# High Resolution Industrial CT Systems: Advances and Comparison with Synchrotron-Based CT

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Abstract. Nowadays, X-ray tube-based high-resolution CT systems are widely used in scientific research and industrial applications. Compact XCT systems are available that can reach resolutions down to 1  $\mu$ m and below. But the potential, convenience and economy of these lab systems is often underestimated. The present paper shows the comparison of sophisticated conventional  $\mu$ CT with synchrotron radiation-based  $\mu$ CT (SR $\mu$ CT). The different aspects and characteristics of both approaches like spatial and density resolution, penetration depth, scanning time or sample size is described in detail. Beside this, the advances in technology of industrial high resolution CT systems are shown.

The paper also presents recent advances in the area of industrial high resolution CT systems from phoenix product line of General Electric. All major parts are designed to make the system extremely stable during the data acquisition process. So, the system is equipped with granite base and very precise rotation unit. The unique nanofocus tube technology with build-in cooling system stabilizes the tube and at the same time the diamond based target allows high photon flux at very small focal spot sizes. The unique detector with excellent contrast resolution and SNR is also thermally stabilized. Also, the user friendliness is increased through the fully automated process chain starting with detector calibration and going through acquisition and data reconstruction process with automated volume data evaluation The application results of this new technology show its high potentials for usage of the state of the art laboratory systems in the industrial and scientific application fields of material research, metrology, petro-industry, etc. To compare the potentials of laboratory based CT with synchrotron based CT, different samples were used: e.g. a low-carbon steel sample, and an aluminium multi-phase sample (AlMg5Si7) and some other. Concerning measurement costs, scanning volume, accessibility and user-friendliness sub-µXCT has significant advantages in comparison to synchrotron-XCT.

## 1. Introduction

High resolution CT nowadays is a well established method for numerous industrial applications [1][2][3] as well as wide range of research areas [4][5]. For both fields the choice of the optimal method is strongly driven by many different factors like sample size and composition, required spatial and contrast resolution or scanning volume and time, etc. For example in today's quality market, achieving the smallest feature recognition possible in the inspection process has become a higher priority than ever before. Due to complex geometries and miniaturization of many high reliability components in the automotive, electronics and aerospace industries, achieving this level of feature recognition has also become increasingly difficult. CT techniques are used to measure internal distances or the



internal wall thickness of complex castings and areas which are often inaccessible for optical scanners or conventional tactile coordinate measurement machines. The CT volume data provides information for reverse engineering or first article inspection of the entire part by merging it with the CAD model to generate a variance map of both data sets [6][7][8]. Combined, these capabilities contribute to early detection of process and product weaknesses therefore increasing yield and productivity.

Regarding high resolution computed tomography with voxel sizes of a few microns or even in the submicron range the state of the art benchmark is defined by CT setups which use synchrotron radiation for the X-ray source. Synchrotron radiation based CT was introduced in the 1980s by Bonse et al [9]. Nowadays it is a standard experiment for users from scientific research as well as industry at numerous Synchrotron laboratories worldwide. The main advantages of these setups are the highly collimated and almost parallel beam and the photon flux which is several orders of magnitude higher than for conventional X-ray sources. Due to this high flux monochromators can be effectively used to perform CT scans with monochromatic radiation at the desired energy level.

However, in recent years major steps in important hardware components like open microfocus or even nanofocus X-ray tube technology (the later was commercially introduced the first time by phoenix|x-ray in 2001) on the one side and the development of highly efficient and large flat panel detectors (by e.g. GE, Perkin-Elmer, Varian or Hamamatsu) using CCD or CMOS technology on the other, allowed the development of very versatile and high resolution laboratory CT systems like the nanotom m (see next section) which are commercially available. Electromagnetic focusing of the electron beam allows generating X-ray beams with an emission spot diameter down to well below one  $\mu$ m which is essential for CT examination with voxels in the sub-micron range. These characteristics principally allow CT measurements which, with respect to spatial resolution, can compete with many absorption contrast setups at synchrotron radiation facilities [10]. The advantages of laboratory X-ray tube based setups like e.g. its accessibility, userfriendliness, high cost effectiveness, large scanning area and thus comparably high scanning speed (especially for cone beam based systems like the nanotom) are unfortunately still quite often not known or neglected.

The purpose of this work is to show the potential of high resolution laboratory CT scanners as a powerful complementary approach, to support the costly, time consuming and complex examination at synchrotron facilities. In the following the comparison of datasets obtained with both, an absorption contrast SR $\mu$ CT setup and a recently developed high resolution cone beam laboratory scanner will show the unique properties of both approaches. The advantages (and limitations) of both methods are shown at several example specimen with high and low absorption characteristics. These cover the materials science sector as well as the biomedical world. Also, a comparison with an older state of the art sub- $\mu$ Ct system is made.

## 2. The CT systems

## 2.1 The phoenix nanotom m laboratory CT system

The first nanotom CT system for sub-micron scans was introduced in 2006 by phoenix|xray in order to cover the growing demands for a compact laboratory CT system for spatial resolutions which could be reached only by synchrotron radiation based setups on the one hand. On the other it should give the user extreme high flexibility for applications in fields such as materials science, micro mechanics, electronics, geology, and biology to name a few. Therefore, it is particularly suitable for examination of sensors, complex mechatronic samples, microelectronic components as well as for material samples such as synthetic materials, ceramics, sintered alloys, composite materials, mineral and organic samples. The nanotom system was used for several years as the state of the art tomography system for material science labs, and also in this paper it will be referred as a state of the art sub- $\mu$ CT device.

To further increase the application range, the successor system nanotom m was introduced 2010 by GE Sensing and Inspection Technologies within its phonix|x-ray product line. This system incorporates most recent developments of major components of that belong to a CT system like x-ray tube, x-ray detector and very user friendly software package. Also, the overall system design (granite based manipulator, an air-conditioned cabinet, a high accuracy direct measuring system, a very precise air bearing rotating unit as well as vibration insulation of the manipulator) significantly contributes to the to excellent overall image quality.

#### 2.1.1 Components of the nanotom m

In order to cover the widest possible range of samples, the system is equipped with the first commercially available 180kV high power nanofocus (HPNF) tube. This tube was further optimized regarding the long term stability specially for the nanotom m system. The internal cooling of tube reduces effectively thermal drifts and therefore allows even sharper imaging also when running very long scanning times. Optionally, a diamond target is available for extremely high focal spot stability and up to 2 times faster data acquisition at the same high image quality level.

This source can be operated in four different modes. On the one hand, in the so called nanofocus mode it provides an X-ray spot size of down to approximately  $< 0.9 \ \mu m$  which allows excellent detail detectability and can be used for highest resolution CT scans with sub-micrometer voxel size. Due to the penumbra effect, the spot size predominates the images sharpness for extreme magnifications (for details see e.g. [11]). In Fig. 1 the resolution capability of the high power nanofocus source is demonstrated. It shows that the 0.6  $\mu m$  structure (line width) of the JIMA test pattern (designed by the Japan Inspection Instruments Manufacturers' Association for testing high resolution X-ray equipment [12]) can clearly be resolved with more than approximately 20% of the CTF, showing the X-ray source size can be as small as below 0.9  $\mu m$ .



**Fig. 1.** X-ray images of test patterns showing the capabilities of resolution and detail detectability of phoenix|x-ray's high power nanofocus tube. On the left side, the 0.6 µm line pair structure of the JIMA test pattern is clearly resolved

In the high power mode (up to 15 Watts at the target) on the other hand, the tube has enough penetration power to examine high-absorption samples like copper, steel or tin alloys and thus allowing e.g. the analysis of new connection systems for electronic devices or high absorbing geological samples, etc. The tube is equipped with a transmission type target. This means the target is a thin layer (a few microns) of W or Mo which has been sputtered on the beryllium or chemical vapor deposited (CVD) diamond exit window which is hit by the focused electron beam. For the transmission geometry, the X-rays are emitted in the same direction as the incoming electron beam.

On the detection side, a unique GE flat panel detector is firstly used in an industrial CT device. This detector is temperature stabilized and is based on amorphous silicon (a-Si) panel with CsI scintillator deposited as needle structure. It offers  $3,072 \times 2,400$  pixels with 100mm pixelsize and excellent dynamic range of up to 10,000 : 1, which is up to  $\sim 10x$  higher compared to the detector in the older nanotom systems. The high dynamic range and signal-to-noise ratio (SNR) allows up to 4 time faster CT acquisition at the same signal-to-noise ratio. To further increase the field of view, the 1.5-fold virtual detector possibility can be used.

For reconstruction of the volume data GE Sensing & Inspection Technologies uses a proprietary implementation based on Feldkamps cone beam reconstruction algorithm [13]. The reconstruction software contains several modules for artefact reduction (e.g. beam hardening, ring artefacts, drift compensation) to optimize the results. In Fig. 2, the effect of the ring artefact suppression method is shown. Here, two identical cross sections of a cortical bone sample (human bone) scanned with the nanotom at 90 kV and 150  $\mu$ A and 1.8  $\mu$ m voxel size are shown. The original study was performed by M. Dalstra et al using the SR $\mu$ CT setups at HASYLAB/DESY to quantitatively evaluate the remodelling process in osteoporotic cortical bone [14]. For quantitative analysis of the datasets it was essential to minimize the artefacts in the reconstructed volume. As it can bee seen in Fig. 2, the approach implemented by phoenix|x-ray effectively eliminates the ring artefacts and therefore a further quantitative analysis could also be performed on the nanotom CT datasets as it was done with the results of the SR $\mu$ CT scans. One remarkable result of the shown nanotom data is the high contrast resolution which even allows a separation of the different density phases in the bone [14].



Fig. 2. Cross section of cortical bone sample scanned with the nanotom. Due to an effective ring artifacts suppression a segmentation of the different phases in the bone structure becomes possible.

With datos x 2.0, the entire CT process chain can be fully automated, significantly reducing operator time: Once the appropriate setup is programmed, the whole scanning and reconstruction process including volume optimization features or surface extraction runs without any operator interaction. Furthermore, 3D metrology or failure analysis tasks performed with third party programs can also be executed automatically. Once programmed, automatic creation of a first article inspection report even with complex internal geometries can be provided within an hour.

### 2.1.2 Performance comparison with state of the art sub-micron CT

To compare the performance of the new nanotom m CT device, a typical sample from the material science application range was chosen: a metallic foam from an material development and characterization lab in automotive industry, sample size ca. 2x2x3 cm, fig. 3. The results made with nanotom m show a clear improvement comparing with a state of the art sub-micron CT system: the signal-to-noise ration is improved by 100% and thus, finer details can be distinguished in the volume data. This benefit can be achieved due to diamond window of the x-ray tube on the one hand and low noise high contrast GE x-ray detector on the other hand.



Fig. 3. Comparison of scans of a metallic foam on the state of the art sub-micron CT system (older nanotom) (left) and on the new phoenix |x-ray nanotom m CT system (right). In both cases, the voxel size of 15μm, the tube settings and scanning time of 1 hour were identical

## 2.2 The synchrotron CT setup

Synchrotron radiation based micro-CT systems (SR $\mu$ CT) offer significant advantages by their adjustability, partial coherence and nearly parallel beam of high brilliance [18]. These advantages cause fewer artifacts, improved contrast and resolution, as well as faster recording for synchrotron tomography. In [16], a comparison between synchrotron based and laboratory CT system is shown. There, a synchrotron based  $\mu$ CT setup at HASYLAB/DESY in Hamburg/Germany was used to investigate some higher absorbing materials and to compare the results with the state of the art sub- $\mu$ CT.

The ID19 beamline of ESRF—European Synchrotron Radiation Facility in Grenoble [17, 18] provided monochromatic X-rays with beam energy of 29 kV in parallel beam geometry. The SR $\mu$ CT projections were recorded by a 2D-CCD camera with 2048x2048 pixels and an effective pixel size of 0.3 mm. For reconstruction 1500 projections were acquired. The samples were measured in phase contrast mode using a distance sample-to-detector of 39 mm. The recordings took about 15 min.

### 3. Comparison

Two different sample types have been chosen to be studied by  $SR\mu CT$  as well as with high resolution industrial laboratory sub-micron CT system. Identical regions of the specimen described in the following have been scanned by both systems. In order to allow a quantitative comparison, the resulting volume data had to be registered to each other using either a software described in [15] or manually using e.g. VGStudio MAX by Volume Graphics, Heidelberg/Germany.

In the material science several typical tasks can be solved using CT technology. One common task is to quantitatively and qualitatively investigate inhomogeneities like pores, cracks, inclusions of higher and lower density, ... Classically used standard methods are mechanical slicing together with subsequent evaluation using either optical microscopy or even scanning electron microscopy (SEM). In the last years, x-ray CT becomes more and more popular due to its capability for volumetric and non-destructive evaluation of the materials.

#### *3.1. Low-carbon steel sample*

The low-carbon steel investigated in this paper was produced using continuously cast condition and has max. diameter of ca. 0.5 mm. Inhomogeneities that are of special interest for this kind of samples are pores and different phases like CaAl-, MgO-, CaS-, NiC-phases. The table 1 shows the CT settings that were used to achieve the results. The results are comparatively shown in the fig. 4.

CT Parameter	State of the art sub-µCT	New nanotom m	SRµCT, ID19 beamline, ESRF Grenoble
Voltage (kV)/ beam	50, W Target	50, W Target	30
energy			
Current (µA)	480	480	-
Tube Mode	3	3	-
Voxel size (µm)	0,5	0,5	0,3
Scanning time (min)	180	180	15

Table 1. CT settings for low-carbon steel sample

State of the art sub-µCT

sub-µCT with new nanotom m

SRµCT at ID19 beamline/ ESRF Grenoble [17]



**Fig. 4.** Comparison of CT results for low carbon steel sample between state of the art sub-µCT (left), subµCT with new nanotom m (middle) and SRµCT (right)

As it was already reported in [17], the ring artefacts are most pronounced for the  $SR\mu CT$ -data, whereas both laboratory devices show almost no ring artefacts due to special settings in the hard- and software on the one hand and also due to unique temperature stabilized detector in the nanotom m device. Ring artefacts are well known and are caused

by non-stabilities or faults of the detector pixels. In [17], it was also reported that both, state of the art sub- $\mu$ CT as well as SR $\mu$ CT, shows very comparable contrast and spatial resolution. But also some drawbacks of the laboratory system were shown: this is the signal-to-noise ratio and the edge sharpness in the volume data.

With the new nanotom m, the sharpness could be increased by 40% comparing to the older state of the art sub- $\mu$ CT. This fact can also be clearly seen in the fig. 4. Also, the SNR is increased by ca. 100%, compare also with fig. 3. These both positive advances are not only due to new GE detector technology, that is firstly available within the new nanotom m system for industrial applications, but also due to increased thermal stability for the whole system (compare section 2.1).

The fig. 5 illustrates also the excellent contrast resolution of the nanotom m, that starts to be comparable with the contrast resolution of  $SR\mu CT$  even for low absorbing inclusions in high absorbing steel sample. This is unique for industrial CT systems.



Fig. 5. View on two different details in the steel sample. The details show pores surrounded by low and high absorbing inclusions Left: results from the nanotom m; right: results from SRµCT. In the

#### 3.2 Aluminium cast alloy AlMg<sub>5</sub>Si<sub>7</sub>

An other material science sample that was investigated to compare different CT systems was an cylindrical  $AlMg_5Si_7$  gravity cast sample with a diameter of ca. 0.4mm. Inhomogeneities that are of interest here include pores, eutectic Si phases as well as different Al-Fe-Si phases. Table 2 shows the CT parameters used at different devices and fig. 6. illustrates the CT results.

CT Parameter	State of the art sub- µCT	nanotom m	SRµCT, ID19 beamline, ESRF Grenoble
Voltage (kV)/ beam energy	50, Mo Target	50, Mo Target	29
Current (µA)	480	480	
Tube Mode	3	3	
Voxel size (µm)	0,5	0,5	0,3
Scanning time (min)	240	240	15

Table 2. CT settings for Aluminium cast alloy AlMg<sub>5</sub>Si<sub>7</sub>



**Fig. 6.** Comparison of CT results for AlMg<sub>5</sub>Si<sub>7</sub>: state of the art sub-µCT (left), sub-µCT with new nanotom m (middle) and SRµCT (right)

Pores and ferroaluminides are clearly visible in all three results, as well as  $Mg_2Si$  phases. But again, the nanotom m results shows better SNR and contrast resolution comparing with the state of the art sub-µCT. In the STµCT results, also the phase contrast effects are clearly observable. This is due to very monochromatic x-ray spectrum, that is typical for synchrotron radiation sources. The phase contrast leads to a kind of "ringing" resp. edge amplification and can be advantageous for visual inspection as well as a drawback for automated inspection that often requires some volume segmentation.

#### 4. Summary and outlook

The present study aimed to show on the one hand new advances in laboratory sub- $\mu$ CT systems and on the other hand a comprehensive comparison of performance between commercial high end CT scanner with a nanofocus x-ray tube and a absorption synchrotron radiation based CT setup. Two samples with different absorption characteristics (a steel and an aluminum sample) have been scanned in a sub-micron voxel size. The chosen specimens are good examples for typical application from the material science.

The analysis of the scans reveals that the new phoenix|x-ray nanotom m has clear advantages comparing to the older state of the art laboratory sub- $\mu$ CT systems due to significant improvements in overall system design, new temperature stabilized detector with better contrast resolution and high performance cooled nanofocus x-ray tube with much better flux at the same focal spot sizes due to diamond window. This system gives excellent data quality which in many cases can even compete with SR $\mu$ CT data. In [16] was reported that especially in some cases where higher voltages are required to penetrate bigger samples, the state of the art sub- $\mu$ CT systems can even outperform the SR $\mu$ CT systems with respect to spatial resolution. In other cases, the SNR and the resolution was very comparable. Also, the bigger scanning volume of a cone beam system like nanotom m is an advantage and can lead to even lower scanning times for bigger samples. With the new nanotom m system even better results can be expected for larger samples with higher absorption materials, what will be put under examination within next research steps.

The synchrotron radiation CT on the other hand provides an excellent contrast resolution, precisely adjustable monochromatic radiation and therefore no beam hardening artefacts. So, for situations in which optimal contrast resolution or artefact free data is needed, the synchrotron radiation based CT would be the system of choice.

In total, the major pros of the laboratory scanner are its large field of view, large scanning volume, high penetration power due to the 180kV tube, scanning speed (scanned volume per time), ease of use and overall cost effectiveness. Also, the recently developed high performance industrial sub-µCT scanners like nanotom m by phoenix x-ray can

adequately support and complement research projects where high quality CT data is required. Due to its flexibility, the nanotom can be used for both, extreme high resolution scans with sub- $\mu$ m voxel size of small samples on the one hand or also fast scans of high absorbing (or larger) specimen using the high power mode on the other.

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