# New Concepts for the Measurement of Focal Spot Parameters of Nano- and Microfocus X-Ray Tubes

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**Abstract**

Accurate measurement of focal spot sizes of X-ray tubes, betatrons and linear accelerators is still an open problem. Several standards are currently active, which provide different results depending on the focal spot shape. CEN published the standard series EN 12543 (five parts) in 1999, which describes the measurement of focal spot sizes of X-ray tubes for NDT applications. The measurement procedure and its tolerances deviate from the measurement standards for medical X-ray tubes, e.g. EN 60336:2006 / IEC 60336:2005. EN 12543 describes different measurement methods for X-ray tubes with focal spots in several size ranges, defined as macrofocus, minifocus and microfocus. CEN TC 138 WG 1 und ASTM E 07.01 are revising (CEN) or have just revised (ASTM) the standards for focal spot size measurements, basing them on pinhole or edge measurements only. Slit cameras are exclusively applied for medical tube evaluation. Tomographic methods for focal spot size shape reconstruction were proposed and will be discussed, but have not yet been used for standardization. The currently available standards cover the range of spot sizes from five µm up to several millimetres. During the last years, more and more nanofocus tubes have been developed for high-resolution applications and microscopy. Manufacturers and users apply different methods for measurement of nanofocus spot sizes and image resolution, which differ by a factor of up to two. These well-known methods and new alternative methods for the measurement of nanofocus spots (size and shape) will be evaluated and improved in the EMPIR project “NanoXSpot” in order to develop a related measurement standard.

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# NEW CONCEPTS FOR THE MEASUREMENT OF FOCAL SPOT PARAMETERS OF NANO- AND MICROFOCUS X-RAY TUBES

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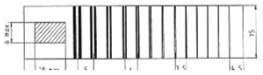
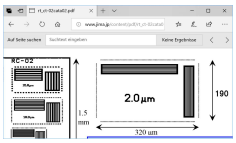
## Standards for Measurement of Focal Spots

- **Standards and Committees:**
  - **CEN TC 138 WG 1** EN 12543 Part 1-5:2011
  - **ASTM International E07.01** E 1165-17, E2903-18
  - **IEC** (International Electrotechnical Commission) IEC 60336:2005, IEC 62976:2017
  - **NEMA** (National Electrical Manufacturers Association) XR 5:1992(R1999)
- **Standards are different and provide different results**.
  - This is critical, if measurement ranges overlap
- **CT algorithms are used** to substitute **pin hole camera measurements** with better sensitivity
- **A standard for measurement of spot sizes of nanofocus tubes will be developed in the** EMPIR-Projekt „**NanoXSpot**" as prEN 12543-6.

## The Currently Unsatisfying Situation …

- **EN 12543 parts 1 - 5 provide different measurement values for the same focal spot in the overlap range of the standards**
- **ASTM and IEC standards provide again different values**
- **IEC 60336 (Medicine) permits different tolerances in comparison to NDT**
- **User standards in NDT shall provide the "right" focal spot size for**
  - **Calculation of the minimum magnification** achieving the standard requirements of image unsharpness $U_{im}$
- **User unsharpness measurements are based on line pattern image quality indicators (IQI) such as**
  - Duplex wire IQI, ISO 19232-5, ASTM E 2002
  - Line pattern IQIs (e.g. Siemens star, JIMA-Target)








ISO 17636-2: Weld testing
EN 12681-2: Casting testing
ASTM E 2698: Standard practice for DDAs

$$u_{\mathrm{im}} = \frac{1}{v}\sqrt{u_{\mathrm{G}}^2 + \left(2 \times \mathrm{SR}_{\mathrm{b}}^{\mathrm{detector}}\right)^2}$$

Cubic formula in ASTM E 2698

**Requirement:**

- Measurement of **image unsharpness $U_{im}$** based on detector unsharpness, geometric unsharpness and magnification
- Not exceeding maximum limits for $U_{im}$ oder $SR_b^{image}$

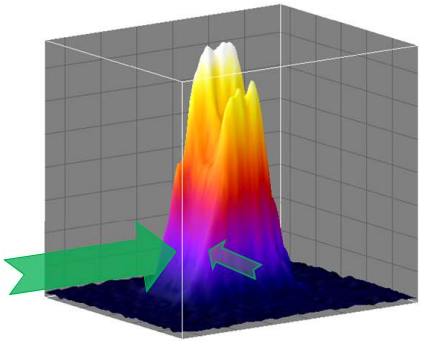
**Measurement of image unsharpness $U_{im}$ und $SR_b^{image}$** is based on duplex wire IQI measurements in most standard practices based on ISO 19232-5 und ASTM E 2002.

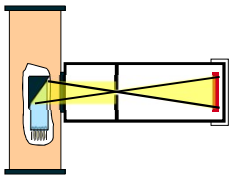
**Only focal spot sizes** measured with **Edge or Line Camera Methods**

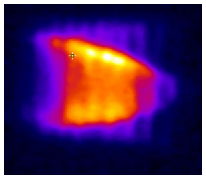
→ conform to the results of measurements with duplex wire IQIs!

→ **Consequently, the results of all measurement methods shall be converted to these values.**

Calibrate the pixel size and calculate the integrated line profile of the pin hole camera image







- Scheme of a pin hole camera
- 2D-image and pseudo 3D image of a focal spot radiograph (0,57 x 0,53 mm²)

## Calculation of the focal spot size with profile integration corresponding to ASTM E 1165



## Evaluation with „Integrated Line Profile Method“ (ILP)

**Set cursors at 16% and 84% in the integrated line profile**
(Klasens method, corresponds to one standard deviation of normal distribution: 68%)

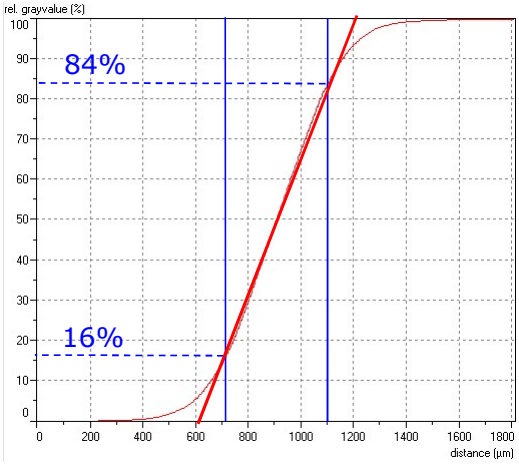
**Measure the distance between the cursors (388µm)**

**Multiply with 1.47**
(68% → 100%)

→ **570 µm focal spot length**

→ **Free Software ISee_demo!**
http://www.uzscherpel.de/BAM/ic/index.html

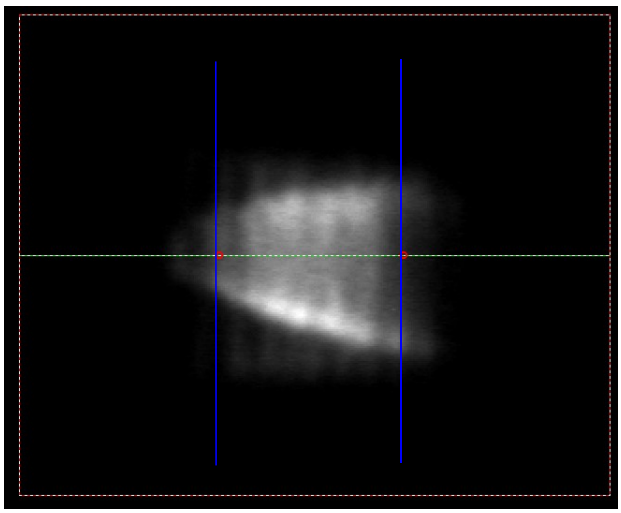
**See Klasens method for measurement of unsharpness in ASTM E 1000**




**See Bavendiek et al., https://www.ndt.net/article/wcndt2012/papers/346_wcndtfinal00346.pdf**

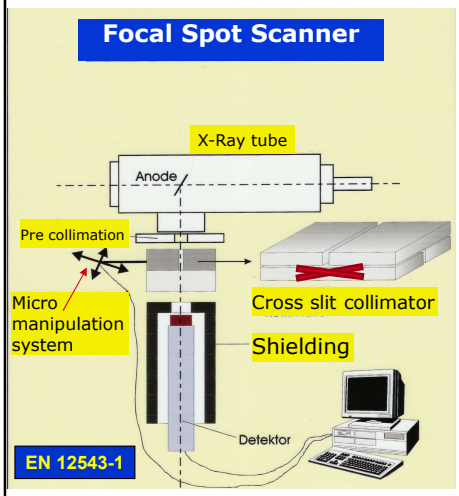
## Focal Spot Length calculated with „Integrated Line Profile Method“

570 µm



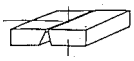


## Focal Spot CT with Slit Camera

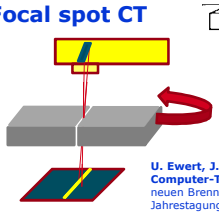



- **Scanner-Method is technically very complex and requires long measurement times**
- Slit cameras are significantly more sensitive
- With a rotating slit a spot CT can be performed with high SNR
  - Reduced measurement time, less expensive, stable results
  - Exact adjustment of rotational axis required
  - Special slit camera design required

**Focal spot CT**



Schlitzblende



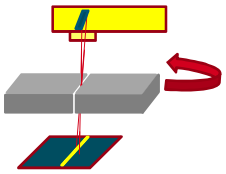
Rotation of slit collimator and acquisition of several hundred slit projections.

**U. Ewert, J. Löffler, and B. Redmer, "Brennfleck-Computer-Tomographie**: Ergebnis einer Studie zu 5 neuen Brennfleck-Normen EN12543 T.1-5," in DGfZP Jahrestagung, 1997, pp. 289–296

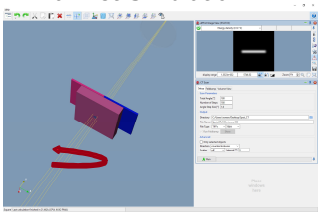
# Focal Spot CT with Slit Camera

Rotation of slit collimator and acquisition of several hundred slit projections,
Backprojection and application of a deconvolution filter or of an "Order Statistic" function

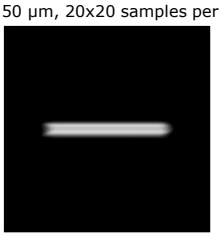
**Focal spot CT**



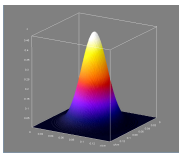
aRTist-Simulation



Projections with slit camera
50 µm, 20x20 samples per spot

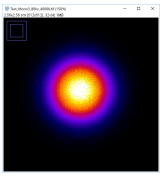


Original 0,61 x 0,61 mm², Gauss



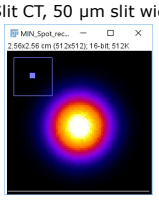
EN 12543-1

Pin hole camera, 50 µm hole diameter



0,62 x 0,62 mm²

Slit CT, 50 µm slit width



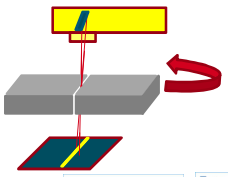
0,62 x 0,62 mm²
Min-Reconstruction



# Focal Spot CT with Slit Camera

Rotation of slit collimator and acquisition of several hundred slit projections, Backprojection and
(1.) application of deconvolution filter or (2.) of an "Order Statistic" function

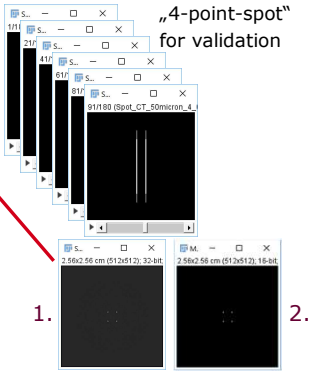
**Focal spot CT**



Gauss spot




„4-point-spot"
for validation




**1. Convolution Backprojection**
- Non-logarithmized projections
- Backprojection as Z-Integration
- Deconvolution from 1/r function (24.08 kernel)

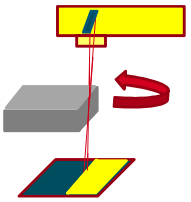
**2. Order-Statistic-Backprojection**
- Non-logarithmized projections
- Backprojection as minimum of all projections in Z direction

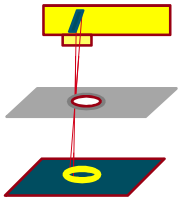
## Direction Dependent Edge Method with large Hole IQIs

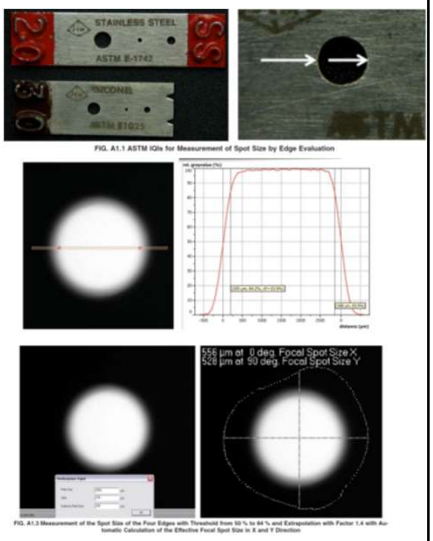
**ASTM E 1165 ANNEX A**

**Focal spot CT with Rotating Edge**

**Focal Spot CT from a "large" hole exposure → „Single Shot CT"**







A "slit camera CT" can be substituted by an "edge CT" based on the derivation of the edge profiles.

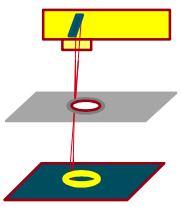
This is equivalent to the reconstruction from edge unsharpeness profiles of hole exposures as sinogram.



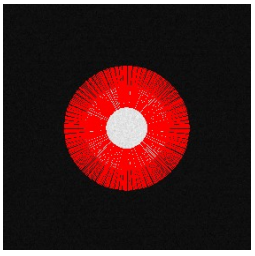
## „Single Shot" Focal Spot CT

U. Ewert , G.-R. Jaenisch , A. Deresch , B.A. Bircher , F. Meli, Neue Konzepte zur Messung von Parametern der Brennflecke von Nano- und Mikrofokus-Röntgenröhren, DGZfP-Jahrestagung, 27. – 29. Mai 2019 in Friedrichshafen

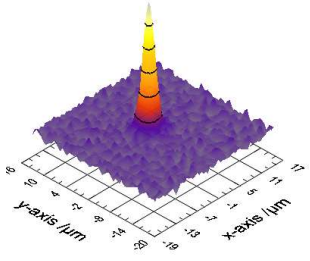
**Focal spot CT from edge profiles of a hole exposure: „Single Shot CT"**



Derived edge profiles



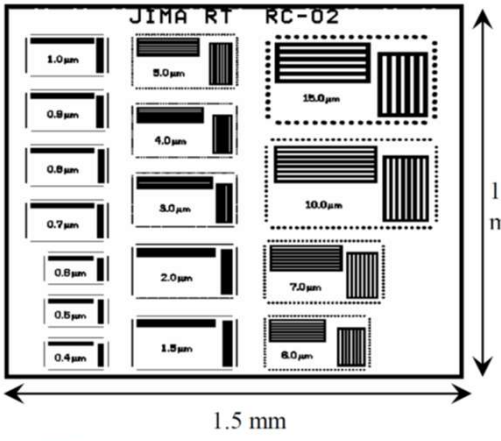
Focal spot distribution




- CT of a focal spot distribution from derived edge profiles.
- Low measurement time, low hardware requirements, stable results.
- Restrictions arise from edge penetration, exposure geometry, kV and adjustment of hole IQI.

## Nanofocus Spot Size Measurement with Line Pattern IQIs

Procedure also valid for spot sizes < 5 µm




**Line pattern targets** are available with different line widths and distances. They can be used for determination of focal spot sizes.

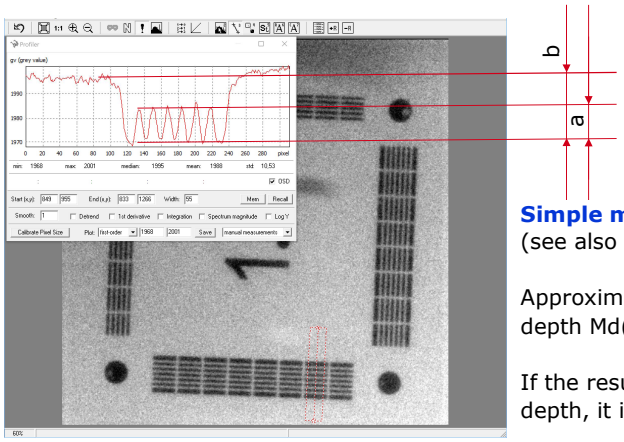
**Attention:** The numbers are given as line widths in µm. Multiply all values by **2** to obtain a spot size value.



## Nanofocus Spot Size Measurement with Line Pattern IQIs

**Alternative line pattern targets with high Aspect ratio (YXLON)**

Procedure also valid for spot sizes < 5 µm



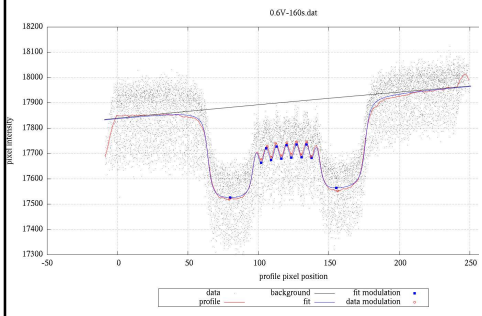

**Simple method for users**
(see also ASTM E 2445)

Approximation of modulation depth Md(%) = 100 * a/b,

If the result is 20% modulation depth, it is equivalent to $MTF_{10}$

# Nanofocus Spot Size Measurement with Line Pattern IQIs

Procedure applies also for spot sizes < 5 µm




**Complex procedure for manufacturers**
(EMPIR-Projekt „NanoXSpot“)

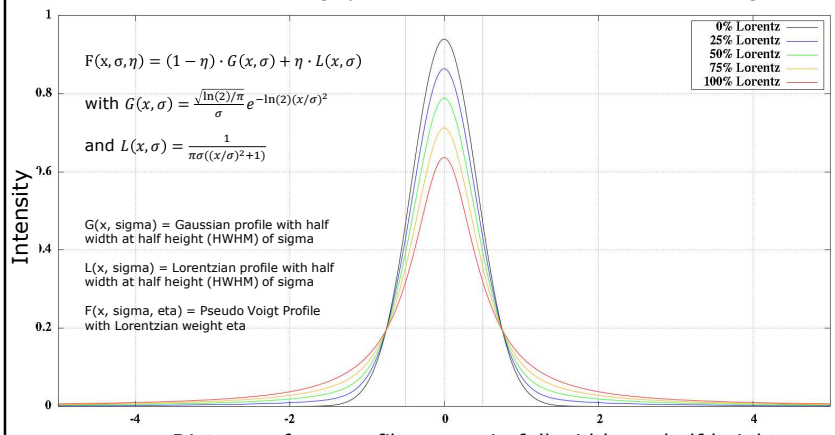
Determination of modulation depth with a numeric fit procedure

- Fit with Pseudo Voigt Profile
  - Weighted sum of Gaussian and Lorentzian Profile (“long foothills”)
  - Defined by the half width at half height and Lorentzian to Gaussian ratio
- Results are the 10% value of the modulation depth, $MTF_{10}$, and the line shape factor Lorentzian/Gaussian for better evaluation of the influence of the focal spot shape on the detail visibility.



# Pseudo Voigt Profile

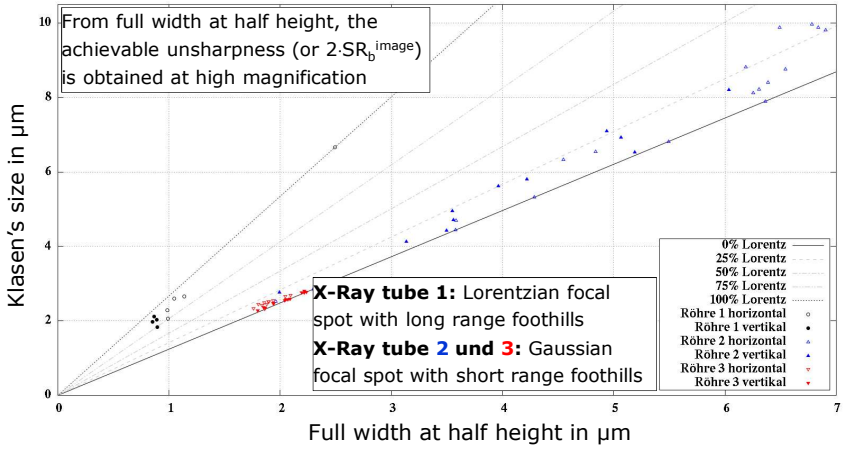
Profile functions of Voigt profiles with different Lorentzian weights



# Focal Spot Sizes

**Measurement of focal spot form factors and half value widths of X-Ray tubes of different manufacturers**

Fit results of real measurements






# Summary

- ASTM standards for focal spot size measurements were revised, to obtain values conforming to duplex wire IQI measurements in user standard practices.
- CEN standards of the series EN 12543 are under revision to be harmonized with the related ASTM measurement standards and the given requirements for maximum unsharpnesses of published standard practices in radiography.
- The scan method EN 12543-1 shall be withdrawn.
- CT algorithms will be developed and tested to calculate focal spot distributions from slit camera exposures and "unsharp" hole radiographs.
- A "Single Shot CT" shall be developed to reconstruct the focal spot distribution from exposures of very small hole targets (Project EMPIR NanoXSpot).
- A draft for a new standard on measurement of focal spot sizes and shapes of X-Ray tubes with spot sizes < 5 µm shall be developed, based on special line pattern targets (Project EMPIR NanoXSpot).
- CEN TC 138 WG 1 supports the EMPIR project NanoXSpot and plans to publish a new standard part EN 12543-6 based on the project results.

# END

**Acknowledgement:**
The authors thank Dr. C. Bellon, BAM,
for support simulating the effect of different spot distributions with aRTist