Atomic and nuclear physics

X-ray physics

X-ray tomography

LD
Leaflets
Physics

P6.3.8.12

Computed tomography of simple geometrical objects

Measurement with the X-ray image sensor

Objects of the experiment

- Understanding the material absorption of the X-rays.
- Understanding the 3D-image reconstruction used for the computed tomography.
- Device adjustment and quantification of the picture resolution restrictions.

Principles

The initial intensity I_0 of an X-ray beam is reduced after passing through a homogeneous material according to the Lambert law

$$I_s = I_o\,\mathrm{e}^{-\mu s}. \qquad (1)$$

Here is I_s the resulting beam intensity, s the length of the way through the material and μ the material absorption coefficient. The latter has the physical dimension 1/Length and is material specific, depending a.o. on the material density, atomic number and the energy (wavelength) of the beam. Absorption coefficient reveals therefore material distribution, knowledge of which is of a great importance in medicine and other fields.

For inhomogeneous materials the constant absorption coefficient μ is replaced by $\mu(s)$ and the exponent in eq. (1) becomes an integral

$$\ln \frac{I_s}{I_0} = -\int_0^s \mu(s')\,\mathrm{d}s'. \qquad (2)$$

For a general absorption coefficient $\mu = \mu(x,y,z)$, given as a function on the three dimensional space, the integral in eq. (2) is written as a path integral

$$\ln \frac{I_s}{I_0} = -\int_0^s \mu(x(s'),y(s'),z(s'))\,\mathrm{d}s' \qquad (3)$$

along the straight beam path. For a fixed plane Σ (in the three dimensional space) parametrized by a coordinate system (x',y'), any line is given by the slope m and the y'-intersect b. For a function $\mu(x',y')$ on the plane Σ the integral along the line given by (m,b) is a functional assignment

$$(m,b) \longmapsto \int_{-\infty}^{+\infty} \mu(x',mx'+b)\,\mathrm{d}x', \qquad (4)$$

called the Radon transformation. According to the Radon's theorem (J. Radon (1917)), the function $\mu(x',y')$ can be reconstructed if function's integral is known for all (m,b).

Computed tomography (CT) is a direct application of Radon's theorem. According to eq. (3) a line integral of the absorption coefficient μ along the beam path in a sectional plane of a body is given by the logarithm of intensity fraction. Measuring therefore intensity fraction for many lines, absorption coefficient μ can be reconstructed. Its graphical representation reveals the sectional plane compound structure. Substance identification with application to medicine is studied in experiments P6.3.8.3-4 and P6.3.8.13-14. A CT measurement scheme is shown in fig. 1. Intensity fraction measurement for many lines is realized by the rotation of the body.

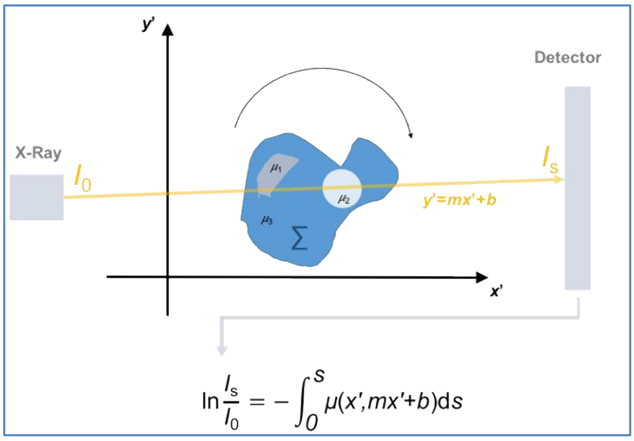


Fig. 1: A schematic representation of a CT-scan. Different colors mark different vales of μ in the sectional plane Σ.

Measurement time restricts the number of rotation angles. A high-pass filter is therefore applied to measured data before reconstructing μ. A high-pass filter highlights boundaries of different materials (like bones and organs in a human body) as it amplifies the contrasts. It reduces therefore errors caused by the finite number of measurements. This procedure is called the *filtered Radon back transformation* and is the key of the CT algorithm.

The number of rotations and the used high-pass filter influence image quality and its resolution. The resolution is also restricted by the pixel size of the detecting device. A further source of image quality error is the continuous X-ray spectrum. Eq. (1) holds only for the monochromatic beam. Passing through material the X-ray beam spectrum is shifted to higher energies. This effect is called beam hardening and is studied in experiments P6.3.8.4 and P6.3.8.14. Absorption coefficient values in the whole body are obtained by combining measured data for different sectional planes. In this case the smallest image unit is called a voxel. Graphical representation of μ is the end result of the computed tomography. Details of the graphical representation are studied in experiments P6.3.8.5 and P6.3.8.15.

The 1979s Nobel Prize in Physiology or Medicine was awarded to Allan M. Cormack and Godfrey N. Hounsfield for their development and application of computed tomography.

YAS 2017-04

Devices

1	X-Ray apparatus	554 800
1	Goniometer	554 831
1	X-Ray tube, Au	554 866
1	Computed Tomography Pro package	554 820P
1	Phantom, 3D	554 823

additionally required:

1 PC with Windows XP/Vista/7/8/10 (x86 or x64)

In this experiment a CT scan of a phantom is done. The phantom is a test block for the computed tomography consisting of several layers for the valuation of the highly and lowly contrast resolution. Students learn device adjustment, sources of errors and resolution restrictions. A quantitative measurement of hole diameter is done to quantify CT's resolution power.

Setup

- Insert the Au tube in the X-ray apparatus.
- Put the dual-link DVI cable through the hole in the X-ray experiment chamber.

a) Outside of the X-ray apparatus:

- Connect the dual-link DVI cable's end with the sensor's USB module. Connect the latter with power supply.

b) Inside of the X-ray apparatus:

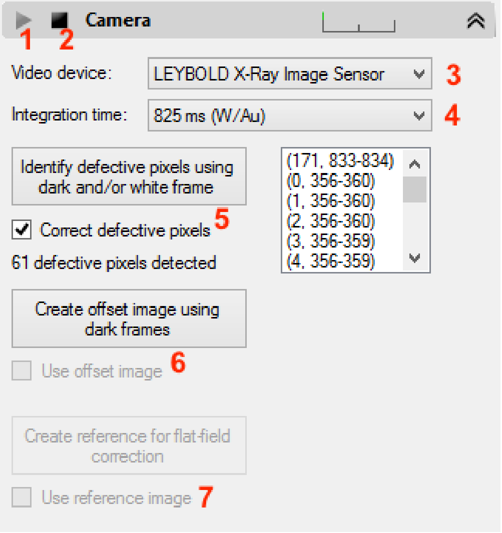
- Mount the goniometer in the X-ray experiment chamber and move it to the right side. Fix the goniometer using the two screws in its lower part.
- Put the precision rails for X-ray image sensor into the experiment chamber.
- Mount the X-ray image sensor onto the precision rails.
- Connect the dual-link DVI cable with the X-ray image sensor.
- Connect the X-ray apparatus and the X-ray image sensor to the PC using USB cables.

Image sensor adjustment

Note

Image sensor adjustment must be performed prior to the measurement.

- Turn off the X-Rays (fig. 3: **2**).
- Identify defective pixels and correct (fig. 2: **6** and **7**).
- While X-Ray beam and high-voltage are off (fig. 3: **2**) create an offset image using dark frames (fig. 2: **6**). Average over app. 10 images and use the offset image.
- Turn on the X-Rays (fig. 3: **1**).
- Record a white image averaging over app. 10 images and use this as a reference image (fig. 2: **7**).
- Turn on the PC and the X-Ray apparatus.
- Start the CT software and find the expandable tabs on the left.
- Choose the video device (fig.2: **3**) and turn it on (fig. 2: **1**).



Video device: LEYBOLD X-Ray Image Sensor

Integration time: 825 ms (W/Au)

☑ Correct defective pixels

61 defective pixels detected

(171, 833-834)
(0, 356-360)
(1, 356-360)
(2, 356-360)
(3, 356-359)
(4, 356-359)

☐ Use offset image

☐ Use reference image

Fig. 2: Video device settings: **1**: Device on, **2**: Device off, **3**: Choose video device, **4**: Choose video input, **5**: Choose average time, **6**: Identify defective pixels, **7**: Correct defective pixels,

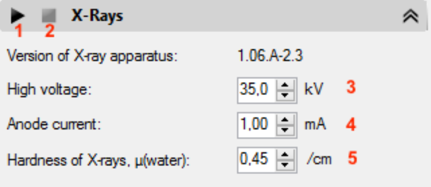
Rotary axis adjustment

Note

Rotary axis adjustment must be performed after every device setup.

- Mount the LEGO® adapter into the goniometer.
- Combine five LEGO® bricks together and mount these on the LEGO® adapter in its middle.
- Close the X-Ray apparatus and turn the on the high voltage.

In the now visible X-ray image of the LEGO® bricks, the prolonged rotation axis should appear horizontal in the middle of the image and coincide with the red line. In case of clearly seen misalignment turn off the X-ray radiation and make a rough image sensor adjustment. Use the screws around the camera inside the CT module to tilt and roll. Turn on the X-rays and the image sensor. Carry out a measurement keeping all settings as shown in figs. 2 – 4 by clicking on the ▶ button.



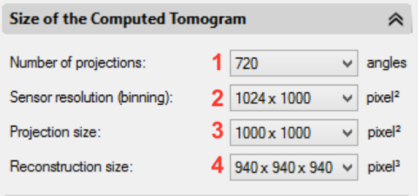
Version of X-ray apparatus: 1.06.A-2.3

High voltage: 35,0 kV

Anode current: 1,00 mA

Hardness of X-rays, µ(water): 0,45 /cm

Fig. 3: X-ray setting: **1**: X-ray on, **2**: X-ray off, **3**: High voltage, **4**: Anode current, **5**: X-ray hardness.



Number of projections: 720 angles

Sensor resolution (binning): 1024 x 1000 pixel²

Projection size: 1000 x 1000 pixel²

Reconstruction size: 940 x 940 x 940 pixel³

Fig. 4: CT size setting: **1**: Number of projections, **2**: Sensor resolution, **3**: Projection size, **4** Reconstruction size.

After the measurement the X-rays are switched off automatically. Perform the following steps:

- Change to the 2D view by clicking on the **2D** button in the upper toolbar.
- Move the slider in the bottom to the **left** until a sectional plane close to the upper end of LEGO® bricks is shown on the screen.
- Vary the rotary axis value (fig. 6: **1**) until the double contours are roughly minimal (fig 5: **b**).
- Press "1st position" button (fig. 6: **2**) and wait until the software optimizes the position.
- Move the slider in the bottom to the **right** until a sectional plane close to the LEGO® bricks' bottom is shown on the screen.
- Vary the rotary axis value (fig. 6: **1**) until the double contours are minimal (fig. 5: **b**).
- Press "2nd position" button (fig. 6: **3**) and wait until the software optimizes the position.
- Turn off the X-Rays and adjust sensor position using the screws in a way the CT software suggest (fig 5: **4** and **5**).

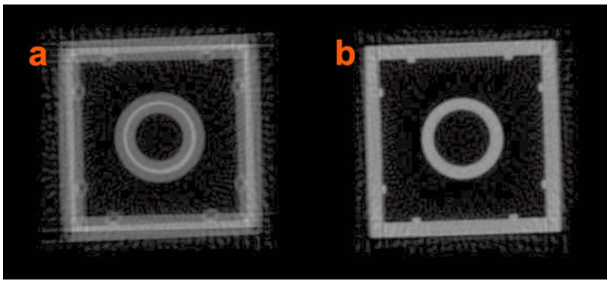
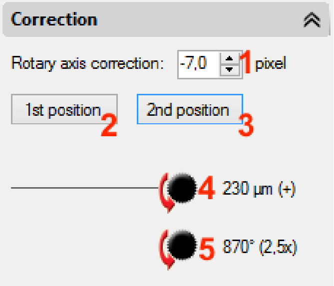


Fig. 7: Rotary axis adjustment: **a**: double contours, **b**: no double contours – the correct position.



Correction

Rotary axis correction: -7,0 pixel

1st position

2nd position

230 µm (+)

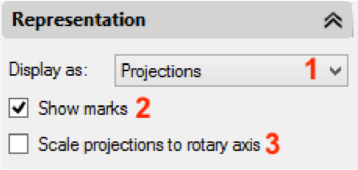
870° (2,5x)

Fig. 8: Correction: **1**: Rotary axis correction, **2**: 1st position, **3**: 2nd position, **4**-**6**: suggested camera position adjustment.

Carrying out the experiment

- Carry out the upper steps for the image sensor and the rotary axis adjustment.
- Unmount the LEGO® bricks from the LEGO® adapter and mount the phantom in the middle of the LEGO® adapter and close the X-ray apparatus.
- Increase the number of projections (fig. 4: **1**) to 360 or higher depending on the graphic card.
- While the Phantom is mounted into the goniometer, carry out a measurement keeping all other settings as shown in figs. 2 – 4.

During the measurement, the image reconstruction can be observed in 2D as well as in 3D mode. Use the **2D** and the **3D** buttons in the upper toolbar to change modes. The image is gradually getting better as more and more angular steps are done and taken into account in the Radon transformation.



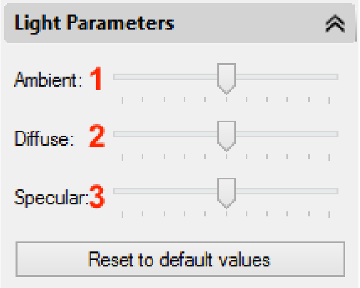
Representation

Display as: Projections

☑ Show marks

☐ Scale projections to rotary axis

Fig. 5: Representation: **1**: Displays as, **2**: Show/Hide Marks, **3**: Scale projections to rotary axis.



Light Parameters

Ambient:

Diffuse:

Specular:

Reset to default values

Fig. 6: Light parameters: **1**: Ambient, **2**: Diffuse, **3**: Specular.

In 2D mode image representation can be changed between "Projection", "Log projection" and "Filtered log projection" (fig. 7: **1**). In this way we can visualize the difference between the standard X-ray image and the filtered projections used for the CT image reconstruction.

Evaluation

(a) General graphical effects:

The main CT software graphical effects are briefly listed below. The detailed analysis of all graphical effects is studied in experiments P6.3.8.5 and P6.3.8.15. A detailed description of the software is available in the instruction sheet. Please see the manual for catalogue number 554821.

a.1) 2D and 3D modes

Use the **2D** and the **3D** buttons in the upper toolbar to switch the modes.

In 2D mode it can be changed between different sectional planes. Use the slider in the bottom. Change displays between "Projection", "Log projection" and "Filtered log projection" (fig. 7: **1**). In this way it can be distinguished between the standard X-ray image and the filtered projections used for the CT image reconstruction. The sectional planes in 2D mode are orthogonal to the rotary axis.

In 3D mode the image of the scanned object can be rotated and observed from different view angels. Use the slider in the bottom to change between different sectional planes. In contrast to 2D view, sectional planes shown in 3D mode are orthogonal to the observer's looking direction and parallel to the screen respectively.

a.2) Arbitrary sectional plane

Use the button in the upper toolbar while in 3D mode to change the representation between the selected sectional plane or the selected sectional plane and the rest of the scanned object behind it. If the button is active, the sectional plane shown on the screen can be chosen for radiographic evaluations by clicking on the button.

a.3) Colour spectrum

Use the button in the upper toolbar to choose one of the 5 different colour spectra can be chosen. Different colours highlight different absorption coefficient values. Some of the colour schemes are better suited to colour blind users.

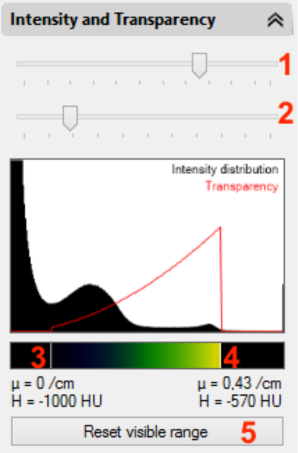


Fig. 9: Intensity and transparency: **1**: Intensity, **2**: Transparency, **3**: Lower transparency limit, **4**: Upper transparency limit, **5**: Reset settings.

a.4) Switching light on

Use the 💡 button to turn on a virtual light source, which amplifies the CT-scan's 3D impression. Expand the "Light Parameters" (fig 8) to change settings.

a.5) Intensity and transparency

In the "Intensity and Transparency" tab (fig. 9) different representation options can be set up. The upper slider (fig 9: **1**) changes the image intensity while the lower slider (fig 9: **2**) changes the transparency.

a.6) Stereoscopic view

An even stronger 3D effect is achieved by activating the stereoscopic view with the 3D button. The image in this mode must be viewed through the anaglyph (red-cyan) glasses.

Measuring example

a) Graphical effects:

Fig. 10 shows how different material can clearly be distinguished by color or brightness respectively. The color gradient in the direction of the rotary axis is due to the hardening effects.

In fig. 11 all four hole sets are recognizable. The diameter measurement is presented below.

The hardening effects are responsible for two colors in the phantom's 3D view (fig. 12, bottom). The phantom appears to be covered by an envelope made out of a soft material.

Fig. 13 shows the stereographic representation. The image must be viewed through the anaglyph (red-cyan) glasses.

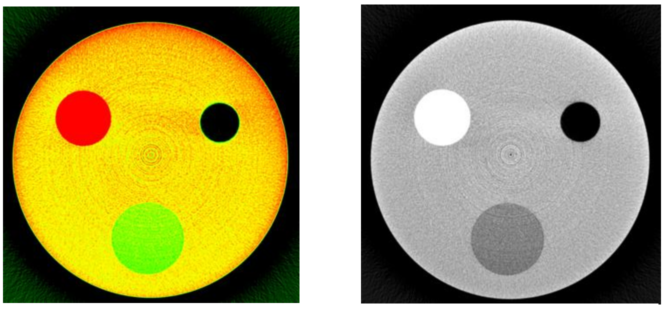


Figure 10: Phantom's sectional plane containing different material samples. (*left*) Color representation, (*right*) Grey scale representation.

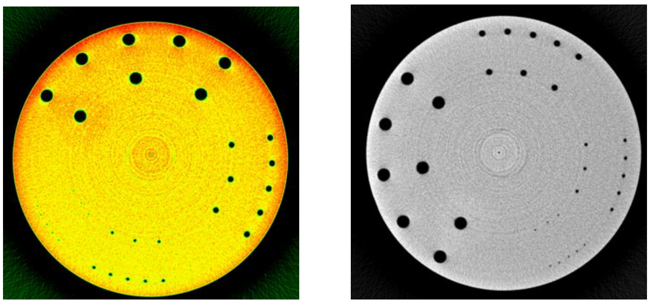


Figure 11: Phantom's sectional plane with holes: (*left*) Color representation, (*right*) Grey scale representation.

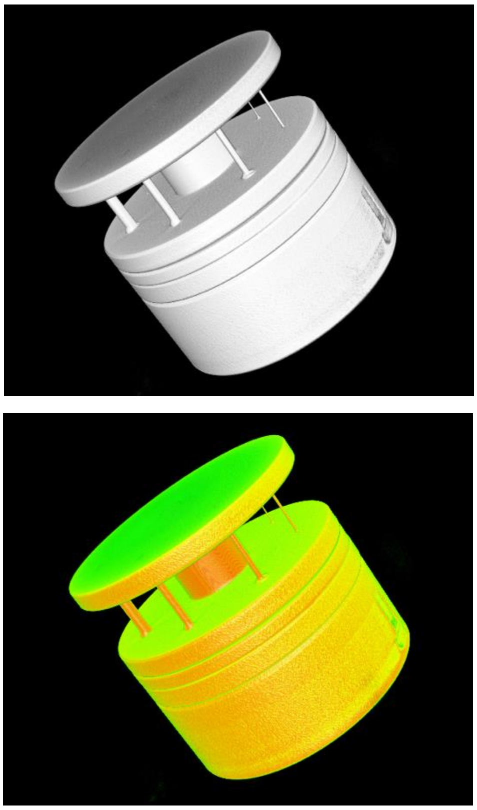


Figure 12: Phantom's 3D view: (*bottom*) Color representation, (*top*) Grey scale representation.

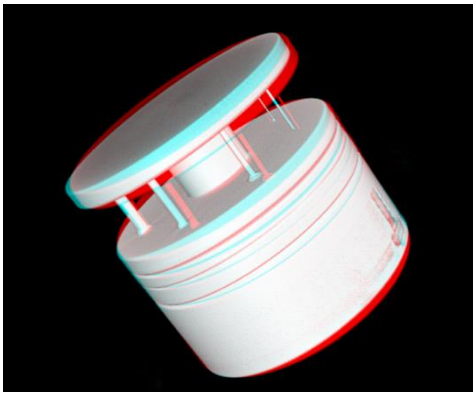


Figure 13: Phantom's 3D view, stereoscopic representation. Must be viewed through the anaglyph (red-cyan) glasses.

b) Resolution power measurement:

As seen from fig. 11, all four hole sets can be seen. Fig. 14 shows examples of line profile measurements. The *x*-axis in the diagrams are scaled differently. The hole diameters obtained from the line profiles are given in tab. 1.

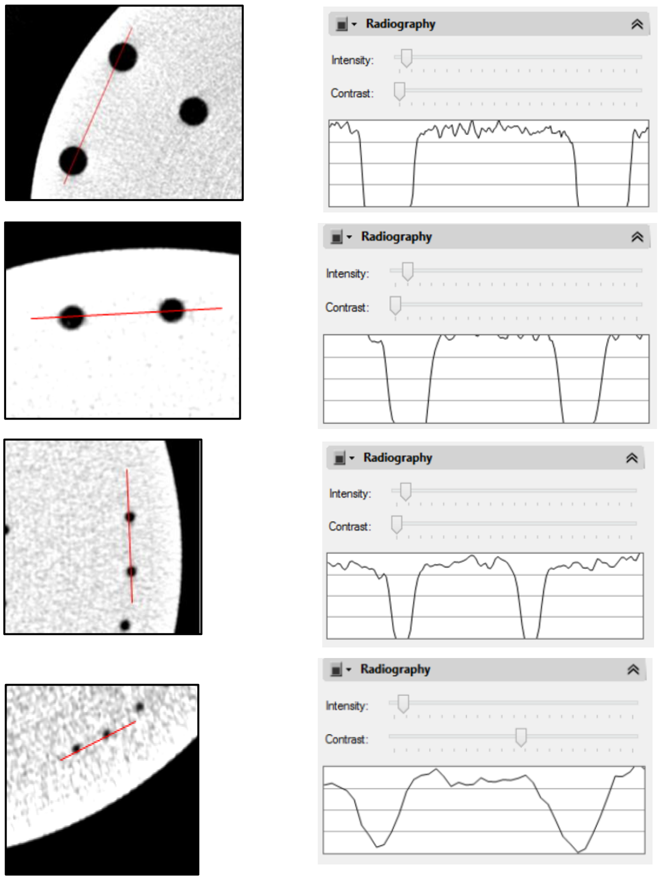


Fig. 14: Resolution power measurement: (*left*) Line profiles in the sectional plane; (*right*) Corresponding diagrams. Red lines highlight the line along which the profile is calculated. Hole diameter is increased by factor of 2 from top to bottom, starting at 1,6 mm. *X*-axis of the diagrams is differently scaled.

	Size 1 in mm	Size 2 in mm	Size 3 in mm	Size 4 in mm
Original Size	1,60	0,80	0,40	0,20
CT Result	1,65	0,90	0,46	0,25

Tab. 1: Hole diameters obtained from the line profiles shown in fig. 14.

Line profiles of the biggest and the smallest hole plotted in the same coordinate system are shown in fig. 15. Absorption coefficient in the line profile of the smallest hole remains clearly large than 0. Thus the resolution power is at most of app. 0,2 mm.

Image resolution restrictions due to CT geometrical setup can be estimated. The X-ray is radiated from an anode with the initial ray size of app. 1,5 mm. The rays reach a point at the object's position in the experiment chamber under an angle. With the distance from the anode to the object of app. 32 cm. The distance from the object to the image sensor is app. 4 cm.

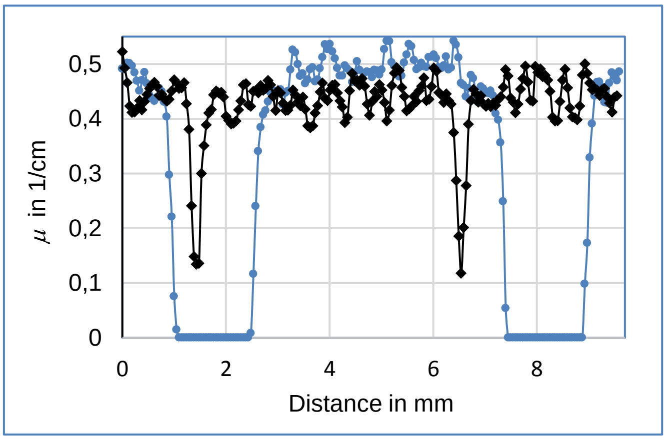


Fig. 15: Line profiles of the smallest and the biggest holes in the same coordinate system: (♦) small hole line profile; (●) big hole line profile.

The point at the object's position is projected on the image sensor's surface with at least a size of

$$x = 1{,}5\ \text{mm}\,\frac{4\ \text{cm}}{32\ \text{cm}} = 0{,}1875\ \text{mm}. \qquad (5)$$

If image sensor resolution is set to 1000x1000 px^2, then pixel width (reps. height) is smaller than 0,05 mm. This is clearly way smaller than the geometric resolution restriction given by eq. (5).
The fact, that the smallest hole is not completely resolved is explained by number of measured angles. Fig. 16 shows line profiles for the 0,4 mm hole, both for a CT scan with 720 and 180 projections. All other settings haven't been changed. The peak of the 180 projections scan is sharply shaped. The curve does not go down to 0.

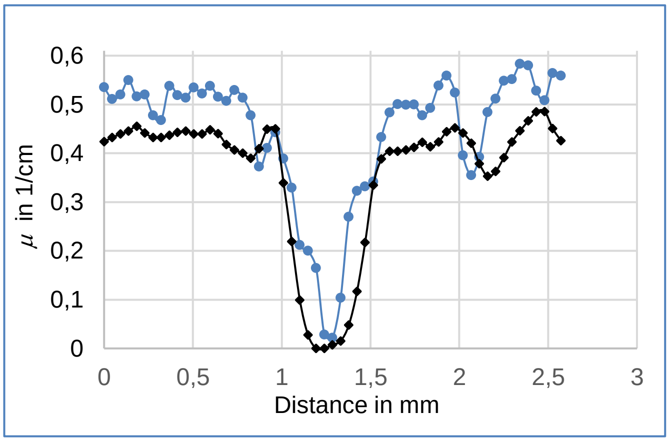


Fig. 16: Line profiles of the 0,4 mm hole: (♦) 720 projections; (●) 180 projections.