ABSOLUTE AIR-KERMA MEASUREMENT IN A SYNCHROTRON RADIATION BEAM BY IONIZATION FREE-AIR CHAMBER

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ABSTRACT

A dosimetric procedure to assure the traceability to the air-kerma standard of the measurements performed in synchrotron radiation beams, was implemented at the "Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti" of ENEA (INMRI-ENEA). To this purpose, absolute air-kerma measurements by the ENEA standard free-air chamber for low energy x-rays have been performed at the SYRMEP (SYnchrotron Radiation for Medical Physics) beamline of the ELETTRA light source in Trieste (Italy) where a program of clinical mammography based on phase contrast imaging has been developed in the framework of the SYRMA project (**SY**nchrotron **R**adiation for **MA**mmography). The synchrotron radiation beams to be characterized were monochromatic x-rays with energy in the range from 8 keV to 35 keV and the reference point for measurements corresponded to the centre of the breast when the patient lies on her support. The absolute air-kerma measurements were also used to calibrate two monitor chambers and an ionization free-air chamber specially designed and realized by ENEA to act as transfer standard in the synchrotron radiation beams. The irradiation conditions for measurements – both beam quality and geometry – were very different from the reference conditions at the INMRI-ENEA. According to the actual conditions, the diaphragm of the ENEA standard chamber was modified and some correction factors were re-determined by Monte Carlo calculations based on the PENELOPE code or by experimental measurements. In particular, the mass air attenuation coefficients of these monochromatic x-rays were experimentally determined to obtain the correction for photon attenuation in air.

1. INTRODUCTION

The advantages of using monochromatic synchrotron X-ray beam for mammography have been widely described since the past years [1]. Essentially synchrotron radiation provides better resolution and sharpness of the radiological image without increasing dose delivered to the patient. Moreover, the entrance skin dose are reduced from 40 % to 70 % and the mean glandular dose estimated resulted reduced from 10% to 50 % according to the dimension and density of the breast.

At the ELETTRA Synchrotron Laboratory operating in Trieste, Italy, a research project for high definition clinical mammography based on phase contrast imaging [2] has been developed in the framework of the SYRMA project at SYRMEP beamline.

To this end, collaboration between the INMRI-ENEA and ELETTRA was started aiming at characterizing the synchrotron light beam in terms of air kerma. Accurate air-kerma measurements in this peculiar beam are necessary in order to optimize the patient absorbed dose with respect to the definition of the radiographic image.

At the SYRMEP beamline the synchrotron radiation beam is monochromatized in the range from 8 keV to 35 keV with laminar shape, whereas the reference radiation used at INMRI-ENEA for air-kerma calibrations is based on filtered x-ray beams with a circular field size.

It was then decided to perform absolute air kerma measurements directly at the beamline bringing the standard low-energy-free-air chamber of INMRI-ENEA to the ELETTRA Synchrotron. The following step was to provide the SYRMA project with a transmission ionization chamber calibrated in terms of air kerma in the synchrotron radiation beam directly against the free-air chamber of INMRI-ENEA.

2. MATERIALS AND METHODS

2.1 Characteristics of the SYRMA beamline and the x-rays beam

Figure 1 shows a schematic diagram of the experimental set-up to obtain the monochromatic synchrotron radiation beam to be used for high definition phase contrast mammography in the framework of the SYRMA project at the ELETTRA light source. The synchrotron radiation in the 8 keV- 35 keV energy range is extracted at the position of one of the 24 bending magnets of the ELETTRA storage ring. The relevant characteristics of the SYRMEP beamline are in table 1. Between the source and the reference point for patient exposure, photons travel a distance of approximately 20 m in vacuum and 10 m in air. The beamline is divided into three sections devoted to: beam preparation (optics hutch); beam monitoring (experimental hutch); patient exposure room.

The main components of the optics hutch are the monochromator, the two slit systems, the beam stopper and the filters. Details are shown in figures 1 and 2.

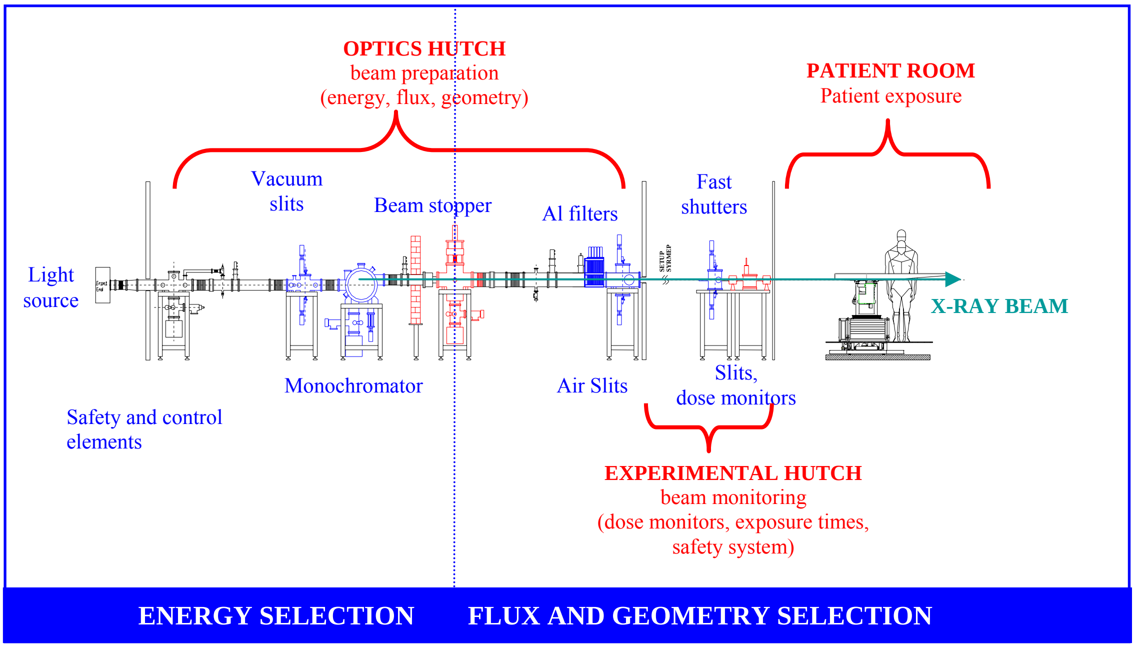


Figure 1. Schematic layout of the ELETTRA medical beamline for phase contrast mammography in the framework of the SYRMA project at the ELETTRA Synchrotron in Trieste, Italy.

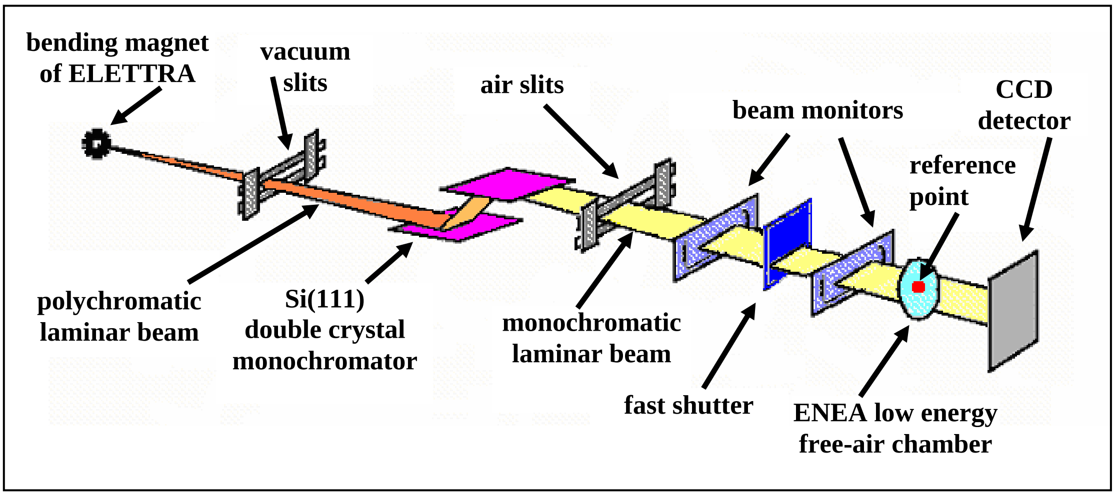


Figure 2. *Schematic diagram of the synchrotron ELETTRA light beam with laminar shape. The two beam monitors were calibrated directly against the INMRI-ENEA low-energy-free-air chamber. The monitors are transmission type ionization chambers specifically designed for measurement in photon beams with laminar shape.*

The monochromator, based on a double silicon crystal assembly working in Bragg configuration, covers the entire angular acceptance of the beamline. The crystals are equipped with high precision motion stages to set the Bragg angle that define the energy to be selected and to perform fine angular alignments of the second crystal with respect to the first one. The intrinsic energy resolution of the monochromator in the order of 10^{-4} is reduced to $2 \cdot 10^{-3}$ because of the natural divergence of the beam. The emerging beam is parallel to the incident one with a vertical displacement of 20 mm.

Table I. *Relevant characteristics of the light source and x-ray beams for high definition mammography in the framework of the SYRMA project at the Synchrotron ELETTRA in Trieste, Italy.*

Characteristic	Value
Light source	
Type	Bending magnet
Critical energy (at 2.0 GeV)	3.21 keV
Critical energy (at 2.4 GeV)	5.59 keV
Source size	100 µm x 1100 µm
Horizontal angular acceptance (beam divergence)	7 mrad
X-ray beam at reference point	
Energy range	8 keV - 35 keV
Energy range for patient exposure	16 keV – 25 keV
Energy Resolution	$\Delta E/E = 2*10^{-3}$
Typical photons fluxes at 15 keV	2 x 10^{8} ./mm^{-2} s^{-1} (at 2 GeV, 300 mA) 7 x 10^{8} /mm^{-2} s^{-1} (at 2.4 GeV, 180 mA)
Beam Size	120 mm x 4 mm
Source-to-sample distance	about 30 m (26.5 m in vacuum)

Relevant characteristics of the monochromatic x-ray beam are in table 1. Any beam energy at the monochromator exit can be chosen in the 8 keV - 35 keV range.

The beam fluence rate as a function of the energy is shown in figure 3. The data in figure 3 refer to the ELETTRA synchrotron operated at 2 GeV and at 2.4 GeV, at the maximum electron beam current of 300 mA (blue) and 140 mA (red), respectively. For the application to clinical mammography, the overall energy range specified in table I is restricted to the range 17 keV - 22 keV. The beam is collimated by two slits systems using tungsten blades to shape the beam and to remove the scattered radiation. Both of them are equipped with high precision motion stages and are remote controlled.

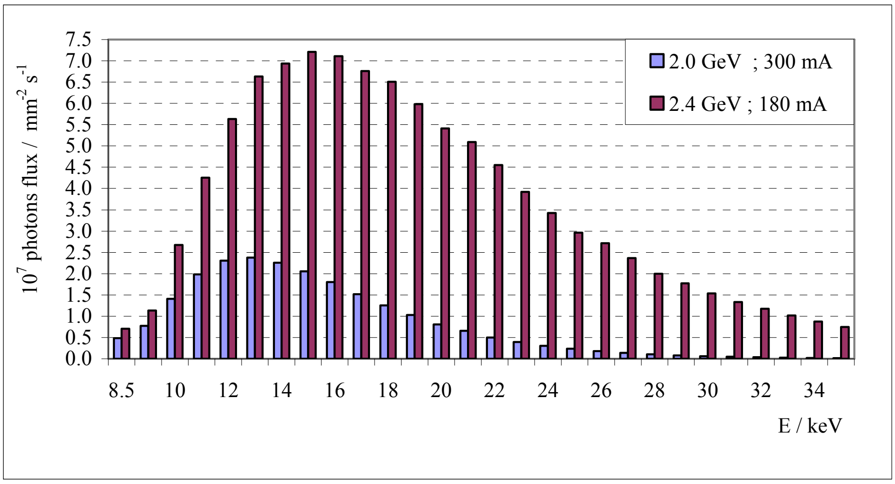


Figure 3. *Photon flux values - as function of the photons energy - at the reference point for patient exposure, when synchrotron Elettra is operated at 2 GeV and 2.4 GeV with stored the maximum electron beam currents of 300 mA and 180 mA, respectively.*

The first slit apparatus - cooled and in vacuum - is used to delimitate the white beam, the second one - in air - is downstream the monochromator and acts on the monochromatic beam. A set of Al filters with calibrated thickness are used to reduce the beam intensity. The beam stopper is the safety element used to determine the access conditions in the experimental hutch.

The monitors providing a continuous monitoring of the laminar beam during the patient examination are shown in figure 4 together with the beam shutters. Just before the radiation monitors, a collimator system is installed to define the effective final dimensions of the beam. The cross section of the X-ray beam in the patient room can be varied from 10 mm x 3.4 mm to about 210 mm x 3.4 mm.

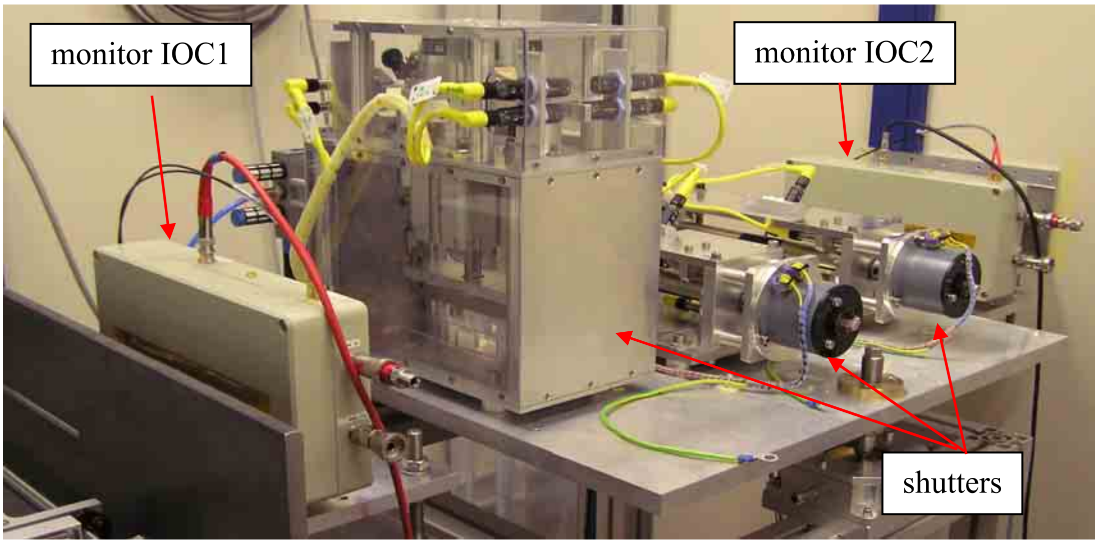


Figure 4. *Detail of the experimental hutch (see figure 1) showing in particular the main core of the patient safety system constituted by the radiation monitors and the fast beam shutters.*

The patient room is equipped with the patient and the detector support. Owing to the laminar shape of the x-ray beam, planar mammograms are obtained by moving the patient with respect to the fixed beam. For this purpose a suitable speed controlled movable support was constructed on which the patient lies down in a prone position (see Fig. 5a) with the breast placed in an appropriate opening. The support is equipped also with a rotational stage that allows producing different breast projections. The reference point for absolute air kerma measurements corresponds to the centre of the breast when the patient is on this support (figure 5b).

The free-air chamber (FAC) and the secondary standard chamber (SSC) of the INMRI-ENEA were alternatively positioned at the patient breast position on a special support equipped with high accuracy vertical, horizontal and rotatory remotely controlled motion stages that allow centring the chamber with respect to the beam and checking that the entrance diaphragm was perpendicular to the X-ray beam.

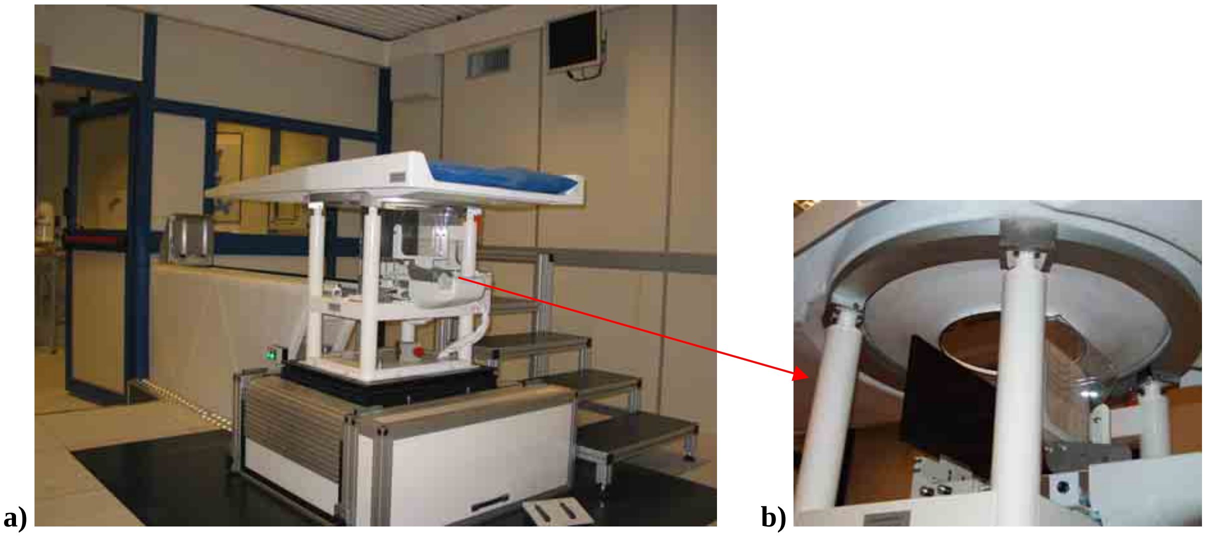


Figure 5. *Speed controlled movable support for patient exposure (a) to obtain phase contrast mammography by scanning the patient through the beam itself at the Synchrotron ELETTRA. Detail in figure 4b shows the position of the compression system used for stretching and equalizing the breast tissues thickness. The standard chambers are placed in this position for air kerma measurements, after removing the compression system.*

2.2 Radiation detectors

2.2.1 Monitor ionization chambers

Continuous monitoring of the beam was assured by two identical ionization chambers of the transmission type, denoted IOC1 and IOC2 and shown in figure 4.

These monitors were designed and constructed at the ELETTRA laboratories specifically for the laminar beam geometry. The chambers are characterized by thin entrance and exit windows suited to the beam shape and dimensions. The sensitive volume is constituted by two regions - 12.5 mm thick - as shown in figure 6b. The two regions are delimited by the two HV electrodes and separated by the central collecting electrode whose dimensions are 250 mm x 50 mm. The electrodes and windows are

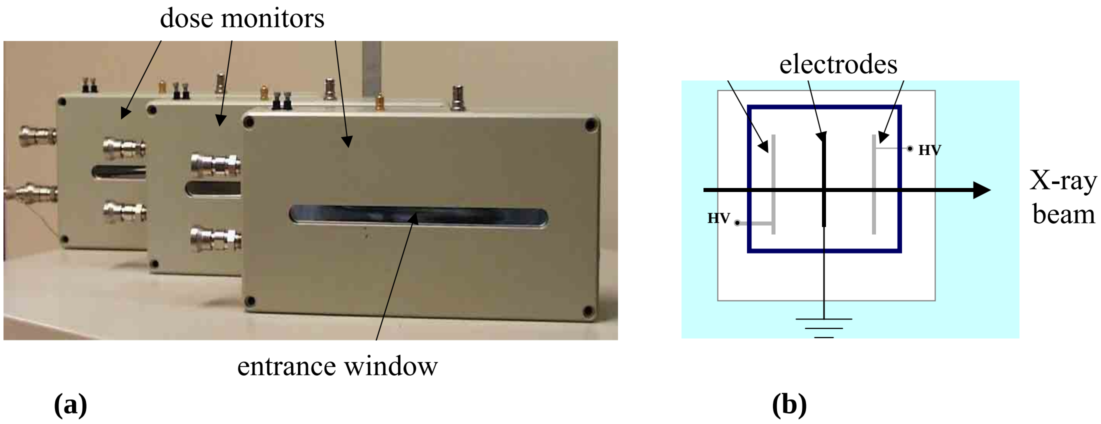


Figure 6. *Ionization chambers (ICs) of the transmission type used as dose monitors in the patient beamline at the synchrotron Elettra. The incidence direction of the beam is perpendicular to the chamber electrodes, as shown in the scheme on figure (b).*

perpendicular to the beam and are realized in Mylar foils - 50 µm thick - covered on each side by a 50 nm layer of Al. The chambers are inside an Al box, shielded against RF, whose external dimensions are 32 x 16 x 6.5 cm^3. In this way the monitors response is not affected by small beam spatial instabilities.

Short and long-term stability of these monitor chambers were accurately verified at the INMRI-ENEA by irradiation in Co-60 gamma beams. To this end, a special shaped collimator was realized at INMRI-ENEA to simulate the laminar structure of the synchrotron beam.

The effect of the ion recombination in the chamber collecting volume was investigated by measurements carried out directly in the synchrotron light beam by the method described by Boutillon [3]. Both monitor chambers, IOC1 and IOC2, were calibrated against the air kerma primary standard of the INMRI-ENEA.

2.2.2 Charge-coupled device

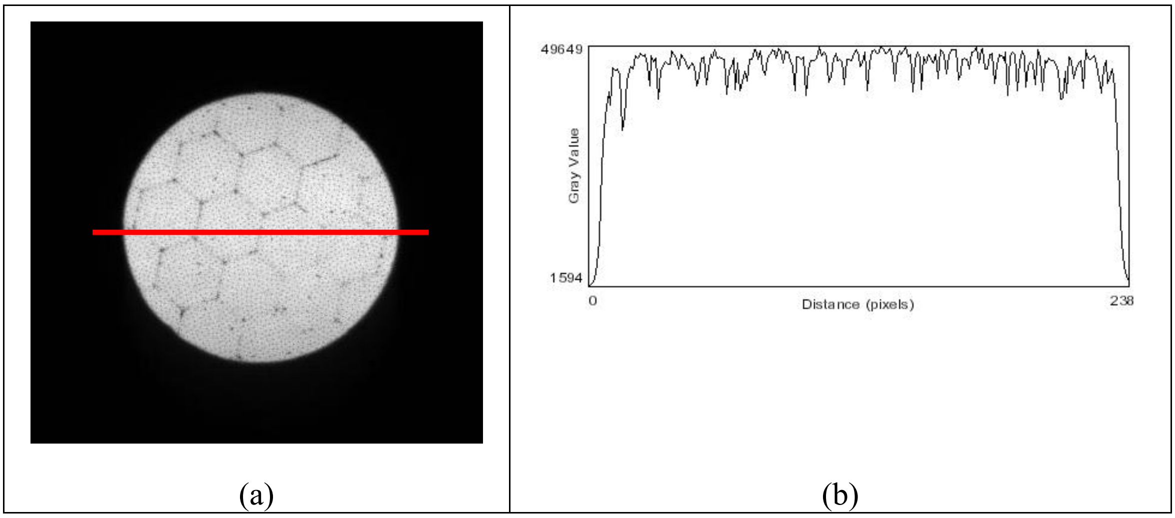
A digital detector based on a charge-coupled device (CCD) was accurately centred and aligned with respect to the radiation beam, in a fixed position downstream the patient support. It allows controlling the digital image of the beam transmitted across the chambers during the irradiation. It was a water-cooled CCD camera (Photonic Science X-ray Hystar) coupled to a Gadolinium Oxysulphide scintillator placed on a 1:1 optic fiber coupler. It covers the maximum beam section and presents to the incident photons a grid of 2048x2048 pixels (each with dimensions of 14 µm x 14 µm). This device and its associated electronics registered the number of photons impinging on each pixel in a given time registered to reproduce a digital image of the beam after the irradiated object.

An image of the beam was taken for each measurement. The analysis of the image profile allowed to evaluate the position of the beam axis with respect to the chamber diaphragms and to accurately position the chamber sensitive volume with respect to the beam. An example of the image and the profile of the beam taken by the CCD at 20 keV with the ENEA-SSC chamber equipped with the 3 mm diameter diaphragm is shown in figure 7. The honeycomb structure visible in the image does not depend on the x-ray beam but is due to the fiber optics assembly in the CCD camera.

2.2.2 The standard free-air chamber

Absolute measurements of air kerma in the monochromatic x-ray synchrotron beam were made by the ENEA parallel- plate free-air chamber (ENEA-FAC), the air-kerma standard for low energy x-rays described in [4, 5]. The ENEA-FAC was positioned at a reference point below the patient support in the X-ray beam (figure 8).

Because of the small size and the laminar shape of the radiation beam, a new diaphragm with a radius of 1.5 mm temporarily replaced the current 4 mm in radius diaphragm of the ENEA-FAC. Then the overall aperture of the new small diaphragm resulted homogeneously irradiated and the



(a) (b)

Figure 7. *Image (a) and profile (b) of the SYRMA x-ray beam taken by the CCD at 20 keV after the ENEA-INMRI secondary chamber equipped with the 3 mm diameter diaphragm.*

chamber measuring volume resulted well defined in this particular beam geometry. This was verified before and after each series of measurements by the CCD that provided beam imaging (section 3.1). To assess the beam homogeneity several measurements were made with the ENEA-FAC positioned at different points along the laminar beam section.

2.2.3 The calibrated free-air chamber

To be able to perform periodical calibration of the beam monitors a special ionization chamber – such to accept the same 1.5 mm in radius diaphragm of the standard free air chamber - was made at INMRI-ENEA. This chamber (ENEA-SSC) even if being a free-air chamber was not designed for absolute measurements but in order to have long term stability. It was then calibrated against the standard free-air chamber (ENEA-FAC) directly in the monochromatic SYRMEP beam in the energy

Figure 8. *The INMRI-FAC chamber for low energy x-rays at the reference measurement point (inside the red circle) under the patient support shown in figures 5, at SYRMEP beamline.*

range from 8 keV to 30 keV, at the reference point (figure 9).

The effect of ion recombination in the chamber (with a kerma rate up to 7 mGy s^{-1}) was corrected for by the method described by Boutillon [3].

2.3 Preliminary measurements to check the beam stability and uniformity

Preliminary experimental measurements have been carried out to characterize the synchrotron beam. The energy calibration of the monochromator has been performed using metal targets made of pure elements whose K-edge energies lie in the useful beamline energy range.

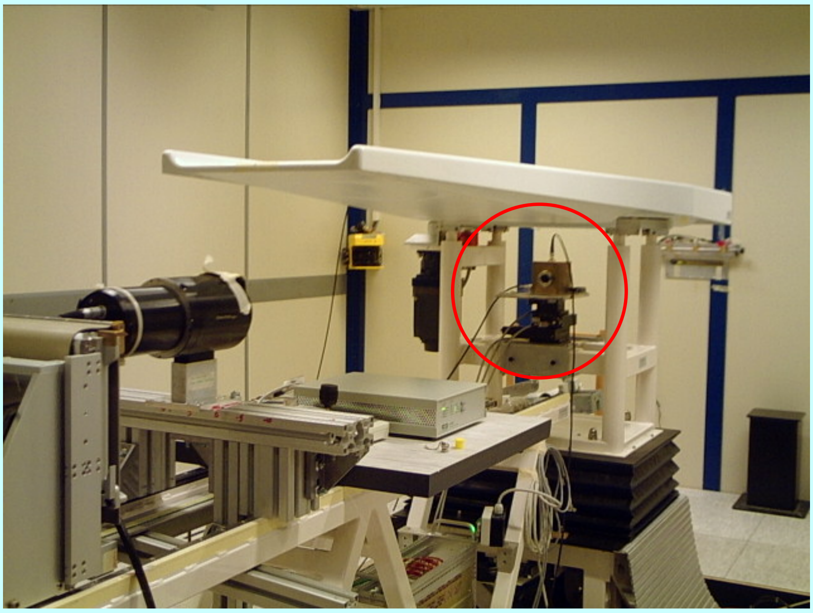


Figure 9. *The calibrated free-air chamber ENEA-SSC (inside the red circle) designed and made at the INMRI-ENEA to perform periodical calibration of the SYRMA beam monitors. The chamber was calibrated against the standard free-air chamber directly in the monochromatic synchrotron radiation beam in the energy range from 8 keV to 30 keV.*

For a given energy of the x radiation selected by operator, the beamline control system automatically sets the crystal assembly to the corresponding Bragg angle. Once the energy is selected, the optimization of beam intensity is performed by applying fine angular adjustments to the second crystal with respect to the first one (rocking). One of the two radiation monitors is used to follow the crystal rocking: the maximum current corresponds to the best alignment of the two crystals.

However, for a given Bragg angle, besides the nominal energy, in this configuration the monochromator Si(111) crystal transmits also the unwanted third harmonic component that is characterized by a rocking curve much narrower than the first one. Therefore, the rejection of the third harmonic is performed by de-rocking the second crystal with respect to the first one reducing the beam intensity of about 10%.

The spatial uniformity and stability of the laminar monochromatic beam was accurately verified by measurements made by the CCD detector. The uniformity of the beam in the horizontal direction has been evaluated by studying the response of the radiation monitors with different dimensions of the beam. For this purpose measurements have been acquired by the two IOC monitors varying the horizontal opening of the patient slits systems from 1 cm to about 14 cm. The reference monitor was the ENEA-SSC chamber placed on its holder on the patient support. Additional measurements were made also by the standard chamber that was moved along the horizontal axes from the centre to the extremity of the beam to cover the beam length of about 21 cm.

After injection, the stored electron current in the ring at 2.4 GeV is 140 mA and exponentially decreases in time with an average lifetime of about 32 hours. To compare measurements carried out at different beam currents, synchronized measurements have been performed with the two monitor chambers and the ENEA-SCC chamber. These data allowed us to verify that the ratio between monitor chambers and the ENEA-SCC chamber does not depend on the electron beam current.

2.4 Absolute determination of the air-kerma rate and monitor chamber calibration

The air-kerma rate as measured by the ENEA-FAC chamber is given by

$$\dot{K} = \frac{I}{\rho_{\mathrm{air}} V} \frac{W_{\mathrm{air}}}{e} \frac{1}{1-g_{\mathrm{air}}} \prod_i k_i \tag{1}$$

where ρ_{air} is the density of air under reference conditions, V is the chamber measuring volume, I is the ionization current under the same conditions, W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in air, g_{air} is the fraction of the initial electron energy lost by bremsstrahlung production in air, and Πk_i is the product of the correction factors to be applied to the standard. The list of the chamber correction factor and the values used for the physical constants ρair and W_{air}/e are given in [5].

The photon attenuation in air, hence μ/ρ was accurately determined using a vacuum tube of about 200 mm length (figure 10) in which the air pressure was varied down to 10^{-3} kPa. A re-determination of relevant correction factors was made for the SYRMEP irradiation conditions (beam and chamber geometry, energy, intensity). In particular, the corrections for the effects due to scattered photons, k_{sc},

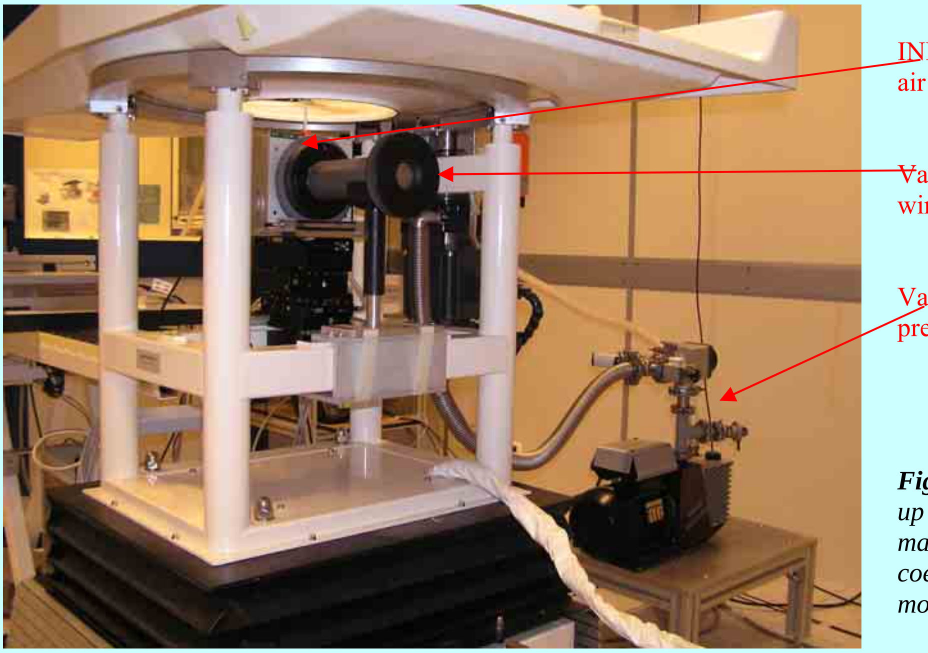


Figure 10. *Experimental set-up for the determination of the mass-air attenuation coefficients of SYRMA monochromatic x-ray beams*

re-absorption of fluorescence photons, k_{fl}, and electron loss in the chamber electrodes, k_e, were determined by the Monte Carlo code PENELOPE for monochromatic photons in the energy range from 8 keV to 30 keV. The calculation procedure is the same described in [6].

Once absolute air-kerma measurements are made, the calibration coefficients in terms of air-kerma were obtained for the two monitor chambers (figure 4) installed along the beamline. To this end repeated series of n = 100 measurements were performed.

To perform the periodical calibration of the monitor chambers at the ELETTRA synchrotron, the free-air ENEA-SSC chamber made at ENEA was also calibrated in the SYRMEP beam against the standard ENEA-FAC chamber.

The ENEA-SSC chamber will be adopted by the beamline users as a secondary standard to calibrate periodically their monitors. In the future, the calibrated chamber, ENEA-SSC, shall be periodically calibrated also at the INMRI-ENEA filtered x-ray beams to check the stability of the calibration made in the synchrotron radiation beam.

The periodical calibration of the ENEA-SSC chamber at INMRI-ENEA should make it unnecessary to repeat its calibration at the ELETTRA beams with the standard ENEA-FAC chamber, whose transport is rather delicate.

3. RESULTS

3.1 Verification of the synchrotron radiation beam

Some images of the beam shape obtained by the CCD detector are shown in figure 11 and 12, respectively.

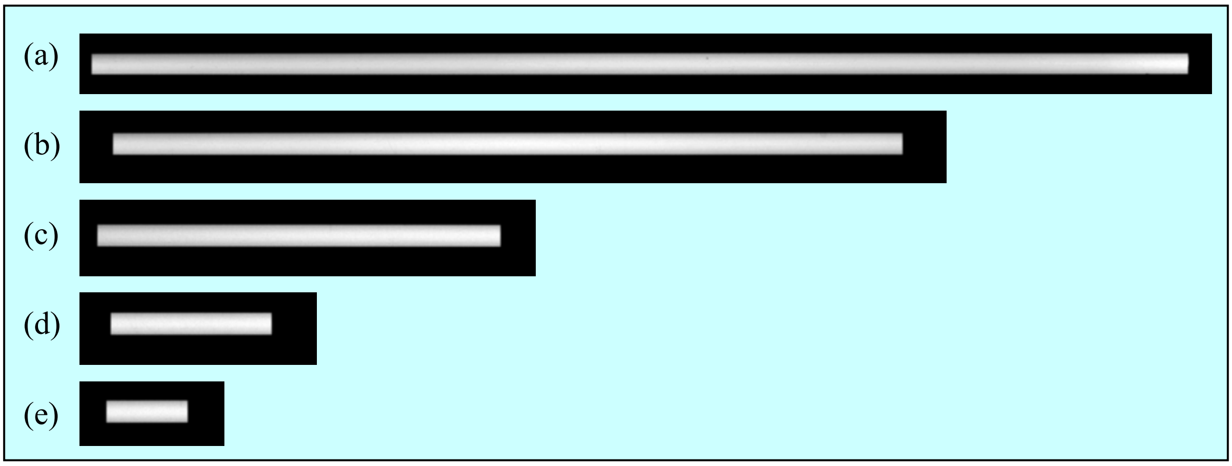


Figure 11. *Examples of images of the synchrotron radiation beam obtained by the CCD as the slit system installed in the experimental hutch changes the dimensions of the beam: (a) 139 mm x 3 mm, (b) 100 mm x 3 mm , (c) 50mm x 3 mm, (d) 20mm x 3 mm and (e) 10mm x 3 mm. Because of the natural divergence of the beam, the dimensions measured at the CCD are larger: 191 mm x 3.7 mm, 138.5 mm x 3.7 mm, 69.4 mm x 3.7 mm, 27.6 mm x3.7 mm, 14.1 mm x 3.7 mm, respectively.*

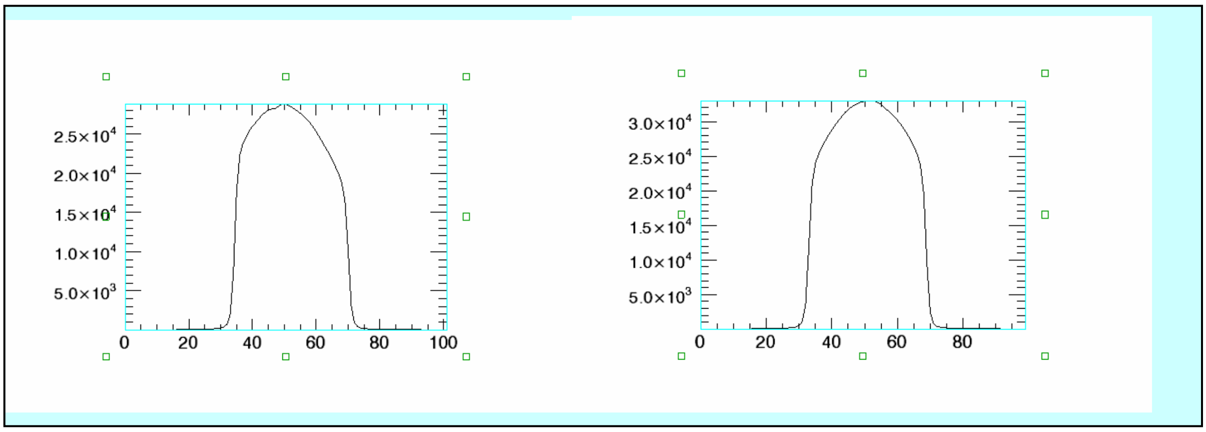


Figure 12. *Beam profiles at the extreme regions of the 22 cm radiation beam, as obtained by the CCD detector. The profiles show that the distributions of the beam energy fluence along the vertical dimension of the beam section are almost the same at the extreme sides of the beam. It can be then assumed that at least the same uniformity occurs in the intermediate regions within the beam size.*

The figure 13 shows the plot of the monitor chambers (IOC1 and IOC2) readings as a function of beam dimension in the horizontal direction, normalized with respect to the ENEA-SSC measurement. A linear trend is obtained by the fit of the experimental points.

The curves in figure 14 show the ratio of the currents measured by the monitor chamber IOC1 (or IOC2) and the free-air chamber ENEA-SSC, respectively. These ratios vary in the time by no more than 0.2% with a standard deviation of about 0.04% so assuring a good stability of the monitoring system.

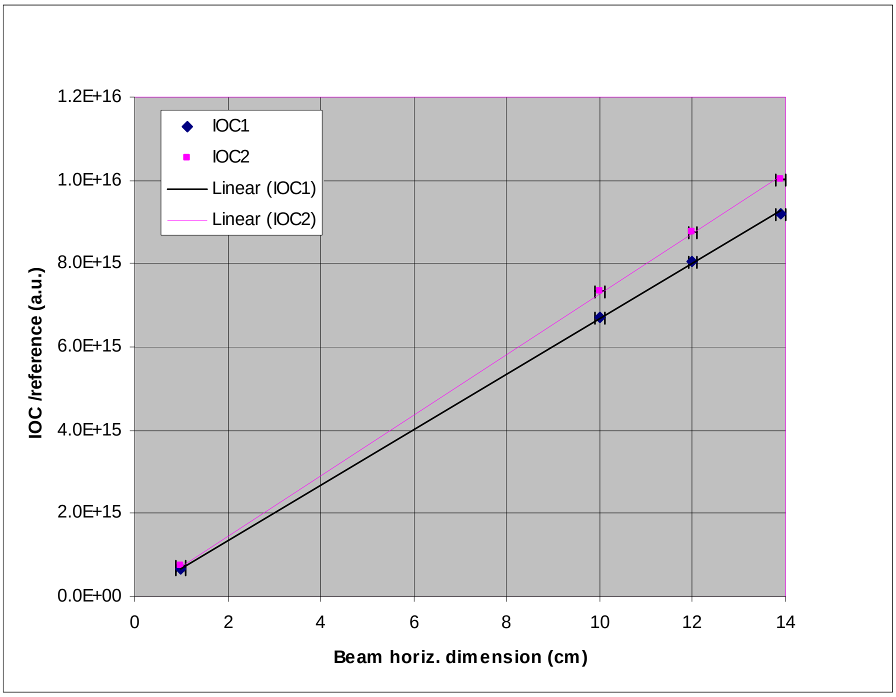


Figure 13. *IOC1 and IOC2 monitor chambers readings as a function of the SYRMA beam horizontal dimension.*

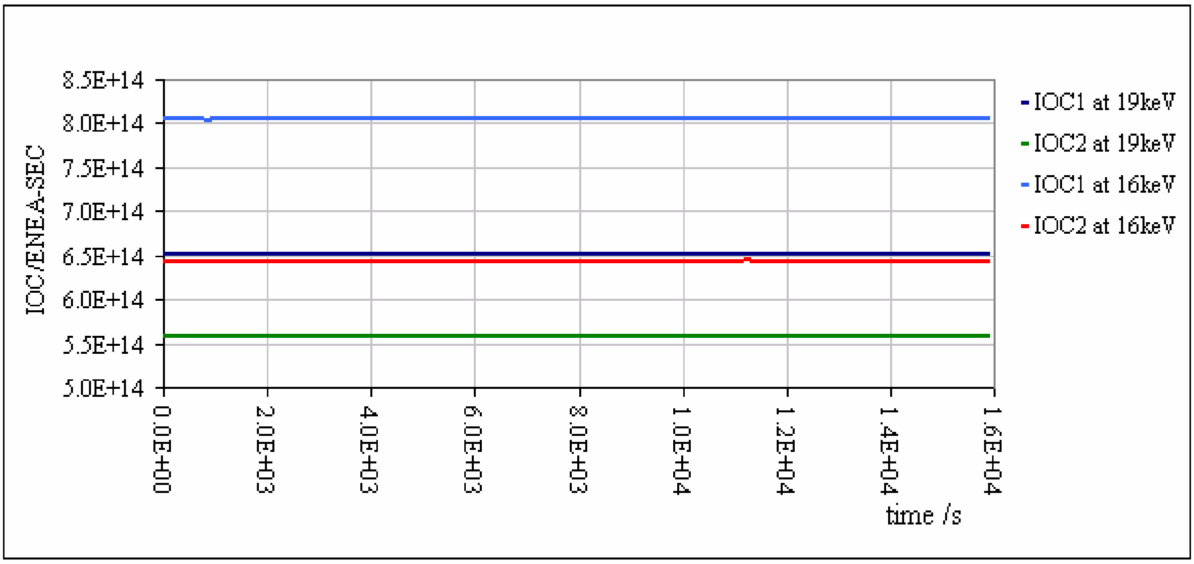


Figure 14. *Values - as function of the time - of the ratio between the ionization currents measured by the monitor chamber IOC1 (or IOC2) and by the free-air chamber ENEA-SSC. The measurements were carried out over a long acquisition time to verify the stability of the beam monitoring system*

3.2 Absolute air-kerma measurements

Figure 15 shows the values of the corrections k_{sc}, k_{fl} and k_e determined by the Monte Carlo code PENELOPE for the standard chamber ENEA-FAC - with the 1.5 mm in radius chamber aperture - in monochromatic photon beams at the energies in the range from 8 keV to 30 keV. The relative combined standard uncertainty estimated for the values of the $k_{fl}k_{sc}k_e$ product is within 0.1%.

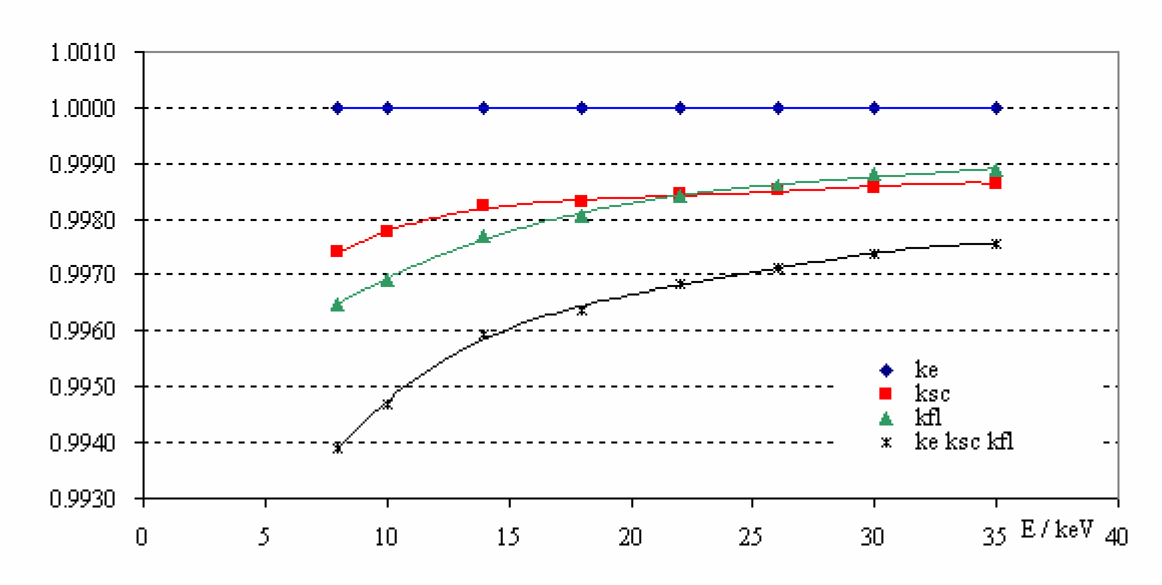


Figure 15. *Values of the corrections for the effects due to scattered photons, k_{sc}, re-absorption of fluorescence photons, k_{fl}, and electron loss in the chamber electrodes, k_e, determined by the Monte Carlo code PENELOPE for the 1.5 in radius free-air chamber aperture as functions of the photons energy. The product $k_{sc}\cdot k_{fl}\cdot k_e$ is also shown in the graph.*

No significative difference was found in the $k_{fl}k_{sc}k_e$ values obtained for the smaller 1.5 mm diaphragm and the usual 4.0 mm diaphragm.

The mass air attenuation coefficients, μ/ρ, measured at the SYRMA monochromatic x-rays, are reported in figure 16 as determined with an estimated combined standard uncertainty of 0.5 %. In the same figure, the μ/ρ values calculated by Hubbell and Seltzer (1995) for monochromatic photons in the same range of energy are reported for comparison. The experimental μ/ρ values measured in the present work resulted lower (up to about 0.9 %) than those given by Hubbell. Even if the deviation between the actual measured values and calculated values is not always negligible, it is worth mentioning that such deviations influence the corresponding correction factors by no more than 0.1 %.

In figure 16 the experimental values - determined at INMRI-ENEA with the same apparatus - for the series of filtered x radiation recommended by the ISO 4037 standard, are also shown. The experimental μ/ρ values obtained for filtered x radiation having a mean energy of the spectra E resulted lower (in the range from 0.7 % to 1 %) than those obtained for monochromatic photons having the same energy E.

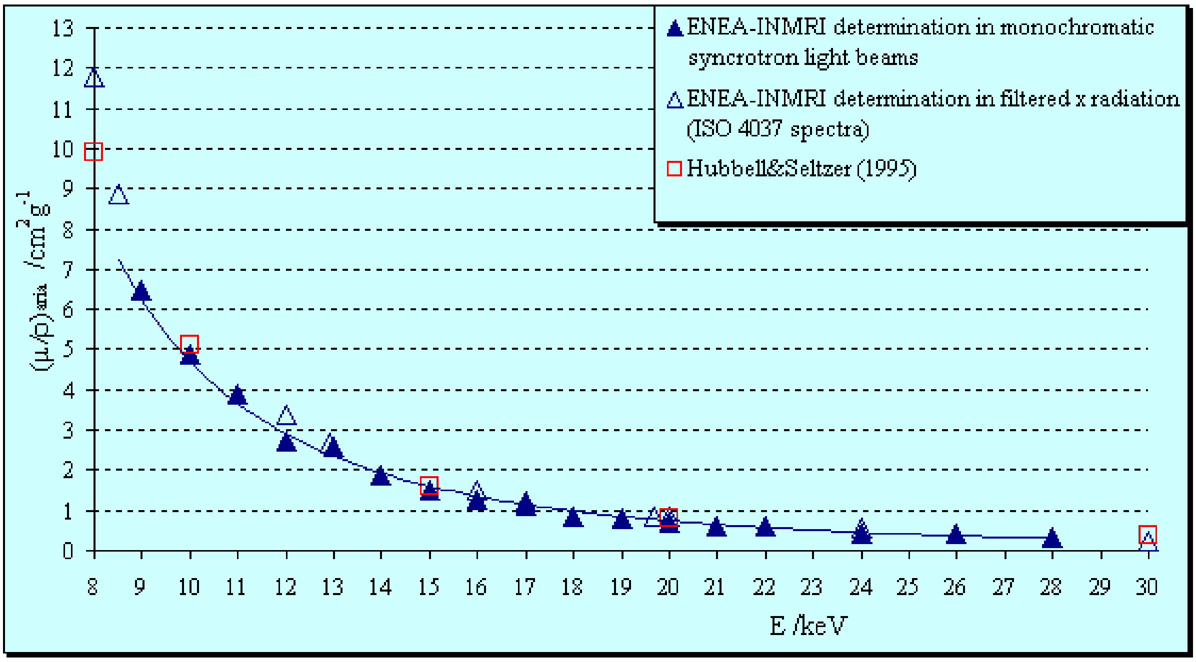


Figure 16. *Mass air attenuation coefficients,* μ/ρ, *measured in synchrotron monochromatic beams (triangles) and ISO 4037 filtered x-radiation (circles), in the energy range from 8 keV to 30 keV. Standard uncertainties were estimated to be within 0.5 %. The values given by Hubbell 95 (squares) and by ICRU 44 (diamonds) are also reported for comparison.*

The correction factor for ion recombination in the standard free-air chamber ENEA-FAC and in the monitor chambers IOC1 and IOC2, for the intensities of the synchrotron radiation beams is given by:

$$k_{sat}(\text{ENEA-FAC, 1600 V}) = 1.0015 + 4.228 \cdot 10^{6} \cdot I(A) \qquad (2)$$

$$k_{sat}(\text{IOC, 400 V}) = 1.0025 + 2.26 \cdot 10^{-8} \cdot I(A)$$

Typical values of k_{sat} factors were < 1.0022 for the chamber ENEA-FAC and <1.0029 for the monitor chambers IOC1 and IOC2. The combined standard uncertainty associated to the k_{sat} values is within 0.05 %.

The values of the air kerma rate measured at the patient position by the ENEA-FAC were in the range from 1 mGy s^{-1} to 7 mGy s^{-1} according to the photon energy. The combined standard uncertainty associated to the determination of the air kerma rate is within 0.55 %.

3.3 Variation of the monitor chambers response with the photons energy

The values of the calibration coefficients for the SYRMA monitor chambers IOC 1 and IOC2 are reported in figure 17, with an associated combined standard uncertainty of 0.75%. The energy response of the monitor chambers is rather pronounced as expected because of the presence of aluminized Mylar foils used for the chamber entrance and exit windows. In principle such a strong dependence would not be acceptable for a monitor chamber, but it should be taken into account that in the case of the synchrotron radiation the energy resolution $\Delta E/E = 2*10^{-3}$ assure a maximum possible variation of the monitor chambers calibration coefficient of 0.6% in the energy range useful for patient exposure (from 17 keV to 22 keV).

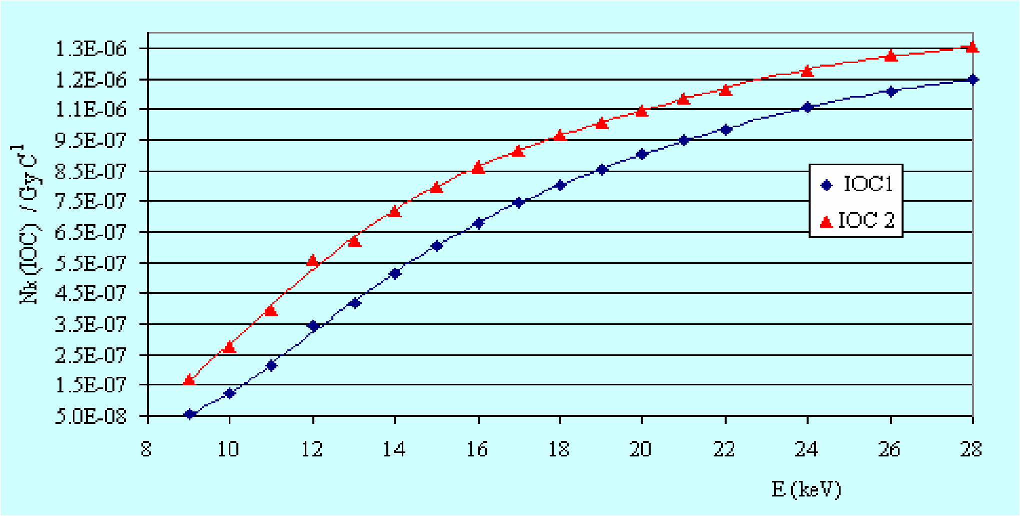


Figure 17. *Calibration coefficients of the SYRMA monitor chambers IOC 1(blue square) and IOC2 (red triangle), normalized at reference ambient conditions (temperature of 293.15 K, pressure of 1013.25 Pa and 50% of relative humidity) of the air density in the path,* d_{air}*, travelled by photons from the monitor to the reference measurement point for patient exposure. The value of* d_{air} *is about 320 cm for the monitor IOC1 and about 220 cm for the monitor IOC2.*

3.4 Calibration of the ENEA-SSC secondary standard

The correction factor for ion recombination in the calibrated (ENEA-SSC) free-air chamber, for the intensities of the synchrotron light beams resulted given by the following expression:

$$k_{sat}(\text{ENEA-SSC, 2000 V}) = 1.0006 + 1.290 \cdot 10^{7} \cdot I(A) \qquad (3)$$

Typical values of k_{sat} factors were < 1.0009 and the combined standard uncertainty associated to the k_{sat} values were within 0.05 %.The values of the calibration coefficients for the calibrated (ENEA-SSC) free-air chamber are reported in figure 18, as determined by monitor IOC1 (blue square) or IOC2 (red triangle). The associated combined standard uncertainty is within 0.80% and the difference between the two determinations is within 0.15%. The energy response of the chamber ENEA-SSC shows a slight energy dependence because of this chamber is neither optimized nor corrected for the effects due to scattered photons, k_{sc}, re-absorption of fluorescence photons, k_{fl}, and electron loss in the chamber electrodes, k_e. However, in the case of the synchrotron radiation the energy resolution $\Delta E/E = 2*10^{-3}$ assure a maximum possible variation of the ENEA-SSC chamber calibration coefficient of 0.03% in the energy range useful for patient exposure (from 17 keV to 22 keV).

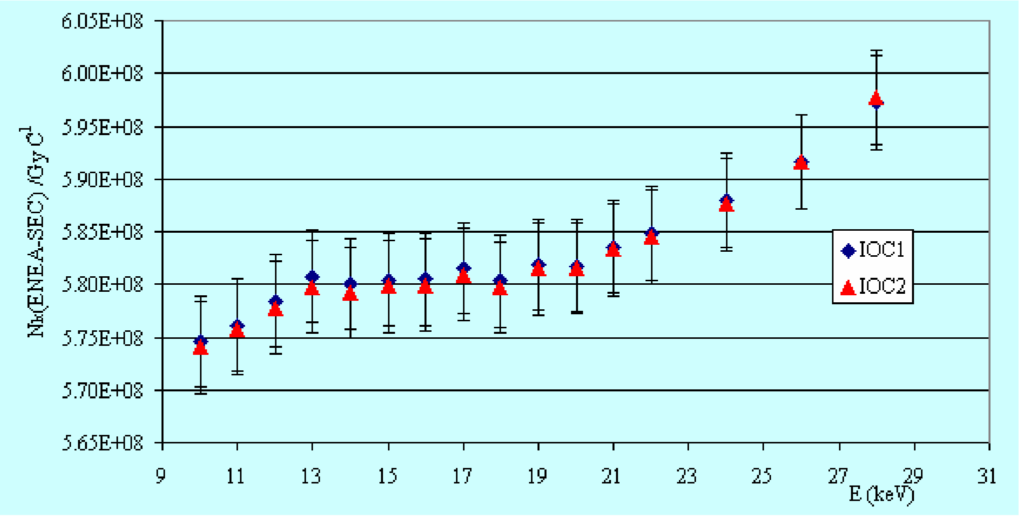


Figure 18. *Calibration coefficients of the ENEA-SSC chamber and the monitor IOC1 (blue square) or IOC2 (red triangle). Values are normalized at reference ambient conditions (temperature of 293.15 K, pressure of 1013.25 Pa and 50% of relative humidity) of the air density in the path,* d_{air}*, travelled by photons from the monitor to the reference measurement point for patient exposure. The value of* d_{air} *is about 320 cm for the monitor IOC1 and about 220 cm for the monitor IOC2. The bar in the graph represents the associated combined standard uncertainty equal to 0.8%.*

4. CONCLUSION

Absolute air-kerma measurements by the ENEA standard free-air chamber for low energy x-rays (ENEA-FAC) were performed in the synchrotron monochromatic x-ray beam used for phase contrast mammography in the framework of the SYRMA project at the ELETTRA Synchrotron in Trieste. These measurements were necessary to perform directly in the synchrotron radiation beam the calibration of the two beam monitors used for evaluating the air kerma during the clinical examinations. This particular calibration performed by a primary air-kerma standard in the x-ray beam is not likely to be routinely repeated in the future. To assure the periodical calibration of the synchrotron beam monitors the synchrotron users are equipped by special free-air chamber (ENEA-SSC) made at INMRI-ENEA and acting as a secondary standard. The ENEA-SSC chamber was calibrated during the present measurements directly against the ENEA-FAC chamber and will be in the future periodically calibrated at the INMRI-ENEA in the low-energy filtered x-ray beams. As long as the ratio of the calibration coefficients obtained in the synchrotron light beam and in the INMRI-ENEA low-energy filtered x-ray beams, respectively, will be constant (within the accepted uncertainty) the traceability of measurements to the national air-kerma standard can be, in this way, assured.

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