td>Global</td>
</tr>
<tr>
<td>cpt.v0x.g1[1]</td>
<td>(c \text{const*int1}(x, y))</td>
<td>m/s</td>
<td>Initial particle velocity, x component</td>
<td>Particles</td>
</tr>
<tr>
<td>cpt.v0y.g1[1]</td>
<td>(c \text{const*int2}(x, y))</td>
<td>m/s</td>
<td>Initial particle velocity, y component</td>
<td>Particles</td>
</tr>
<tr>
<td>cpt.v0z.g1[1]</td>
<td>(c \text{const*int3}(x, y))</td>
<td>m/s</td>
<td>Initial particle velocity, z component</td>
<td>Particles</td>
</tr>
</tbody>
</table>

### Mesh

Mesh 1

### Result (intermediate)

Surface: Electric potential (kV)
D. COMSOL program report (extract) combined from the different simulation dimensions 1D, 2D and 3D: Simulation of heat transfer

Global Definitions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FocusAngle</td>
<td>6.0 [deg]</td>
<td>Anode angle</td>
</tr>
<tr>
<td>FocusLength</td>
<td>2.0 [mm]/sin(FocusAngle)</td>
<td>Length of thermal focal spot</td>
</tr>
<tr>
<td>FocusWidth</td>
<td>1.4 [mm]</td>
<td>Width of thermal focal spot</td>
</tr>
<tr>
<td>AnodeLayerW</td>
<td>0.5 [mm]</td>
<td>Height of tungsten (W) target</td>
</tr>
<tr>
<td>AnodeLayerCu</td>
<td>20 [mm]</td>
<td>Height of copper (Cu) block</td>
</tr>
<tr>
<td>AnodeHeight</td>
<td>25 [mm]</td>
<td>Length of anode</td>
</tr>
<tr>
<td>TimeInterval</td>
<td>1E-6 [s]</td>
<td>Variable for the time interval (initial)</td>
</tr>
<tr>
<td>FocusA</td>
<td>FocusLength*FocusWidth</td>
<td>Thermal focal spot area</td>
</tr>
<tr>
<td>dT</td>
<td>2200 [K]</td>
<td>Maximum of temperature increase</td>
</tr>
<tr>
<td>dM</td>
<td>1</td>
<td>Material factor</td>
</tr>
<tr>
<td>MaterialDensity</td>
<td>dM*19.25 [g/cm³]</td>
<td>Density of tungsten (W), for Oosterkamp formula</td>
</tr>
<tr>
<td>MaterialHeatCapacity</td>
<td>dM*138 [J/kg/K]</td>
<td>Heat capacity of tungsten (W), for Oosterkamp formula</td>
</tr>
<tr>
<td>MaterialThermalConductivity</td>
<td>dM*170 [W/m/K]</td>
<td>Thermal conductivity, for Oosterkamp formula</td>
</tr>
<tr>
<td>Oosterkamp_P,FixedAnode</td>
<td>1/(2/(dT<em>FocusA)</em>(TimeInterval/(pi<em>MaterialDensity</em>MaterialHeatCapacity*MaterialThermalConductivity))ˆ.5)</td>
<td>Thermal focal spot power, Oosterkamp for fixed anode</td>
</tr>
<tr>
<td>RotatingAnodeRadius</td>
<td>60 [mm]</td>
<td>Radius of rotating anode</td>
</tr>
<tr>
<td>RotatingAnodeTrackRadius</td>
<td>58 [mm]</td>
<td>Focal track radius</td>
</tr>
<tr>
<td>RotationalFrequency</td>
<td>300 [Hz]</td>
<td>Anode rotating frequency f</td>
</tr>
<tr>
<td>AngularFrequency</td>
<td>7π/6*RotationalFrequency</td>
<td>Angular frequency</td>
</tr>
<tr>
<td>Oosterkamp_P,Drehanode</td>
<td>1/(2/(dT<em>FocusA)</em>(FocusWidth/2/(piˆ2<em>RotationalFrequency</em>RotatingAnodeTrackRadius<em>MaterialDensity</em>MaterialHeatCapacity*MaterialThermalConductivity))ˆ.5)</td>
<td>Thermal focal spot power, Oosterkamp for rotating anode</td>
</tr>
<tr>
<td>Oosterkamp_T</td>
<td>2<em>Oosterkamp_P,Drehanode/FocusA</em>((InputFocusWidth/2/(piˆ2<em>RotationalFrequency</em>RotatingAnodeTrackRadius<em>MaterialDensity</em>MaterialHeatCapacity*MaterialThermalConductivity))ˆ.5)</td>
<td>Temperature rise at the focal spot for rotating anode</td>
</tr>
<tr>
<td>InputQ1D_Integral</td>
<td>2.4997770782857557E10</td>
<td>Integral power as normal factor (for 1D)</td>
</tr>
<tr>
<td>InputQ1D_Adaptation</td>
<td>1/(InputQ1D_Integral<em>FocusLength</em>FocusWidth)</td>
<td>Normed input power (1D)</td>
</tr>
<tr>
<td>Source1D</td>
<td>InputQ1D_Adaptation*Oosterkamp_P,FixedAnode</td>
<td>Source power (1D) with Oosterkamp prediction</td>
</tr>
<tr>
<td>InputQ2D_Integral</td>
<td>3.4918189111749235487</td>
<td>Integral power as normal factor (for 2D)</td>
</tr>
<tr>
<td>InputQ2D_Adaptation</td>
<td>1/(InputQ2D_Integral*FocusLength)</td>
<td>Normed input power (2D)</td>
</tr>
<tr>
<td>Source2D</td>
<td>InputQ2D_Adaptation*Oosterkamp_P,FixedAnode</td>
<td>Source power (2D) with Oosterkamp prediction</td>
</tr>
<tr>
<td>InputQ3D_Integral</td>
<td>66.74153900900581</td>
<td>Integral power as normal factor (for 3D)</td>
</tr>
<tr>
<td>InputQ3D_Adaptation</td>
<td>1/(InputQ3D_Integral)</td>
<td>Normed input power (3D)</td>
</tr>
<tr>
<td>Source3D</td>
<td>InputQ3D_Adaptation*Oosterkamp_P,FixedAnode</td>
<td>Source power (3D) with Oosterkamp prediction</td>
</tr>
</tbody>
</table>

Functions

<table>
<thead>
<tr>
<th>Function name</th>
<th>Function type</th>
</tr>
</thead>
<tbody>
<tr>
<td>rect1</td>
<td>Rectangle</td>
</tr>
<tr>
<td>rect2</td>
<td>Rectangle</td>
</tr>
</tbody>
</table>

Rectangle 1 and 2 function for precise and regular on and off the input power

Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower limit</td>
<td>FocusLength/2</td>
</tr>
<tr>
<td>Upper limit</td>
<td>FocusLength/2</td>
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Smoothing

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Size of transition zone</td>
<td>0.01*FocusLength</td>
</tr>
</tbody>
</table>
Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower limit</td>
<td>FocusWidth/2</td>
</tr>
<tr>
<td>Upper limit</td>
<td>FocusWall/2</td>
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Smoothing

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of transition zone</td>
<td>0.001*FocusLength</td>
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Functions: Interpolation

<table>
<thead>
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<th>Function type</th>
</tr>
</thead>
<tbody>
<tr>
<td>int1</td>
<td>Interpolation</td>
</tr>
</tbody>
</table>

(c) Interpolation 1 (explicit for 120 keV)

(d) Interpolation 2

Interpolation 1 function as input power function. Interpolation 2 function as one of several, which have been determined interactively for \( \frac{P_{th}}{A}_{\text{max}} \)

Model (mod1)

(e) Geometry, 1D

(f) Geometry, 2D

(g) Geometry, 3D

Geometry for the different dimensions

Material: Tungsten

<table>
<thead>
<tr>
<th>Selection</th>
<th>Domain</th>
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</thead>
<tbody>
<tr>
<td>Geometric entity level</td>
<td>Domain 2-4</td>
</tr>
<tr>
<td>Selection</td>
<td>Domain 2-4</td>
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Material parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>dM'\text{[J/(mK)]} \frac{\text{W}}{\text{m}^2\text{K}}</td>
<td>W/(m*K)</td>
</tr>
<tr>
<td>Heat capacity at constant pressure</td>
<td>dM'\text{[J/(kg*K)]}</td>
<td>J/(kg*K)</td>
</tr>
<tr>
<td>Density</td>
<td>dM'\text{[kg/m}^3\text{]}</td>
<td>kg/m^3</td>
</tr>
</tbody>
</table>
Domain of tungsten (W) material for the different dimensions

<table>
<thead>
<tr>
<th>Basic Settings</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>dL</td>
<td>dL solid 1(T[1/K]) - dL solid 2(Tempref[1/K])</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>dM \cdot k solid Ho et al 1(T[1/K])[W/(m*K)], 0, 0</td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>dM \cdot res solid Ho et al 1(T[1/K])[ohm*m], 0, 0</td>
<td></td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>dM \cdot \alpha solid Ho et al 1(T[1/K])[1/K] + (Tempref - 293[K])/(T - Tempref)*(dM \cdot \alpha solid Ho et al 1(T[1/K])[1/K] - dM \cdot \alpha solid Ho et al 1(Tempref[1/K])[1/K]), 0, 0</td>
<td></td>
</tr>
<tr>
<td>Heat capacity at constant pressure</td>
<td>dM \cdot C solid Ho et al 1(T[1/K])[J/(kg*K)], 0, 0</td>
<td></td>
</tr>
</tbody>
</table>

Material: Copper

<table>
<thead>
<tr>
<th>Young's modulus and Poisson's ratio Settings</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus</td>
<td>E[1/K][Pa]</td>
<td></td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>nu[1/K]</td>
<td></td>
</tr>
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</table>

Domain of copper (Cu) material for the different dimensions

<table>
<thead>
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<th>Domain</th>
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<tbody>
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<td>Selection</td>
<td>Domain</td>
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<table>
<thead>
<tr>
<th>Material parameters</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Thermal conductivity</td>
<td>k solid Cu(T[1/K])[W/(m*K)], 0, 0</td>
<td>W/(m*K)</td>
</tr>
<tr>
<td></td>
<td>Heat capacity at constant pressure</td>
<td>C solid Cu(T[1/K])[J/(kg*K)], 0, 0</td>
<td>J/(kg*K)</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>rho solid Cu(T[1/K])[kg/m^3], 0, 0</td>
<td>kg/m^3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Basic Settings</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>dL</td>
<td>dL solid Cu(T[1/K]) - dL solid Cu(Tempref[1/K])</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>C solid Cu(T[1/K])[W/(m*K)], 0, 0</td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>C solid Cu(T[1/K])[ohm*m], 0, 0</td>
<td></td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>C solid Cu(T[1/K])[1/K] + (Tempref - 293[K])/(T - Tempref)*(C solid Cu(T[1/K])[1/K] - C solid Cu(Tempref[1/K])[1/K]), 0, 0</td>
<td></td>
</tr>
<tr>
<td>Heat capacity at constant pressure</td>
<td>C solid Cu(T[1/K])[J/(kg*K)], 0, 0</td>
<td></td>
</tr>
</tbody>
</table>
**Young’s modulus and Poisson’s ratio Settings**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>E(T[1/K][Pa])</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>nu(T[1/K])</td>
</tr>
</tbody>
</table>

**Heat Transfer (ht)**

- **Material Copper, 1D**
- **Material Copper, 2D**
- **Material Copper, 3D**

**Domains for simulation of heat transfer for the different dimensions**

<table>
<thead>
<tr>
<th>Selection</th>
<th>Domains 1-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric entity level</td>
<td>Domain</td>
</tr>
</tbody>
</table>

**Equations**

\[
\rho C_v \frac{dT}{dt} + \rho c_v u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q
\]

**Settings**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Quadratic</td>
</tr>
<tr>
<td>Value type when using splitting of complex variables</td>
<td>Complex</td>
</tr>
<tr>
<td>Compute boundary fluxes</td>
<td>Off</td>
</tr>
<tr>
<td>Streamline diffusion</td>
<td>Off</td>
</tr>
<tr>
<td>Convergent diffusion</td>
<td>Off</td>
</tr>
<tr>
<td>Lowest gradient limit</td>
<td>0.01[K]/ht.helem</td>
</tr>
<tr>
<td>Isotropic diffusion</td>
<td>Off</td>
</tr>
<tr>
<td>Heat transfer in biological tissue</td>
<td>Off</td>
</tr>
<tr>
<td>Heat transfer in porous media</td>
<td>Off</td>
</tr>
<tr>
<td>Surface-to-surface radiation</td>
<td>Off</td>
</tr>
<tr>
<td>Radiation in participating media</td>
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<tr>
<td>Shape function</td>
<td>Discontinuous Lagrange</td>
</tr>
<tr>
<td>Order</td>
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</tr>
</tbody>
</table>

**Heat Transfer in Solids (explicit for 3D)**

**Equations**

\[
\rho C_v \frac{dT}{dt} + \rho c_v u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q
\]

**Settings**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>From material</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>{ (0, 0, 0), (0, 0, 0), (0, 0, 0) }</td>
</tr>
<tr>
<td>Density</td>
<td>From material</td>
</tr>
<tr>
<td>Heat capacity at constant pressure</td>
<td>From material</td>
</tr>
</tbody>
</table>

**Properties from material**

<table>
<thead>
<tr>
<th>Property</th>
<th>Material</th>
<th>Property group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>Tungsten, new for ParamSweep [solid.Ho et al]</td>
<td>Basic</td>
</tr>
<tr>
<td>Density</td>
<td>Tungsten, new for ParamSweep [solid.Ho et al]</td>
<td></td>
</tr>
<tr>
<td>Heat capacity at constant pressure</td>
<td>Copper (solid), residual resistivity ratio of 50</td>
<td>Basic</td>
</tr>
<tr>
<td>Density</td>
<td>Copper (solid), residual resistivity ratio of 50</td>
<td></td>
</tr>
</tbody>
</table>

**Variables**

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Unit</th>
<th>Description</th>
<th>Selection</th>
</tr>
</thead>
</table>
| dhtflux. Tz   | hht.k[flux] (Tz)
               | W/m²K     | Domain Flux                        | Domains 1-4 |
| dhtflux. Ty   | hht.k[flux] (Ty)
               | W/m²K     | Domain Flux                        | Domains 1-4 |
| dhtflux. Tz   | hht.k[flux] (Tz)
               | W/m²K     | Domain Flux                        | Domains 1-4 |
| ht.WnsInt     | ht.solid1.intDiv(ht.pA*(d(ht.ux,x)+d(ht.uy,y)+d(ht.uz,z))) | W         | Total work source                  | Global    |
| ht.Q          | 0                                       | W/m³K     | Heat source                        | Domains 1-4 |
| ht.Qtot       | 0                                       | W/m³K     | Total heat source                  | Domains 1-4 |
| ht.kxx        | model input.k11                         | W/m²K     | Thermal conductivity, xx component | Domains 2-4 |
| ht.kyy        | model input.k21                         | W/m²K     | Thermal conductivity, yy component | Domains 2-4 |
| ht.kzz        | model input.k31                         | W/m²K     | Thermal conductivity, zz component | Domains 2-4 |
Heat Source (explicit for 3D)

Heat Source 1

Selection

Geometric entity level | Domain
--- | ---
| Domain 4

Equations

\[
p_{\text{m}} \frac{\partial V}{\partial t} = \nabla \cdot (- \mathbf{k} \nabla T) + Q_0 + W_0
\]

Settings

Description | Value
--- | ---
Heat source | User defined
Heat source | rec11(x)*rec21(y)*int1(z)*Source3D*int2(TimeInterval)*int3(TimeInterval)*int4(TimeInterval)*int5(TimeInterval)
Heat source | General source
Total power | int1(x) - Rotating Anode/Track Radius, y, z, \(10^7\)

Variables

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Unit</th>
<th>Description</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>ht.Q</td>
<td>ht.hs1.Q</td>
<td>W/m³</td>
<td>Heat source</td>
<td>Domain 4</td>
</tr>
<tr>
<td>ht.Qtot</td>
<td>ht.hs1.Q</td>
<td>W/m³</td>
<td>Total heat source</td>
<td>Domain 4</td>
</tr>
<tr>
<td>ht.hs1.Q</td>
<td>rec11(x)*rec21(y)*int1(z)<em>Source3D</em>int2(TimeInterval)*int3(TimeInterval)*int4(TimeInterval)*int5(TimeInterval)</td>
<td>W/m³</td>
<td>Heat source</td>
<td>Domain 4</td>
</tr>
</tbody>
</table>
Temperature (explicit for 3D)

Heat Temperature 1 (Heat bath)

<table>
<thead>
<tr>
<th>Selection</th>
<th>Geometric entity level</th>
<th>Boundary</th>
</tr>
</thead>
</table>

Equations

\[ T = T_0 \]

Settings

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>300[K]</td>
</tr>
<tr>
<td>Classic constraints</td>
<td>Apply reaction terms on All physics components</td>
</tr>
<tr>
<td>Use weak constraints</td>
<td>Off</td>
</tr>
</tbody>
</table>

Variables

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Unit</th>
<th>Description</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>ht.T0</td>
<td>300[K]</td>
<td>K</td>
<td>Temperature</td>
<td>Boundary 3</td>
</tr>
<tr>
<td>ht.temp1 inlinflux</td>
<td>ht.temp1 inlinflux(ht inlinflux)</td>
<td>W</td>
<td>Total net heat power</td>
<td>Global</td>
</tr>
<tr>
<td>ht.temp1 inlinflux,pt</td>
<td>ht.temp1 inlinflux(ht inlinflux,pt)</td>
<td>W</td>
<td>Total net energy power</td>
<td>Global</td>
</tr>
<tr>
<td>ht.temp1 inlinflux,pt,up</td>
<td>ht.temp1 inlinflux(ht inlinflux,pt,up)</td>
<td>W</td>
<td>Total net heat power, upside</td>
<td>Global</td>
</tr>
<tr>
<td>ht.temp1 inlinflux,pt,do</td>
<td>ht.temp1 inlinflux(ht inlinflux,pt,do)</td>
<td>W</td>
<td>Total net heat power, downside</td>
<td>Global</td>
</tr>
<tr>
<td>ht.temp1 inlinflux,pt,dr</td>
<td>ht.temp1 inlinflux(ht inlinflux,pt,dr)</td>
<td>W</td>
<td>Total net energy power, upside</td>
<td>Global</td>
</tr>
<tr>
<td>ht.temp1 inlinflux,pt,dd</td>
<td>ht.temp1 inlinflux(ht inlinflux,pt,dd)</td>
<td>W</td>
<td>Total net energy power, downside</td>
<td>Global</td>
</tr>
<tr>
<td>ht.temp1.Tave</td>
<td>if(ht.temp1.intBnd(ht.rho<em>ht.Cp</em>(ht.ux<em>ht.nx+ht.uy</em>ht.ny+ht.uz<em>ht.nz))==0,ht.temp1.intBnd(T)/ht.temp1.intBnd(1),ht.temp1.intBnd(ht.rho</em>ht.Cp<em>T</em>(ht.ux<em>ht.nx+ht.uy</em>ht.ny+ht.uz<em>ht.nz))/ht.temp1.intBnd(ht.rho</em>ht.Cp*(ht.ux<em>ht.nx+ht.uy</em>ht.ny+ht.uz*ht.nz)))</td>
<td>K</td>
<td>Weighted average temperature</td>
<td>Global</td>
</tr>
</tbody>
</table>

Mesh

Mesh examples for the different dimensions
Danksagung

Mein Dank gilt all denjenigen, die mich ein Stück weit auf dem Weg durch diese Promotionsarbeit begleitet haben, sei es nun fachlich oder menschlich.


Anknüpfend daran ein Dank an Direktor Prof. Rainer Fietkau, der es mir am Strahlenklinikum ermöglichte diese Promotion durchzuführen und dabei unterstütze über den Tellerrand hinauszuschauen. Meine Highlights waren: ein Workshop und zwei Kongresse in den USA, ein Workshop am CERN in Genf und zu Beginn meiner Promotion mehrere Kooperationstage am Entwicklungs­zentrum für Röntgentechnik des Fraunhofer Instituts in Fürth, welche mit meiner Installation eines leistungsfähigen Rechners am Strahlenklinikum ein jähes Ende fanden, ich aber dankbar auf die menschlichen Kontakte zurückblicken möchte.

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Besonders vom Herzen kommt der Dank an meine Freundin Martina, die mir den Rücken gestärkt und mich immer wieder zum Lachen gebracht hat.
Curriculum vitae

Name: Markus Kellermeier
Date and place of birth: 2nd May 1977 at Parsberg, Germany
Place of residence: Erlangen

Basic education and vocational training
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09/1992 - 01/1996 Education in industrial mechanics
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Professional activity and military service
02/1996 - 09/1998 Industrial mechanic
Dehn + Söhne Neumarkt i.d. OPf., Germany
01/1997 - 10/1997 Basic military service
Hemau, Germany

Further education
09/1998 - 07/2000 11th and 12th grades at public vocational high school
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09/2000 - 07/2001 13th grade at public vocational high school
Regensburg, Germany
10/2001 - 05/2008 University studies of Medical Physics
Martin Luther University Halle-Wittenberg, Germany

Doctoral dissertation
12/2010 - 12/2014 Physical assessment of a novel concept for computed tomo-
graphy with a stationary source ring of fixed X-ray anodes
for medical imaging
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Friedrich-Alexander University Erlangen-Nuremberg, Germany
Scientific assistant during the university studies

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    Department of Orthopedics
    Martin Luther University Halle-Wittenberg, Germany

04/2007 - 01/2008  Institute of Medical Physics (IMP Erlangen)
    Friedrich-Alexander University Erlangen-Nuremberg, Germany

Scientific and professional activity

05/2008 - 05/2014  Radiotherapy
    University Clinic, Erlangen, Germany

Since 09/2014  Medical Radiophysics
    University Clinic, Erlangen, Germany

Academic supervision

2011/2012  Scattering of Gamma Rays from Concrete Walls in Radiation Treatment Facilities
            University Clinic, Erlangen, Germany

Conference contributions

Helmut Schneider, Markus Kellermeier, Fabio Monticelli, Stefan Tangl and Kay Raum
Age prediction by microelastic evaluation of cortical bone sections with 200-MHz scanning acoustic microscopy
International Congress on Ultrasonics, Vienna, Austria, 2007

Markus Kellermeier, Reinhold Müller
FA-CT (Fixed Anodes CT) – ein Konzept zu einem Computertomographen mit Festanoden
DGMP Congress, Cologne, Germany, 2013

Markus Kellermeier, Reinhold Müller
New Concept of CT with Fixed Anodes (Fixed Anodes CT, FA-CT)
Radiological Society of North America 2013 Scientific Assembly and Annual Meeting, Chicago IL, USA, 2013

Publications

Willi A Kalender, Stefanie Buchenau, Paul Deak, Markus Kellermeier, Oliver Langner, Marcel van Straten, Sabrina Vollmar and Sylvia Wilharm
Technical approaches to the optimisation of CT
Physica Medica. 07/2008; 24(2):71-9

Willi A Kalender, Paul Deak, Markus Kellermeier, Marcel van Straten and Sabrina Vollmar
Application- and patient size-dependent optimization of x-ray spectra for CT
Medical Physics. 02/2009; 36(3):993-1007

Markus Kellermeier, Christoph Bert and Reinhold Müller
A Novel Concept for CT with Fixed Anodes (FACT): Medical Imaging Based on the Feasibility of Thermal Load Capacity
Physica Medica. submitted