Setup and Characterization of X-ray Reference Calibration Fields in a Dosimetry Laboratory

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Abstract

For testing and calibrating radiation detectors a new X-ray irradiation facility was installed in the dosimetry laboratory Seibersdorf jointly operated by Seibersdorf Laboratories and the BEV (Federal Office of Metrology and Surveying). The X-ray assembly consists of a 160 kV X-ray high voltage generator, a calibrated voltage divider, and three x-ray tubes of tungsten, molybdenum and rhodium target material, respectively. The objective of this work was to establish geometrical irradiation conditions for the introduction of various photon reference radiation qualities according to international standards. The precise positioning and orientation of the x-ray tubes, diaphragms, filter holders, and transmission ionization monitor chamber along the central beam axis were carried out to finally provide accurate and traceable calibrations according to requirements of a primary and secondary standards dosimetry laboratory. The components of the X-ray irradiation facility were installed and adjusted in a stepwise procedure using a laser alignment system and a digital X-ray imaging detector. Setup and characterization of the X-ray field parameters such as field-size and field-homogeneity were based on measured 1024 x 1024 pixel intensity maps and derived relative intensity profiles at two different focus-detector-distances.

Key words

X-ray facility, X-ray radiation, radiation field, calibration, dosimetry laboratory

Introduction

A new X-ray irradiation facility was set-up in the Dosimetry Laboratory Seibersdorf (DEL) jointly operated by Seibersdorf Laboratories (SL) and the Federal Office of Metrology and Surveying (BEV), which is the national metrology institute (NMI) and the national authority of legal metrology in Austria. The X-ray assembly was installed in an acclimatized, shielded room (DEL Bunker) of 6.2 m x 3.8 m x 2.8 m inner dimensions. It consists of a 160 kV X-ray high voltage generator (ISOVOLT HS160, Pantak Seifert, GE Inspection Technologies), a calibrated voltage divider, and three water-cooled X-ray tubes of tungsten, molybdenum and rhodium target material, respectively. The new X-ray facility is intended for carrying out calibrations, type-testing and verifications of dosemeters mainly used for quality assurance applications in field of mammography and conventional radiology. Other applications will be introduced in the near future, e.g. calibration of kV-meters. The objective of this work was to establish the basic geometrical irradiation conditions of the X-ray unit for the introduction of various photon reference radiation qualities according to international standards, e.g. IEC 61267 for medical diagnostic x-ray equipment. The precise positioning and orientation of the x-ray tubes, diaphragms, filters (mounted on a filterwheel, see Fig. 1), and transmission ionization monitor chamber along the central beam axis were carried out to finally provide accurate and traceable calibrations according to requirements of a primary and secondary standards dosimetry laboratory. The components of the X-ray irradiation facility were installed and adjusted in a stepwise procedure using a laser alignment system and a digital X-ray imaging detector XRD (PerkinElmer Technologies). Setup and characterization of the X-ray field parameters were based on measured 1024 x 1024 pixel maps and derived relative intensity profiles at two application distances, 600 mm and 1000 mm.

The HS160 X-ray facility

The X-ray facility consists of an ISOVOLT HS160-02202028 high voltage generator, a cooling system and an invasive high-voltage divider ZD763900-022624 (ratio 100000:1) for measuring the actual high voltage. An operator panel outside the controlled area is used for selecting one of three X-ray tubes (W160, Mo100, and Rh100) with different anode materials and the irradiation parameters, i.e. tube voltage (kV) and tube current (mA). Various additional filter materials can be selected by mounting the appropriate filter wheel including up to 12 filters with different filter materials or combination of filter materials and filter thicknesses. An in-house constructed transmission ionization chamber M50E-8502 was installed defining the final field-size and for monitoring the actual X-ray beam output. A pneumatic operated shutter with reproducible shutter opening and closing times in the order of 0.1 s is part of the approved security system. Horizontal and vertical laser lines were introduced defining the main beam axis. A carriage movable on fixed ground rails within the DEL Bunker length and a digital distance system are available for reproducible detector positioning. Some of the HS160 X-ray facility components can be seen in Fig. 1.

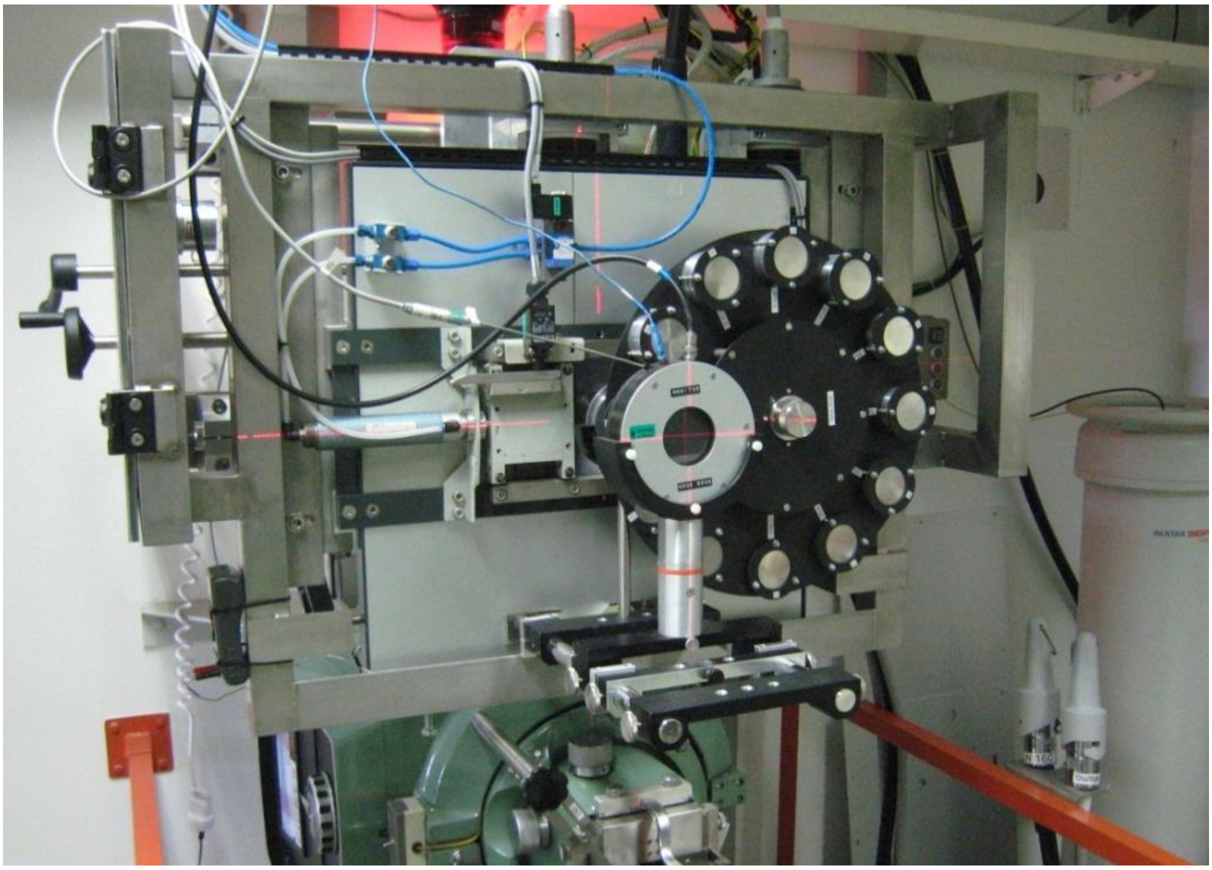

Figure 1: The setup of the HS160 X-ray facility in the DEL Bunker of the Seibersdorf Laboratories is shown. The three X-ray tubes are installed behind the shielding structure, their high-voltage cable connectors can be seen on top. At the center of the figure, the opened shutter, a filter wheel (RQA filter wheel), and the monitor chamber can be seen. All components were aligned according to the visible laser cross (red horizontal and vertical lines). A part of the cylindrical high voltage divider can be seen in the lower right corner of the picture. The Picker teletherapy Co-60 unit can be partly seen below the X-ray facility.

X-ray beam shaping components

The positioning and partly the size and shape of the main components (numbered A to F) responsible for the final calibration field characteristics were optimized. A schematic diagram of the final setup along the main beam axis is shown in Fig. 2.

(A) X-ray tube: Three X-ray tubes can be moved manually along the horizontal axis perpendicular to the beam axis. The position is displayed precisely by a digital positioning system. The selected (within the control panel) X-tube has to be connected to the HV-divider and moved to the final irradiation position.

> Mo100 (Panalytical X-ray fluorescence side window tube, molybdenum target, maximum 100 kV, 20° anode angle and 1.0 mm Be inherent filtration) irradiation position: 0.00 mm
>
> W160 (ISOVOLT 160 M2, Comet MXR-161 tube, tungsten target, maximum 160 kV, 20° anode angle and 0.8 mm Be inherent filtration) irradiation position: 160.42 mm
>
> Rh100 (Panalytical X-ray fluorescence side window tube, rhodium target, maximum 100 kV, 20° anode angle and 0.15 mm Be inherent filtration) irradiation position: 318.31 mm

(B) tungsten collimator: This collimator is part of the radiation protection shielding construction around the tubes. A small aperture (pin hole) can be inserted there for imaging of the focal spot.

(C) lead diaphragm: This aperture limits the beam size to within the subsequent filter size.

(D) filter: Various filter materials and filter thicknesses can be positioned automatically by choosing the appropriate filter wheel and filter number.

(E) monitor chamber: The entrance aperture of 55.3 mm diameter of the monitor chamber is determining the final radiation field size.

(F) 400 mm reference distance point: A removable steel stick with a marked cross at the main beam axis can be inserted and removed for reproducible detector positioning. The distance of a detector reference point to the nominal focal spot is adjusted according to the 400 mm reference point.

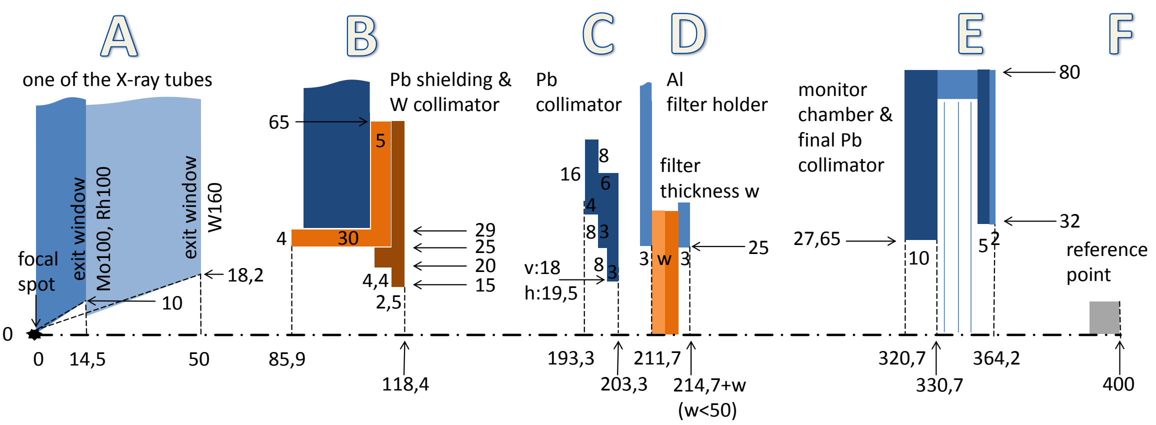

Figure 2: Schematic diagram (not to scale) of the setup of the six beam shaping components of the HS160 X-ray facility: one of the three X-ray tubes (A), tungsten collimator within the lead shielding (B), lead collimator (C) in front of the selected filter of width w within the filter wheel holder (D), monitor chamber (E), and 400 mm reference distance point (F). Dimensions are given in mm.

Geometrical calculations

The final circular radiation field size is restricted by the position of the lead entrance aperture of the monitor chamber with its fixed diameter of 55.3 mm. To finally get a 100 mm diameter field size at 600 mm focus-detector-distance, the aperture has to be positioned at 330.7 mm. The real size and shape of the focus is not taken into account in this geometrical calculation. In Fig. 3 the calculated radial beam sizes as a function of the distance to the focal spot are presented. The radial beam size limited by the monitor chamber entrance aperture (E) is shown as a red line. The beam size due to the aperture of the collimators and filter should not be smaller than the diameter of the monitor chamber entrance window. The aperture of the tungsten collimator (B) should limit the beam (shown as a green line) to within the filter holder diameter of 50 mm for the minimum filter thickness w=0 mm. The distance from the focus to the filter wheel (D) (the beam limited by the filter with maximum filter thickness w=50 mm is shown as an orange line) cannot be varied, because the filter wheel is mounted at the shielding structure surrounding the X-ray tube assemblies. Therefore, the size of the lead aperture (C) in front of the filter has to be chosen to limit the beam within the filter holder diameter of 50 mm for the maximum filter thickness. Actually, there was some flexibility regarding the position of the filter wheel due to the possibility of varying the position of the focal spot of the X-ray tubes within the shielding structure.

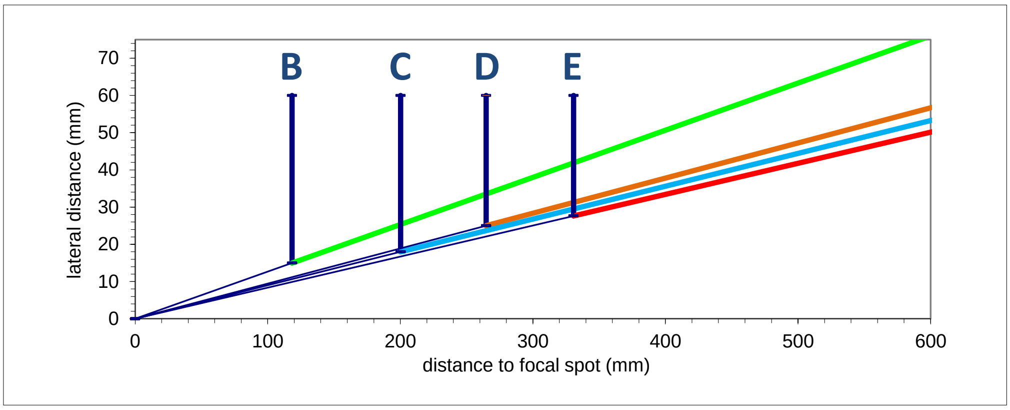

Figure 3. Geometrical beam sizes were calculated (Microsoft Excel) for choosing the appropriate distances and diameters of the diaphragms: tungsten aperture (B) at 118.4 mm, lead aperture (C) at 200.3 mm, filter holder aperture (D) for the maximum filter width of w=50 mm at 264.7 mm, and final monitor chamber aperture (E) at 330.7 mm.

The setup procedure

The setup procedure for the components of the X-ray facility was carried out step-wise:

- laser beam setup: The laser beam axis was adjusted according to the center of the tungsten collimator (B) within the fixed shielding structure. Additionally, the laser beam was aligned parallel to the rails mounted to the floor, where detectors can be positioned on the movable measuring carriage at focus-detector-distances up to several meters.

- XRD detector positioning: The flat-panel imaging detector was positioned on the measuring carriage with its center at the laser beam axis. The correct perpendicular orientation was achieved using a mirror at the detector rear side and adjusting the detector positioning according the reflection of the laser light close to the laser exit window. The correct positioning of the center of the detector was verified by imaging a metal peak (details see below). The detector center was finally marked at its rear side. The fields of the various components were imaged step-wise and for each re-positioning the detector was moved out of the laser beam line.

- X-ray tube (A) position and orientation adjustment: The lateral position, the longitudinal position along the laser beam axis and the orientation of the tube were iteratively adjusted by moving the tube and imaging the 2D field intensity distributions. The flat-panel detector allowed a fast determination of the main axis intensity profiles measured at two distances. Calculations of the X-ray field sizes according to the intensity profiles revealed deviations of the field center as compared to the center of the laser beam axis.

- tungsten (B) and lead diaphragm (C) positioning: The size of the lead diaphragm aperture was increased in horizontal direction to produce a maximum homogenous field region and minimum penumbra for the asymmetric focal spots of the Mo100 and Rh100 X-ray tubes. Both diaphragms were centered (using a PMMA insert with a cross in its center) and adjusted perpendicular (using a mirror) to the laser beam line.

- filter wheel (D) positioning: Different filter wheels with up to 12 possible filter windows of circular size with 50 mm diameter can be selected. There is a slight variation of the position of the actual chosen filter due to the weight distribution of the various filters within the automatic wheel positioning system.

- monitor chamber (E) positioning: The final field size is determined by the entrance window of the monitor chamber. The chamber was centered and adjusted similar to the other components.

- 400 mm reference distance point (F) positioning: The reference distance from the nominal focal spot was checked by imaging radiation fields at two application distances. Actually, the precise value of the distance was not important because reference air kerma values will be determined for each application distance.

A field size of about 100 mm in diameter was finally verified at the distance of 600 mm. At this distance, a positioning uncertainty of 1 mm along the main beam axis will result in a dose uncertainty of about 0.3%. Closer distances are not recommended for detector positioning.

Flat-panel imaging detector

The PerkinElmer XRD 0822 CO 14 IND GbIF 1.40 8-2542 is a digital X-ray detector used for field intensity imaging. The amorphous silicon photodiode array uses Gd_2O_2S:Tb scintillator material. Its specifications are: a broad photon energy sensitivity range (15 keV – 15 MeV), an active area of 204.8 mm x 204.8 mm, a 14 bit ADC, a variable integration time (66 ms to 2 s) for a single frame (averaging over a sequence of up to 10000 frames is possible). The characterization of the X-ray fields depending on the distances can be measured by the 1024 x 1024 pixel map of the field intensity adjusted to within the possible 16384 gray values. PerkinElmer XIS 3.0 X-ray imaging software was used to export ‘his’ and ‘bmp’ file formats. With the Mathematica 4.2 software package it was possible to import the 1024 x 1024 16-bit integer (proceeded by a 100 byte header) ‘his’ image data files and to carry out calculations of profiles and derived field parameters. Offset, Gain and Pixelmask correction images have to be determined before taking images with selected detector parameters. It is important to shield the detector electronics outside the active area during homogeneous detector irradiations for special Gain and Pixelmask (pixel error) correction irradiations.

The reference plane of the flat-panel detector was assumed 5 mm behind the surface as specified by the manufacturer. The distance in air between the 400 mm reference point and the detector surface was adjusted by: µ(600)=600-400-5 mm=195 mm.

Pixel images (with cables connected to the detector on top) are defined by the (horizontal) x-axis: pixel 1 (left) to 1024 (right, viewing the front surface of the detector) and the (vertical) y-axis: pixel 1 (top) to 1024 (bottom). The exported 8-bit integer ‘bmp’ image files include additional border pixels resulting in 1028 x 1026 pixel maps with the center pixel at x=514.5 and y=513.5. The position of the image center was verified for the position of the laser beam at the marked cross at the rear side of the detector.

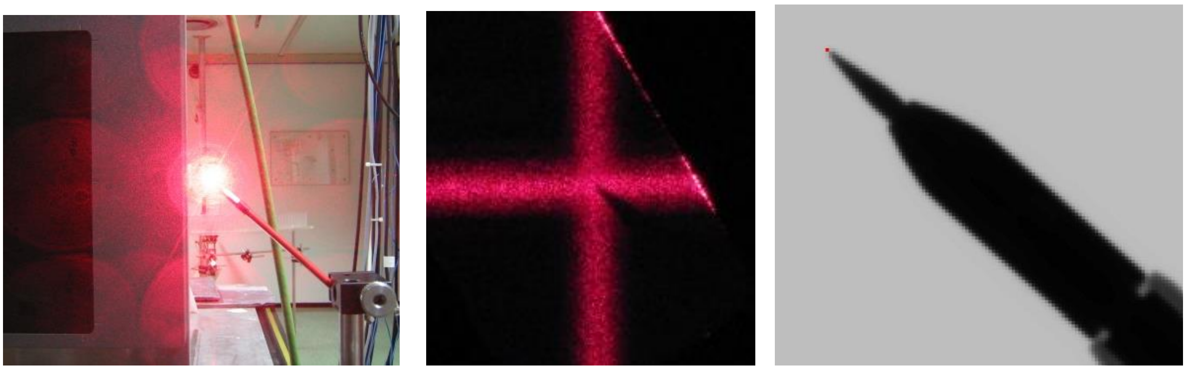

Figure 4: Metal peak positioned at the center of the laser beam cross center (left picture). Although the laser beam line exceeds the width of 1 mm, the positioning can be carried out more precise than 1 mm (middle picture). Afterwards, the detector was moved independently from the metal peak to the center of the laser beam directly in front of the metal peak. The red pixel (right picture) at the estimated peak of the imaged metal peak was at pixel position x=515, y=514, which is only about 1 pixel (0.2 mm) from to the actual image center.

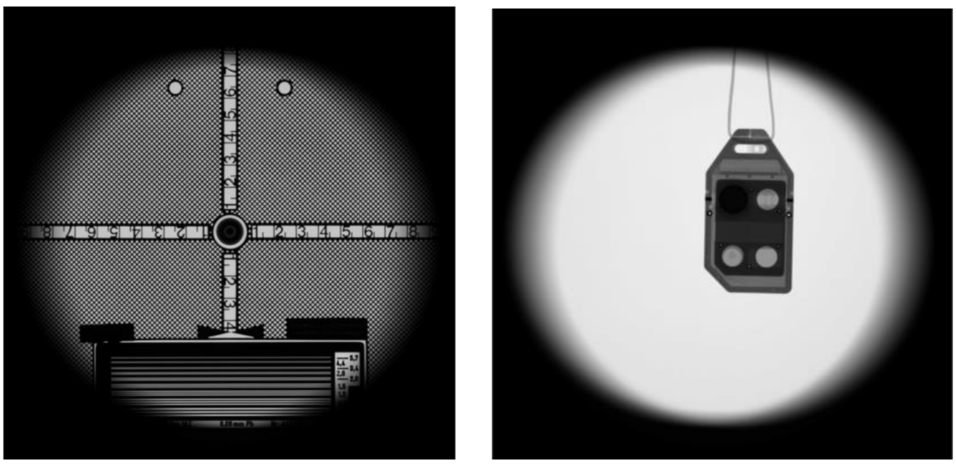

Figure 5: Rh100 (at 25 kV in 1000 mm distance) image of a test pattern for checking the alignment of the flat-panel detector (left picture). The photon energy spectrum for tube voltage 25 kV (without additional filtration) is close to the lower energy range of the detection capability. Mo100 (at 30 kV in 1000 mm distance) image of a personal dosemeter Seibersdorf (right picture). ‘bmp’ images consist of linear distributed gray values according to measured pixel intensities, where zero intensity is black and maximum intensity is white.

Focal spot imaging

A collimator with very small aperture was inserted instead of the tungsten collimator (B). The size of the drilled hole within the collimator is not known to the authors. The hole is so small that it is not visible except when looking directly to the sun. The pin-hole collimator was inserted at the X-ray tube side with an estimated distance of the pin-hole center of 80.7 mm from the nominal focal spot position. Therefore, the resulting inverted image is magnified by a factor of 6.45. Due to the small aperture the maximum tube current was chosen. The tube potential should not be too high to avoid additional radiation transmission.

For W160 (at 50kV) the determined focal spot size was about 3.4 mm x 4.3 mm. The manufacturer given focal spot size of the W160 tube is 4 mm x 4 mm according IEC 336 and 7.5 mm in diameter according EN 12543. For Mo100 (at 50 kV) the determined focal spot size was about 12 mm x 5 mm, see Fig. 6. The measured focal spot sizes were used to verify the position and shape of the penumbra for the calibration field images, see Fig. 7, 8, and 9. Intensity map calculations using Mathematica software were carried out assuming homogeneous rectangular focal spot shapes. Three circular apertures were included in the simplified ray-tracing simulations, i.e. the tungsten (B), the lead (C) and the final monitor chamber aperture (E).

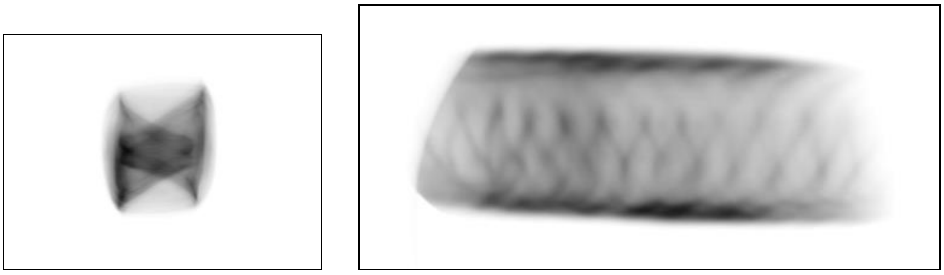

Figure 6: W160 measured focal spot 3.4 mm x 4.3 mm (left picture), Mo100 measured focal spot 12 mm x 5 mm (right picture). Linear distributed but inverted gray values according to the pixel intensities, where zero intensity is white and maximum intensity is black.

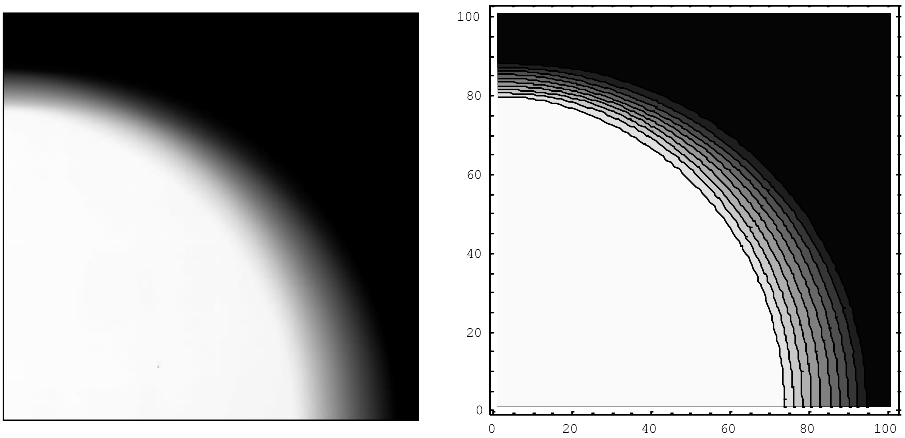

Figure 7: Mo100 (30 kV, no additional filtration) upper right quadrant of the measured intensity pixel map at the detector distance of 1000 mm (left picture). Mo100 intensity map calculation (Mathematica) assuming a rectangular focal spot shape of 12 mm x 5 mm (right picture). Horizontal and vertical axes are in mm.

Calibration field characterization

Beam profiles along horizontal and vertical axes were determined at two focus-detector-distances, 600 mm and 1000 mm. A Mathematica code was implemented for evaluating profiles by averaging over 10 pixel rows and 10 pixel columns for x-axis and y-axis, respectively. Relative intensity profiles were normalized to the center pixel intensities (therefore profile values exceeding 100% are possible). Profiles presented in Fig. 8 are for Mo100 (30 kV tube potential, RQR-M filtration) and for W160 (70 kV tube potential and RQR-5 filtration). XRD intensity images were taken as an average over 1000 frames with a detector timing of 99 ms per frame. The maximum pixel intensities were about 12000. It was important to keep intensity pixel values right below the maximum value of 16384 to avoid image artifacts. Generally, y-axis (vertical, in-tube axis) profiles show smaller penumbra due to the smaller focal y-axis dimensions. No inhomogeneity in the plateau region of the vertical profiles due to the Heel effect is visible due to the low tube potentials. Penumbra of W160 profiles are steep compared to the Mo100 profiles due to the smaller focal spot size.

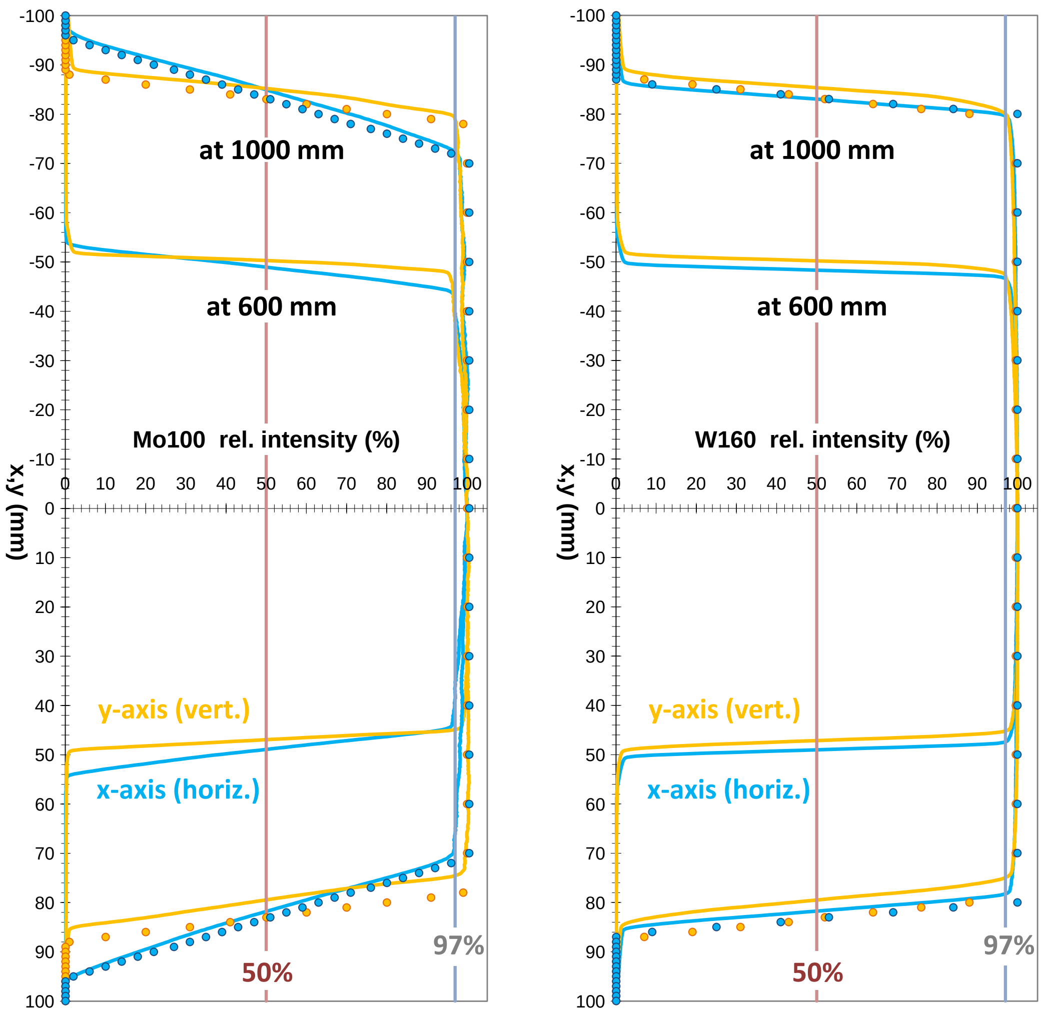

Figure 8: Mo100 (at 30 kV without additional filtration) relative horizontal (blue line) and vertical (orange line) main axis intensity profiles at 600 mm distance (inner profiles) and at 1000 mm distance (outer profiles) (left figure), W160 (at 70 kV without additional filtration) (right figure). Simulated intensity profiles at 1000 mm (blue and orange circles) were based on the rectangular focal spot sizes of 12 mm x 5 mm and 3.4 mm x 4.3 mm for Mo100 and W160, respectively.

The field-size (profile region within 50% intensity) were calculated based on the measured horizontal and vertical relative intensity profiles for W160, Mo100 and Rh100, respectively. As can be seen in the results of table 1, the three X-ray tubes agree well with the calculated geometrical field-sizes of 100 mm and 167 mm for the reference distances of 600 mm and 1000 mm, respectively. Additionally, the homogeneous profile regions (97% field-sizes) were determined. The size of the homogeneous region is important for determining maximum allowed detector sizes at certain distances and uncertainties due to field inhomogeneity. The values of the deviation of the calculated center of the field compared to the laser main beam axis are also included. The slightly negative values of the field center deviations in y-axis means that the X-ray tubes should be positioned higher by about 2 mm for perfect alignment. Due to the small deviations and the critical vertical re-positioning procedure, no changes of the X-ray tube positions are currently planned.

Table 1: W160, Mo100 and Rh100 field sizes defined by 50% and 97% relative intensity, horizontally (x-axis) and vertically (y-axis), for two focus-detector-distances of 600 mm and 1000 mm. The deviation of the field centers are calculated from the 50% profiles.

		W160		**Mo100**		**Rh100**	
	distance (mm)	x-axis (mm)	y-axis (mm)	x-axis (mm)	y-axis (mm)	x-axis (mm)	y-axis (mm)
field size (50%)	600	101	101	102	101	102	101
field size (97%)	600	98	94	77	83	88	98
field center deviation	600	0	-2	0	-2	0	-2
field size (50%)	1000	169	169	170	169	170	169
field size (97%)	1000	162	159	137	157	146	161
field center deviation	1000	-1	-3	-2	-3	0	-4

Conclusion and Outlook

Geometrical setup of X-ray facility components and field sizes of about 100 mm in diameter were verified at the reference distance of 600 mm for three X-ray tubes, Mo100, W160, and Rh100. Penumbra, field-sizes (50% and 97%) and center of radiation fields were optimized based on horizontal and vertical relative flat-panel image intensity profiles. Flat-panel imaging was limited to a focus-detector-distance of 1000 mm due to the active pixel area of about 205 mm x 205 mm. Compared to former time-consuming analog film processing, the new digital detector allows more iteration steps in the optimization process of the X-ray facility setup. The next step will be the field characterization of the whole series of reference calibration qualities currently setup in the dosimetry laboratory. Relative air kerma profiles along the horizontal and vertical axes at the reference distance will be measured only for a limited number of beam qualities using a small volume thimble ionization chamber. As the reference plane of the flat-panel detector is not well specified, slight differences in field-sizes may occur between the air kerma profiles and the image intensity profiles. Not included in this paper are the results of the air kerma half-value layer measurements with the medium-sized free air parallel plate ionization chamber and results of practical peak voltage measurements. It is planned, that photon fluence spectra will be measured using a Germanium spectrometry system. Finally, results may be compared to Monte Carlo simulations for verification purposes and for determining other influences such as scattering contributions.