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New Measurement Methods of Focal Spot Size and Shape of X-ray Tubes in Digital Radiological Applications in Comparison to Current Standards

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Abstract
Unsharpness in the image may reduce the visibility of details. Magnification is often required to achieve a spatial resolution similar to film technique, when using digital systems. A part of the unsharpness results from the focal spot size. To determine the effective focal spot size, thousands of images with different tubes, energies, magnifications and IQIs from different EN and ASTM standards were taken to evaluate the influence of the unsharpness in the digital image due to the focal spot. This leads to reference values for the effective focal spot size of the different tubes. These reference values were compared with the values of the pin hole camera images according to EN 12543-2 and they deviated significantly. Several modifications of the evaluation method were proposed and a method with Integrated Line Profiles which produces results like an edge profile method was developed and tested providing similar results as the reference values. A second more simple method for end-users was introduced based on the evaluation of Penetrameter hole edges. A proposed update of the standards for focal spot measurements in ASTM and ISO is introduced. New classes will help the users to identify more simple and reliable the X-ray tube for their application.

Keywords: Non-destructive testing, radiography, X-ray tubes, focal spot size, standards, integrated line profile method (ILP).

1. Introduction

The exact focal spot size is required for optimization of image quality in radiological testing. The current standards (EN 12543 and ASTM E 1165) describe different measurement methods, which do not provide identical values. In practice the operator needs to achieve a sufficient image quality. This depends among other factors on the total image unsharpness too. Both, the inherent detector unsharpness and the geometric unsharpness contribute to the total unsharpness. The geometric unsharpness is determined by the focal spot intensity distribution and the magnification used. Therefore, the shape of the focal spot cannot be neglected, even if the shape distribution is not required by any standard practice.

2. Shape of an X-ray focal spot

The shape of an X-ray focal spot is formed by the filament, the target, the internal “way of flight of the electrons” and the target angle with the X-ray window. The classical X-ray tubes for exposure of films typically have large focal spots. The newer digital systems, with larger pixel sizes in comparison to film resolution, require magnification technique for resolution of small details. With magnification the focal spot shape and size become more important. The development of X-ray tubes with high dose power AND small focal spot leads to different focal spot shapes. The existing standards for measurement of focal spot shapes, like EN 12543 or ASTM E 1165, do not provide useful values, which could be used for the calculation of unsharpness in the radiological images, as required in ASTM E 2698 or ISO 17636-2. Sometimes the values are significantly too large, sometimes the nominal focal spot values are too small because of “side-wings” in the focal spot.

Beside CT applications four different main areas for the use of X-ray tubes can be identified:

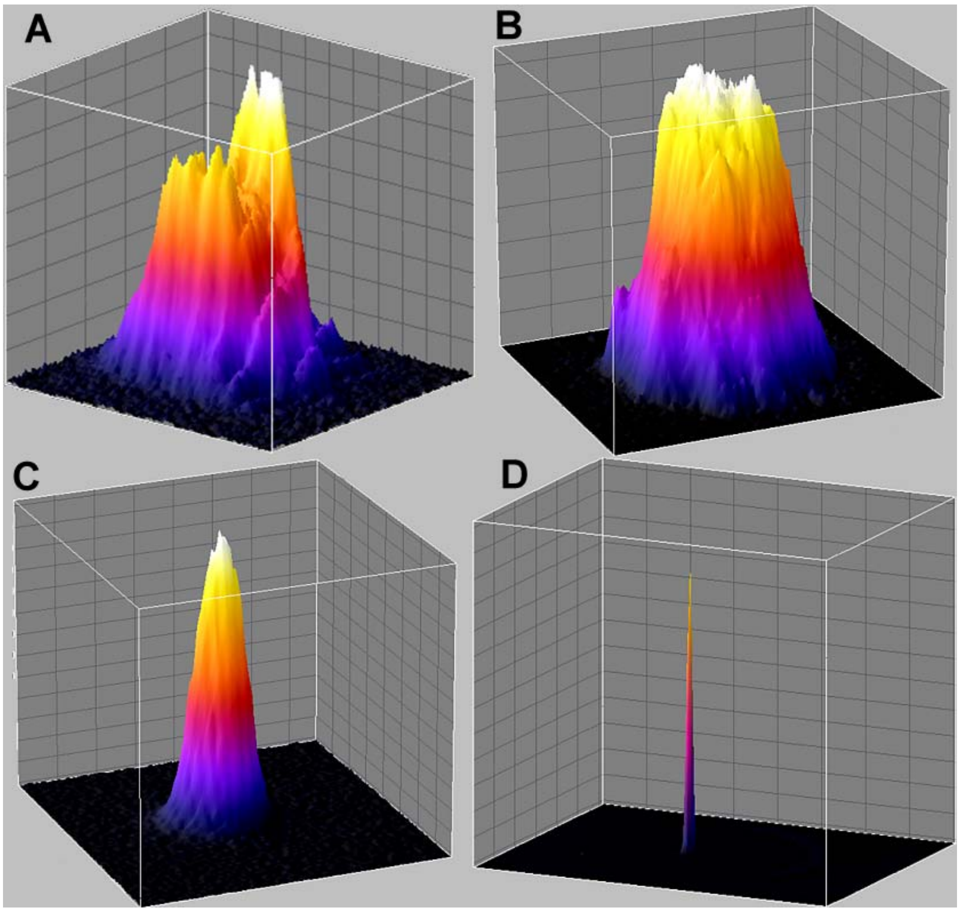


Figure 1. Different Focal Spots of tubes for
(A) film radiography
(B) inspection of Automotive Castings (mini focus)
(C) inspection of Aerospace & Welds (small mini focus)
(D) µ-Focus tube

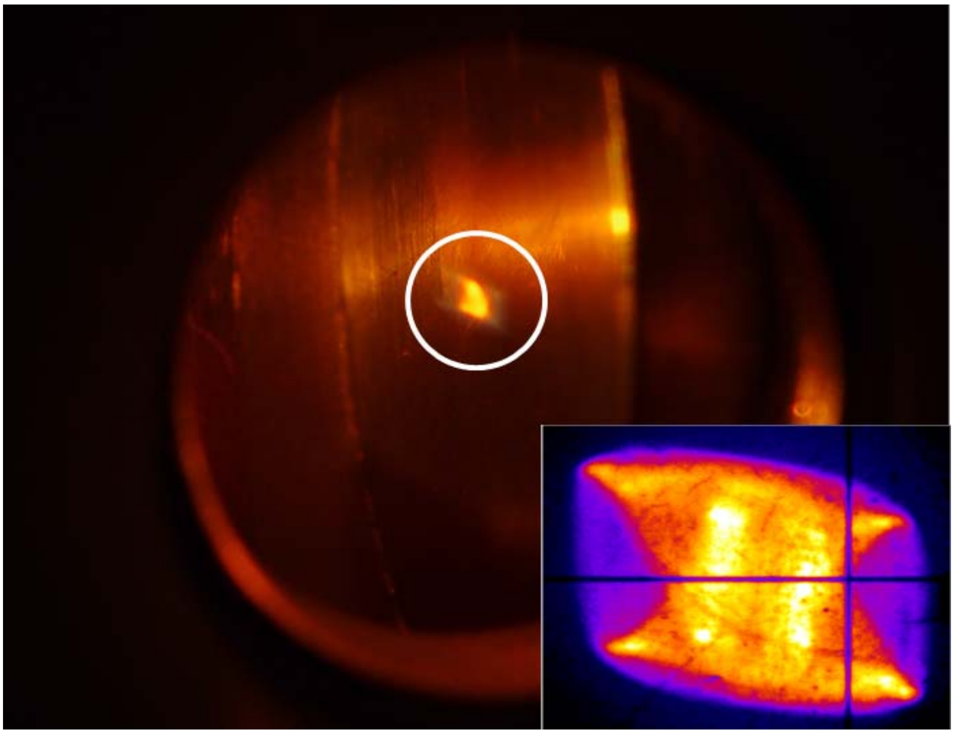


Figure 2. Photograph and pin hole image of a „burning“ Focal Spot with low dose power of a high power X-ray tube for film radiography with large spot (see Fig. 1A).

The X-ray tubes for film radiography typically have focal spot sizes of a few mm and power up to 5kW. Focal spot sizes below 1 mm are used for radiography of light metal castings, mainly for automotive industry. Focal spots which are smaller than 0.4mm at tube power of < 1kW are used for aerospace castings and weld inspection. Finally µ-focus tubes have focal spots below 100 µm. Its industrial use is mainly in the field of inspection of thin welds or in the semiconductor industry.

2.1 Standards for measurement of focal spot size

The measurement of the focal spot size is specified by the following standards today:

- EN 12543 –Characteristics of focal spots in industrial X-ray systems for use in non-destructive testing Parts 1 to 5
  - Part 1: Scanning method (*reference method, but no more equipment available*)
  - Part 2: Pinhole camera radiographic method (*mainly used method for manufacturers*)
  - Part 3: Slit camera radiographic method
  - Part 4: Edge method
  - Part 5: Measurement of the effective focal spot size of mini and micro focus X-ray tubes
- ASTM E1165 - Standard Test Method for Measurement of Focal Spots of Industrial X-Ray Tubes by Pinhole Imaging
- IEC 60336: Medical electrical equipment – X-ray tube assemblies for medical diagnosis – Characteristics of focal spots (*Slit, Pin hole and Star methods*)

These standards are not consistent; different methods lead to different values for the identical X-ray tube – even in the same standard, if different parts are used.

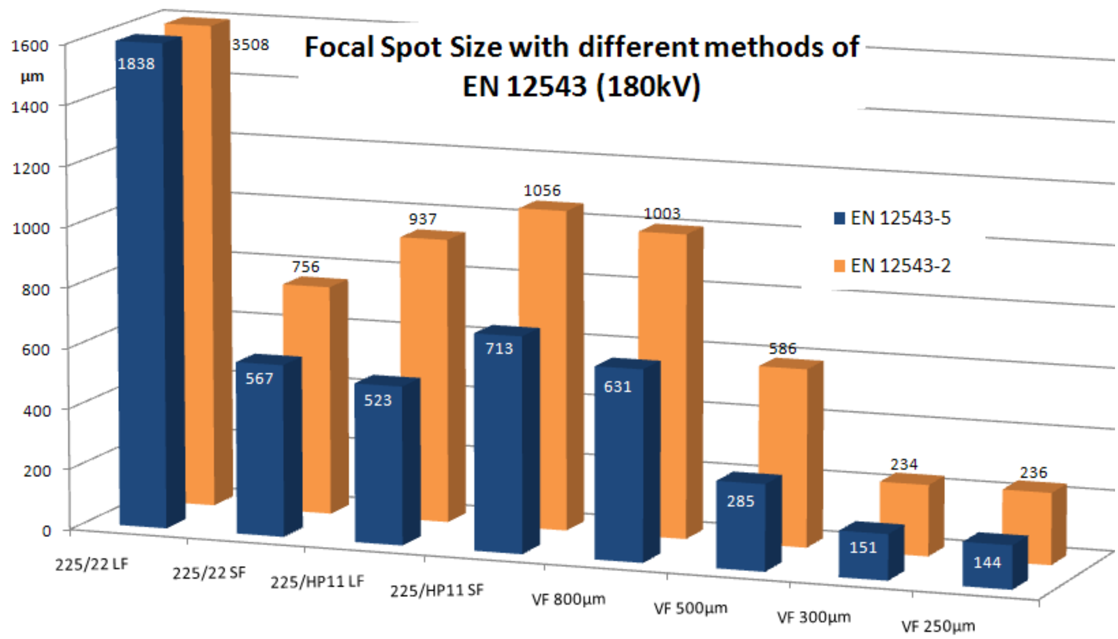


Figure 3. Different Values for identical Focal Spots of 8 different X-ray tubes measured by EN12543-2 and -5

Using EN12543-2 the values are often up to a factor of 2 larger than measured with EN 12345-5. ASTM E1165 uses the same pinhole method as EN12543-2 but a different procedure for evaluation. Some of the focal spots do not fit to the evaluation method of the pin hole image.

➔ The new types of X-ray tubes for digital radiology require improved methods for measurement of the focal spot size.

3. Measurement of Unsharpness in the Image due to the Focal Spot Size

The X-ray user usually does not need to consider the focal spot shape, only the unsharpness due to the focal spot size is of interest to the user. The total unsharpness in the image is measured with an edge method or by a duplex wire IQI as described in EN 462-5 or ASTM E 2002. It is required to know the total image unsharpness in several standards; e.g. in ASTM E 2698. Equation (1) (taken from ASTM E 2698) can be used for evaluation of the unsharpness due to the limited focal spot size:

- U_{Im} maximum image unsharpness
- U_g geometrical unsharpness
- Φ focal spot size ($\triangleq$ FS)
- SR_b basic spatial resolution
- v magnification (Vergrößerung)

$$U_{Im} = \frac{1}{\upsilon} \cdot \sqrt[3]{U_g^3 + (1.6 \cdot SR_b)^3} \qquad (1)$$

$$U_g = (\upsilon - 1) * \Phi \qquad (2)$$

$$U_g = \upsilon \cdot \sqrt[3]{U_{Im}^3 - (\frac{1.6}{\upsilon} \cdot SR_b)^3} \qquad (3)$$

$$\Phi = \mathrm{FS} = \frac{\mathrm{v}}{\mathrm{v}-1} \sqrt[3]{\mathrm{U}_{Im}{}^3 - (\frac{1.6}{\mathrm{v}} * \mathrm{SR_b})^3} \qquad (4)$$

Applied to images from the performed experiments formula (5) fits better for measurement of the unsharpness due to the focal spot size than formula (4) (see also: Robert F. Wagner [1]).

$$\Phi = \mathrm{FS} = \frac{\mathrm{v}}{\mathrm{v}-1} \sqrt[2]{\mathrm{U}_{Im}{}^2 - (\frac{2.0}{\mathrm{v}} * \mathrm{SR_b})^2} \qquad (5)$$

The unsharpness in radiographic images was studied at YXLON with COMET and BAM as partners. Three different Image Quality Indicators (IQIs) were used with high and medium contrast – known from different standards.

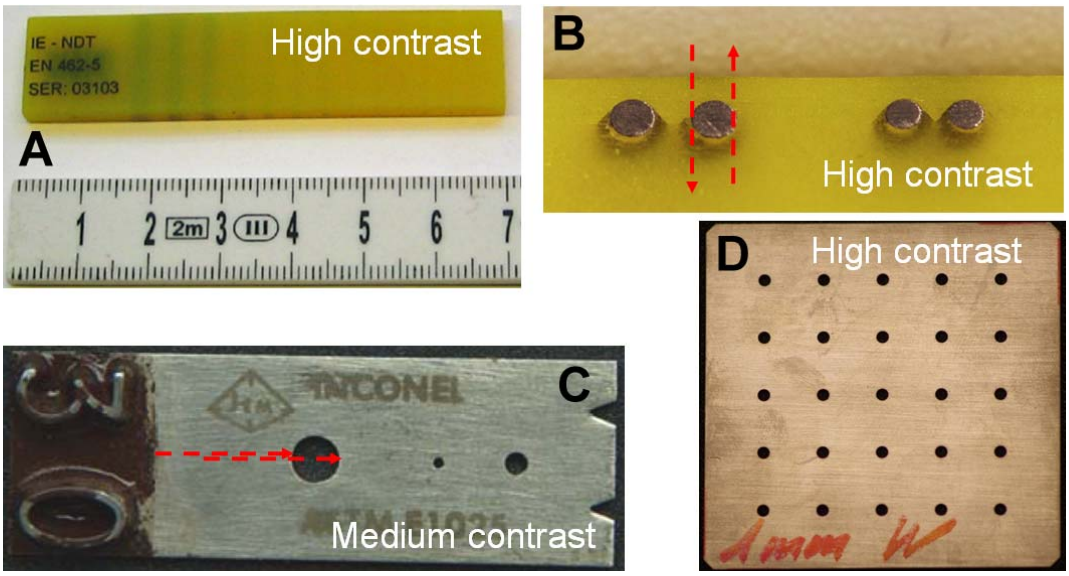


Figure 4. Used IQIs: (A) EN 462-5 (B) Edge of DW 1 of EN 461-5 (C) Plaque Hole IQI (D) Tungsten plate with holes

(A) EN 462-5 duplex wire IQI was evaluated as given in ASTM E 2597 (20% dip evaluation)
(B) From same IQI the wire 1 (800µm) was used as an edge target on both sides of the wire
(C) Both sides of the 4T or 2T hole of a plaque hole type IQI were used as an edge
(D) A 1mm Tungsten plate with several holes of 2.05mm diameter was used similar to (C)

The edges from (B), (C), (D) were measured from 85% to 45% and on the other side from 45% to 85% (together 40% + 40% as required by EN 12543-5, but with shifted thresholds). The results were multiplied with the factor of 1.25 to extrapolate from 80% to 100%.

The evaluation procedures are based on the above mentioned standards– with minor modifications.

- Magnification was varied from 1.5 up to 15.
- Four different energies were used: 90kV, 120kV, 180kV and 225kV.
- Nine different focal spots were measured with all the four IQIs; the sizes varied from 250µm to 7.5mm nominal size (EN 12543-2); the IQIs were placed exactly in the center of the beam.
- The detector was a PerkinElmer XRD 822 with a SR_b of 230µm. Similar tests were done with a Thales FS 35 and Hamamatsu C 7942.
- For evaluation the YXLON software IMAGE 3500 was used; special software algorithm were added, e.g. for the unsharpness measurement of the holes (see Fig. 5 for example).

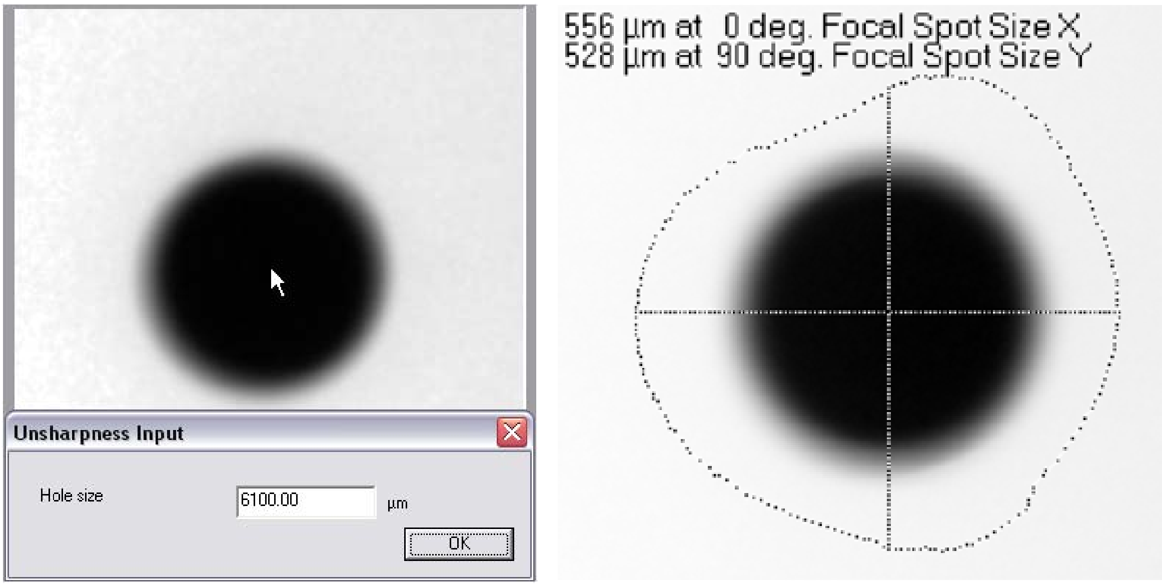


Figure 5. Automated evaluation procedure with the Plaque Hole IQI in IMAGE 3500 using the hole diameter as reference
A) Projection radiograph of an hole target with magnification. Due to the focal spot shape, the hole rim is blurred.
B) The graph shows the blurred hole image and a radial line, indicating the spot size as distance from center.

384 images were taken and analyzed for (A), 384 images for (B), 168 images for (C), 168 images for (D).

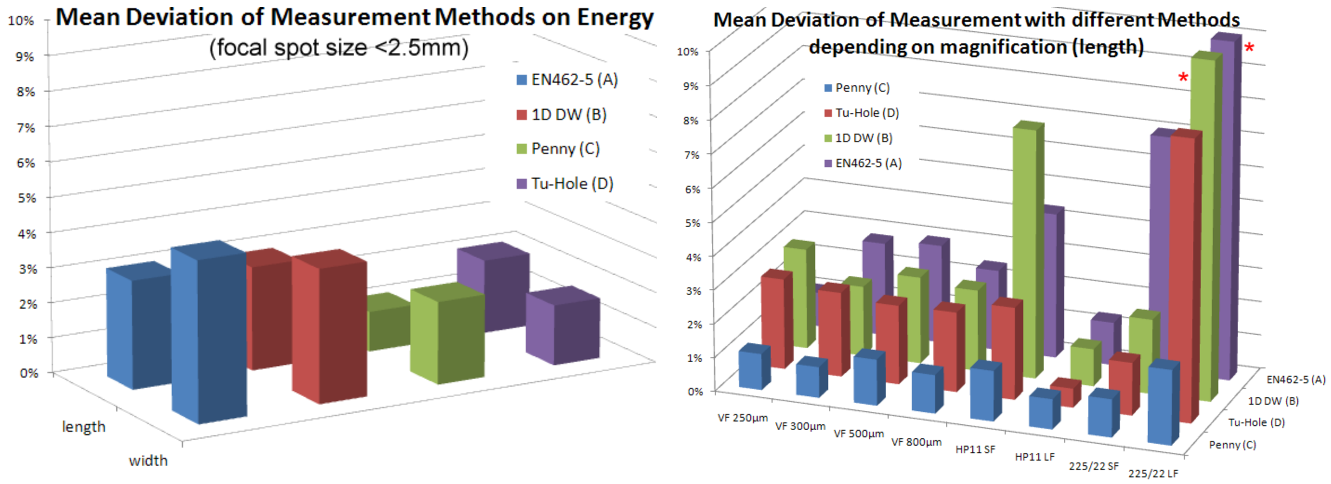


Figure 6. The measured focal spot sizes deviate less than 3 % when varying the energy (90 kV – 225 kV) or less than 10% when varying the magnification (2.0 to 15)
(* results not relevant because IQI to small for the large focal spot)

Because the international standards, referenced above, describe different procedures for the measurement of the focal spot size, different values are obtained. Therefore, a median value of the applied four different methods was determined as reference value for the spot size (RVSS).

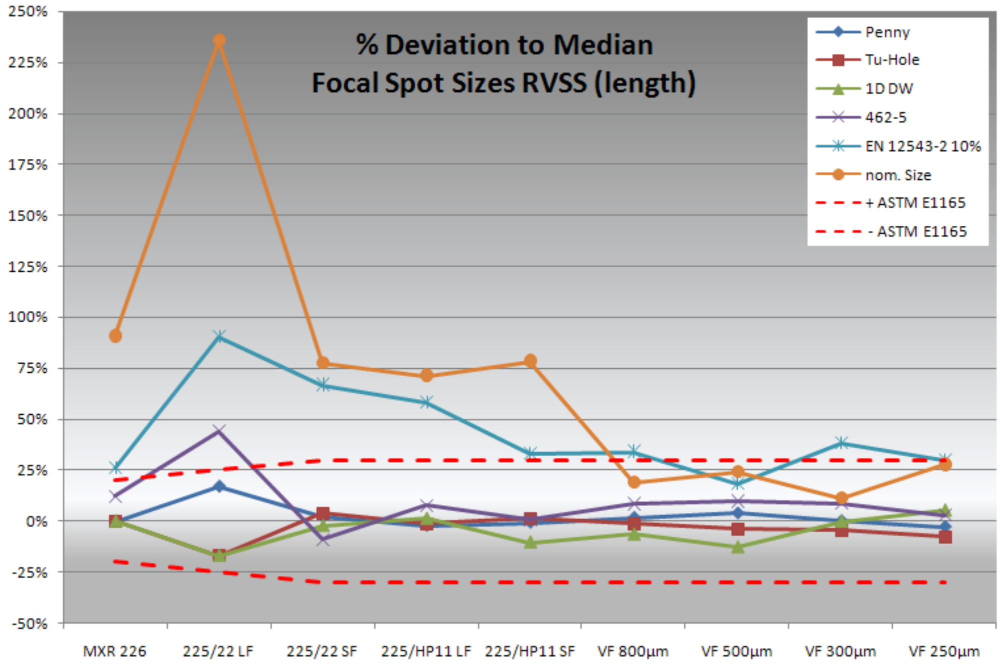
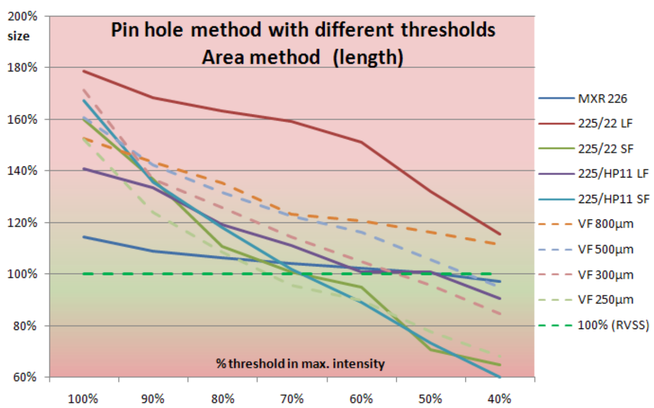


Figure 7. Deviation of the four different focal spot measurement methods (A – D) and the pin hole method of EN 12543-2 to the RVSS.

Figure 7 shows the results of the 4 different methods within the limits ASTM E 1165 is giving. The green line (1D DW) shows the results in compliance with EN 12543-5. The values measured with EN 12543-2 are larger and outside of the ASTM tolerance – the nominal values deviate even more.

4. Transfer of the RVSS to the pin hole image of EN 12543-2 or ASTM E 1165

With the determined spot sizes by the method A – D, as described above, the measured unsharpness in the X-ray images could be correctly calculated. Therefore, these methods should be the reference for revised standards. The question is now, if new methods for the two different pin hole standards (ASTM E 1165, EN 12543-2) have to be found or if the “traditional” pin hole image can be used in a way that the results are similar to the values measured in production radiographs. In EN 12543-2 a 10% threshold for the background value is defined. Vice versa it means that the upper 90% of the maximum intensity is taken for determination of the “focal spot size” **area**.



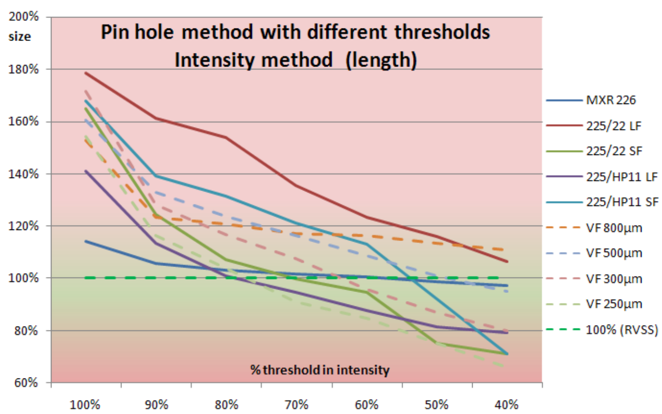


Figure 8. Focal spot sizes in reference to the RVSS for different tubes; Area method (left) and Intensity method (right)

As shown in Fig. 7 these values are much larger than the RVSS. The first approach is to decrease the 90% and see, if a lower value would give a size similar to the RVSS for most of the tubes. Fig. 8 shows on the left side that a value of about 70% would fit for some of the tubes but not for all. For the "classical" tube for film radiography even a 40% value would not fit. Due to the different shape of the focal spot there is no standard value that fits all.
The next approach is to take the integral photon **intensity** instead of a threshold based on the maximum intensity of the pin hole image and define a threshold that would give sizes similar to the RVSS. The gradients are much lower than the ones which are measured with the area method (Fig. 8 right picture) and a threshold of 70% would fit for most of the focal spots. The disadvantage is that a physical relationship to the edge method is missing.

4.1 Conversion of the pin hole image to an edge profile by integrated line profiles (ILP)

A profile line is measured through the center of the focal spot. The length of the profile line is about three times the expected size in length or width. Profiles parallel to the center profile are averaged, covering about 3 times of the other spot dimension (see Fig. 9a). Figure 9a shows an example spot. Figure 9b presents the averaged profile. It is the averaged intensity across the width of the focal spot (9a). Now the line profile is integrated along the green arrow direction to obtain the *integrated line profile (ILP);* see Fig9c. This picture represents the transformation of the measured pin hole image of the focal spot to an edge profile as described by EN 12543-5. It is physically equivalent.

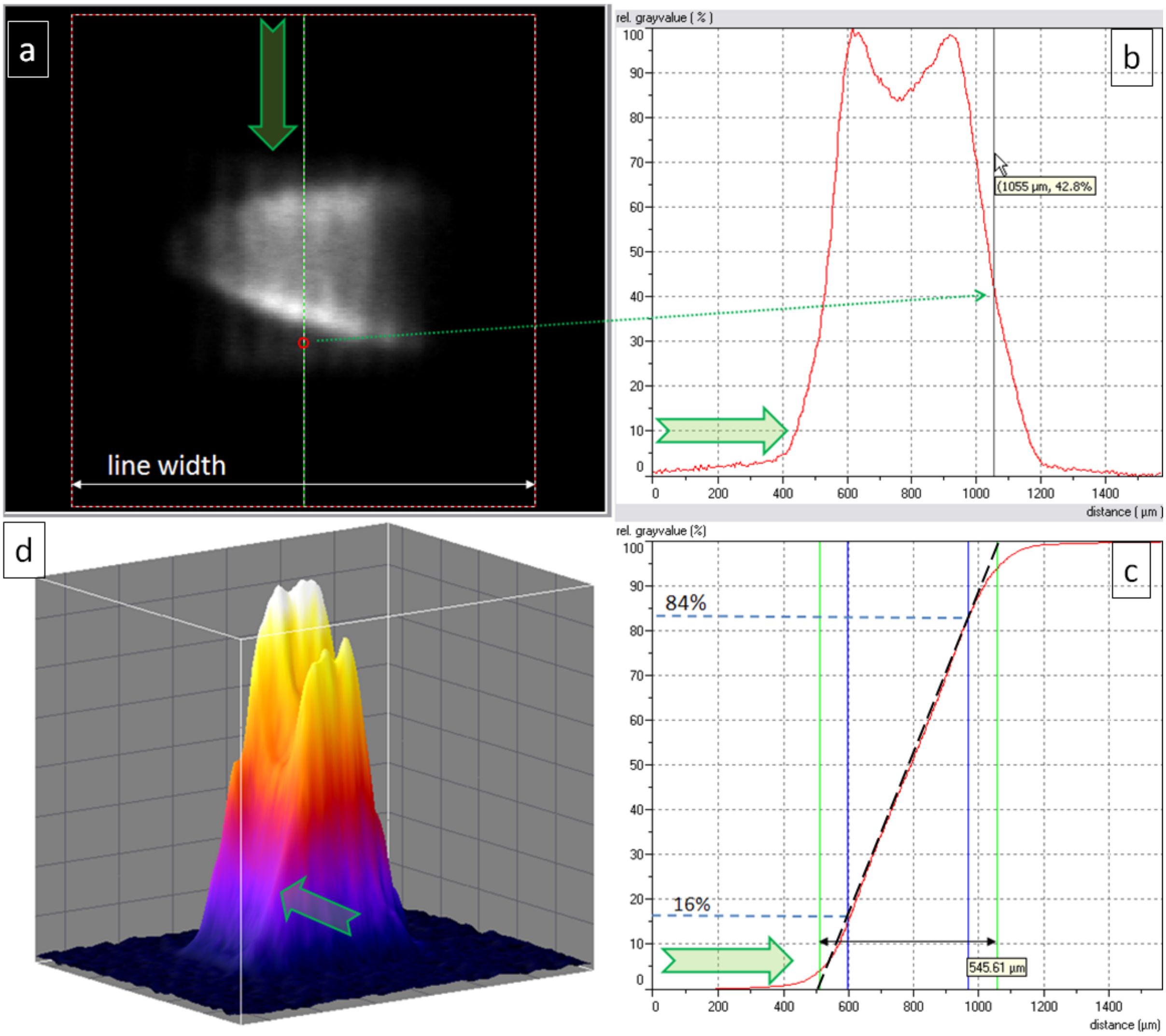


Figure 9. Calculation of an edge profile by integration of an averaged line profile

a) Pin hole camera image with marked averaging area of profile lines
b) averaged line profile within the marked area of interest
c) integrated line profile from (b) with extrapolation line through 16% and 84% intensity thresholds
d) pseudo 3D representation of the focal spot for better visualization

In the center of the integrated line profile is a steep slope. The soft wings at the beginning and at the end of the profile are disturbed due to base line inaccuracies. Therefore, the line profile is evaluated in the center 68 % and the value is extrapolated to 100% to determine the value of the focal spot size The reference values for the straight center line of 16% and 84% are taken in accordance to the Klasens method [2], which is also described in ASTM E 1000 [3] for unsharpness measurements. As 16% is missing on the one side and additional 16% on the other side, 32% is missing to the 100% spot size. The extrapolation factor, to correct this, is 1.47 [= 100% / (100% - 32%)].

Before integration across the line profile an affine linear (straight line) background subtraction was applied to the averaged line profile (Fig. 9b), using at least the averaged profile values of 10% of the line profile at both ends for base line correction.

The ILP method was applied two times for a focal spot size measurement (length and width). In Fig. 9 the length of the focal spot was measured; a second line profile perpendicular to the first one provides the size of the width of the focal spot.

4.2 Deviation between different methods

The results of the ILP method for the different tubes were compared with the Penny method [C] of chapter 3 using similar thresholds (84% -> 50% and 50% -> 84%) and interpolation factor (1.47) for evaluation. The difference is within the ASTM E 1165 limits and – with exception of the length of one focal spot – even inside a 10% limit.

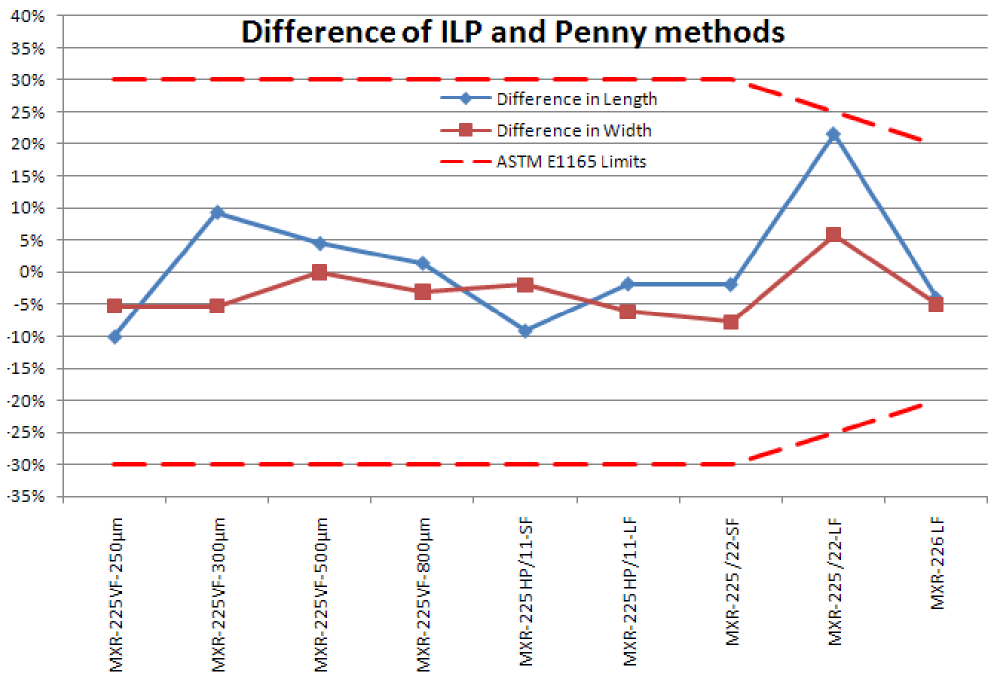


Figure 10. Difference of the IPL method to the Penny method with similar thresholds

This very small deviation allows creating a more simple method for users of X-ray tubes for measurement of their focal spots with the Penny method [C].

5. Reliability of the ILP method

The size of five different focal spots from recent production of COMET was measured with the ILP method to prove the precision of the ILP method with practical results and to compare with the EN method. The focal spot images contain cross hair lines for the indication of the focal spot center. This influences slightly the accuracy of the results. Even with this handicap the standard deviation is in maximum 12.9%, in medium 6.1%. The absolute values of the determined focal spot sizes decrease as expected in comparison to the threshold method of EN 12543-2 (see Chapter 2).

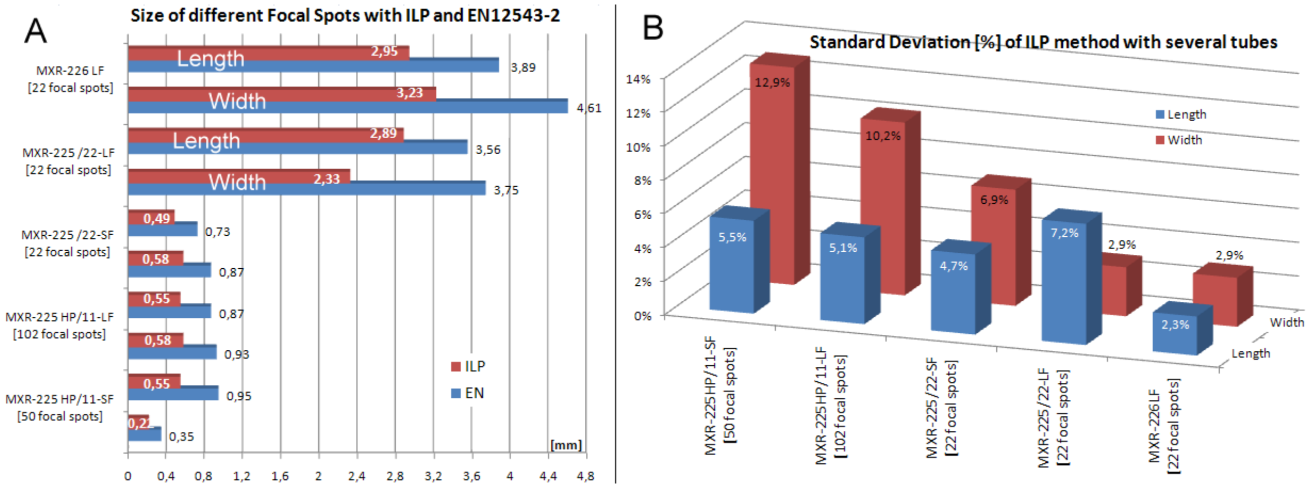


Figure 11. Results of focal spot measurement with two methods (A) and standard deviation of ILP method (B)

This deviation of the measurements may be caused by the method itself or by the deviation of the different focal spots. To evaluate the origin for this deviation, 19 different focal spots of an HP11 focus were measured with the ILP method. These results contain the deviation of the focal spot size and shape itself *and* the measurement procedure. Then, one identical HP11 focal spot was used and the measurement equipment was built into the cabinet for 25 different positions and 5 different CR plates (75 images) to measure the precision due to the measurement procedure. Finally, all the hardware stayed in position and only the same CR plate was used 30 times; this provides the standard deviation due to the X-ray flux and scanning procedure.

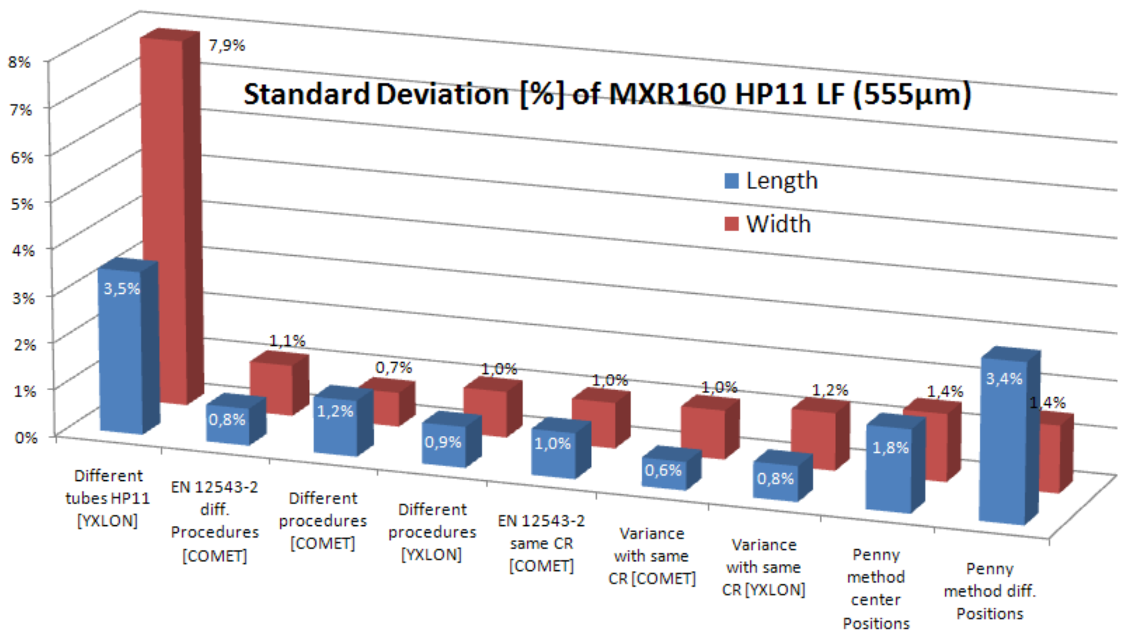


Figure 12. Standard deviation of EN 12543-2, ILP and Penny method for same X-ray focal spot at two test labs

The standard deviation of the different HP11 focal spot size measurements is 3.5% in length and 7.9% in width direction – averaged about 6%.
The standard deviation of the measurement procedure – measured with one HP11 focal spot - is in the range of only 1% for the EN 12543-2 and ILP method. In absolute values the ILP method shows lower deviations (6.6µm x 4.0µm) than the EN method (6.6µm x 8.9µm) as the absolute values are smaller. This proves that the ILP method delivers reliable and reproducible results and is less sensitive to the shape of the focal spot. The tests were done at COMET in Flamatt (Switzerland) and repeated at YXLON in Hamburg (Germany) using different Software-Tools (COMET: Matlab program; YXLON: Image 3500). The differences are very small in both directions of the focal spot. The mean size of the focal spot using the ILP method is measured at COMET to 0.552mm in length and 0.547mm in width direction and at YXLON to 0.559mm and 0.555mm.

Additionally, the same tube was used for the acquisition of 50 different images with different positions using the plaque hole or Penny method [C]. The mean size of the focal spot using the Penny method is 0.540mm in length and 0.558mm in width direction which is -2,34% and -0.48% compared to the mean values of the ILP method of COMET and YXLON. This is significantly below the tolerance of tube manufacturing. When the IQI is positioned within the tolerance of the size of the 4T hole in the center of the beam the standard deviation is 1.8% and 1.4% (length and width). There is a larger deviation in length direction when the IQI is moved because the angle of the target changes. Fig. 12 shows in the last columns the values if the position deviates by the size of the IQI itself.

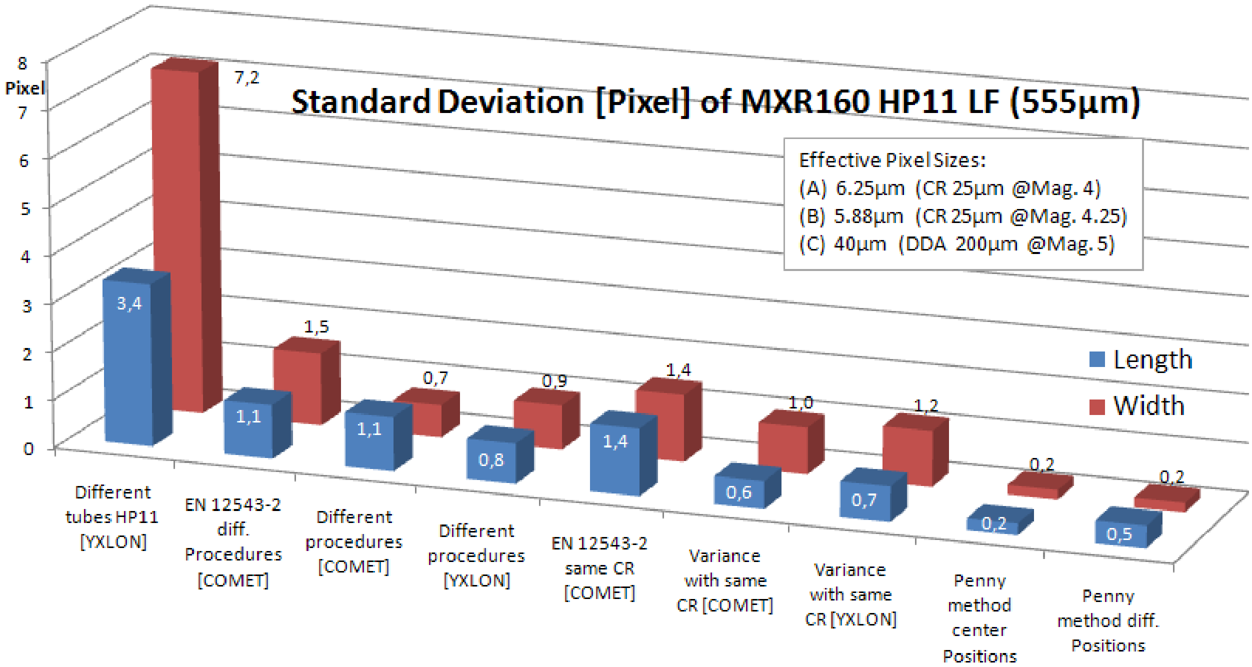


Figure 13. Standard deviation of EN 12543-2, ILP and Penny method at same type of X-ray focal spot in Pixel

The measurement with the plaque hole IQI type was performed using a DDA with 200µm pixel size. The magnification was set to 5 giving an effective pixel size of 40µm. With 2s exposure time a SNR of 420 was achieved. The standard deviation with this method is just a fifth of a pixel when the IQI is positioned properly; this is below 10µm at a focal spot size of 555µm.

6. Future activities for standardization

The ILP method for the measurement of focal spot sizes has proven its reliability. It provides suitable results for the users since the image unsharpness measured in production radiographs and the calculated image unsharpness from the focal spot sizes fit accurately. The equation (5) permits the calculation of the image unsharpness, considering the geometric and detector unsharpness. The ILP method should replace the 10% area method of EN 12543-2 and should also be applied in ASTM E 1165. The advantage of this new measurement method is the agreement of the results of the edge method of EN 12543-5 for mini and micro focus tubes with the results of the pin hole method EN 12543-2, because both methods cover the application range for focal spots between 100µm and 300µm and should provide identical data.

As it is intended to submit EN 12543 by the Vienna agreement to ISO, the new version will be prepared as an EN ISO standard. ASTM standardization is mostly faster than EN and ISO standardization; therefore, the revision of ASTM E 1165 is already in ballot and may be released mid of the year 2012. Additionally, ASTM working group E 07 has prepared a focal spot measurement standard for µ-Focus tubes with focal spot sizes between 5µm and 300µm, which is an extended standard of EN 12543-5.

As the pin hole camera is an expensive and sensitive measurement tool, users do not like to work with it. With the new digital detector systems and the required application of magnification technique, the exact value of the focal spot size is of more importance. Newer standards require that the focal spot is measured on a regular base by the user. For this task the method with the plaque hole IQI [C] – which provides similar results to the ILP method (see Figs. 10, 12 and 13) – is included in the Appendix of ASTM E 1165 and may be used by end users of X-ray tubes as an alternative to the pin hole camera method.

Fig. 11 shows a typical variation of the focal spot size when manufactured. To avoid different spot size values for individual tubes, new classes are proposed. Table 1 shows the limits and class names for the new focal spot classes. The “old table” in EN12543-2 defines a lot of classes above 1mm spot size, but only a few below. Today, most of the tubes have focal spots below 1mm. The steps and names of the new classes were selected in relation to the ISO 19232, EN 462 and ASTM E 2002. E.g. the class FS 19 is intended for focal spots between 50µm and 63µm; the wire #19 of EN 462-1 and ISO 19232-1 has a diameter of 50µm, #18 of 63µm.

The reader may consider that above 4mm there is only one class (FS 0). With the new ILP method the focal spot of the MXR226 with nominal 7.5mm spot size (old EN 12543-2) is characterized by values of 2.95mm length and 3.23mm width (see Fig. 11 A) and would fit into the class FS 1.

Table 1. Classes and sizes for mini- and µ-focus focal spot sizes

Classes for mini-focus focal spot sizes								Classes for µ-focus focal spot sizes							
FS 0				FS	≥	4,0	mm	MF 0	50	µm	>	MFS	≥	40	µm
FS 1	4,0	mm	>	FS	≥	3,2	mm	MF 1	40	µm	>	MFS	≥	32	µm
FS 2	3,2	mm	>	FS	≥	2,5	mm	MF 2	32	µm	>	MFS	≥	25	µm
FS 3	2,5	mm	>	FS	≥	2	mm	MF 3	25	µm	>	MFS	≥	20	µm
FS 4	2	mm	>	FS	≥	1,6	mm	MF 4	20	µm	>	MFS	≥	16	µm
FS 5	1,6	mm	>	FS	≥	1,27	mm	MF 5	16	µm	>	MFS	≥	12,7	µm
FS 6	1,27	mm	>	FS	≥	1	mm	MF 6	12,7	µm	>	MFS	≥	10	µm
FS 7	1	mm	>	FS	≥	0,8	mm	MF 7	10	µm	>	MFS	≥	8	µm
FS 8	0,8	mm	>	FS	≥	0,63	mm	MF 8	8	µm	>	MFS	≥	6,3	µm
FS 9	0,63	mm	>	FS	≥	0,5	mm	MF 9	6,3	µm	>	MFS	≥	5	µm
FS 10	0,5	mm	>	FS	≥	0,4	mm	MF 10	5	µm	>	MFS	≥	4	µm

FS 11	0,4	mm	>	FS	≥	0,32	mm	MF 11	4	µm	>	MFS	≥	3	µm
FS 12	0,32	mm	>	FS	≥	0,25	mm	MF 12	3	µm	>	MFS	≥	2	µm
FS 13	0,25	mm	>	FS	≥	0,2	mm	MF 13	2	µm	>	MFS	≥	1,5	µm
FS 14	0,2	mm	>	FS	≥	0,16	mm	MF 14	1,5	µm	>	MFS	≥	1	µm
FS 15	0,16	mm	>	FS	≥	0,127	mm	MF 15	1	µm	>	MFS	≥	0,9	µm
FS 16	0,127	mm	>	FS	≥	0,1	mm	MF 16	0,9	µm	>	MFS	≥	0,8	µm
FS 17	0,1	mm	>	FS	≥	0,08	mm	MF 17	0,8	µm	>	MFS	≥	0,7	µm
FS 18	0,08	mm	>	FS	≥	0,063	mm	MF 18	0,7	µm	>	MFS	≥	0,6	µm
FS 19	0,063	mm	>	FS	≥	0,05	mm	MF 19	0,6	µm	>	MFS	≥	0,5	µm
FS 20	0,05	mm	>	FS	≥	0,04	mm	MF 20	0,5	µm	>	MFS	≥	0,4	µm
								MF 21	0,4	µm	>	MFS			

7. Conclusions

A study was performed on the basis of more than 1000 images from nine different focal spots to measure the size of focal spots in digital images. The results showed small variations (<<10%) for the four different IQIs applied, energies from 90keV to 225keV and magnifications from 2.0 to 15. This leads to the validated **r**eference **v**alues of **s**pot **s**ize (RVSS), which the users will measure as geometric unsharpness in their images.

The pin hole method from EN 12543-2 or E 1165 was evaluated in reference to the RVSS. It could be shown that the image capture procedures with pin hole cameras as described in EN 12543-2 and ASTM E 1165 provide accurate results, and only a different evaluation method is required to meet the values of RVSS. The integrated line profile (ILP) method provides the best results. These are in the range of the RVSS. Since the ILP method converts the pin hole images to physically equivalent edge profiles, the new pin hole method with the ILP evaluation provides values for the spot sizes similar to the standard procedure of EN 12543-5. This resolves the inconsistency of EN 12543-2 and -5 and will lead to compatible standards for measurement of spot sizes of Mini to µ-Focus tubes.

A classification with new class limits from 0.4µm to > 4mm is proposed for a new ISO standard.

A more simple procedure for the users of X-ray tubes, using plaque hole IQIs (e.g. ASTM E 1025), is proposed. The standard deviations of the ILP method and the user method are smaller than 2%.
The new ILP method is already integrated in a proposed update of ASTM E 1165 and the user method with the plaque hole IQI is described in the Annex A of this standard. The same procedures and methods will be proposed for revision of EN 12543 and this revised standard will be submitted to ISO on basis of the Vienna agreement.

References

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