REPORT TO THE CCRI SECTION I ON THE ACTIVITY CARRIED OUT AT ENEA-INMRI ON PHOTON AND CHARGED PARTICLE DOSIMETRY IN THE PERIOD 2005 – 2007

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1. INTRODUCTION

The present report is a summary of the 2005-2007 activities carried out (or ongoing) at the ENEA-INMRI in the field of interest of CCRI Section I, i.e. photon and charged particle dosimetry. The main characteristics of the national standards maintained in Italy at the ENEA-INMRI in the field of radiation dosimetry are reported in Table I.

Table I. National standards maintained at ENEA-INMRI in the field of photon and charged particle dosimetry

Quantity	Standard	Radiation Quality	Measurement Range
Exposure and Air-Kerma	-Free-air ion chamber	10-50 kV X-ray	$(1\ 10^{-6} - 7\ 10^{-3})$ Gy s^{-1}
	-Free-air ion chamber	60-300 kV X-ray	$(7\ 10^{-7} - 3\ 10^{-4})$ Gy s^{-1}
	-Cavity ion chamber	^{60}Co gamma-ray	$(2\ 10^{-4} - 7\ 10^{-3})$ Gy s^{-1}
	- Calibrated ion chamber	^{137}Cs gamma-ray	$(2\ 10^{-6} - 3\ 10^{-4})$ Gy s^{-1}
Absorbed Dose to graphite, water and tissue equivalent materials	-Graphite calorimeter -Water calorimeter (under test)	^{60}Co gamma-ray	$(2\ 10^{-3} - 2\ 10^{-2})$ Gy s^{-1}
	-Extrapolation ion chamber	^{147}Pm, ^{85}Kr and ^{90}Sr/^{90}Y beta sources	$(3\ 10^{-7} - 5\ 10^{-4})$ Gy s^{-1}

2. STANDARDS DEVELOPMENT AND COMPARISONS

2.1. Air- kerma standards

The air-kerma standards at ENEA-INMRI are:
- two free-air chambers for low and medium energy x rays, respectively;
- six cavity ionization chambers (different size, graphite wall) for Co-60 gamma rays;
- a 30 cm^3 ionization chamber (plastic wall) for Cs-137 gamma rays.

In particular, the air-kerma standard for the Cs-137 gamma rays is derived from the medium-energy x-ray and Co-60 air-kerma standards.

2.1.a Low and medium-energy x-ray standards

Extensive restructure works in the low and medium-energy x-ray irradiation rooms, as requested by the control authority for radiological protection, lasted about all the year. In this period, the research and calibration activity in this field was strongly reduced.

Table II. Relevant characteristics of the in synchrotron light beams to be used for high definition mammography in the framework of the SYRMA project at the Synchrotron ELETTRA in Trieste, Italy.

Characteristic	Value
Source size	100 µm x 1100 µm
Source-to-sample distance	about 30 m
Energy range	8 ÷ 35 keV
Bandwidth ΔE/E	10^{-3}
Typical fluxes at 15 keV	2 x 10^8 phot./mm^2 s (@ 2 GeV, 300 mA) 7 x 10^8 phot./mm^2 s (@ 2.4 GeV, 180 mA)
Transverse coherence length at 15 keV (Lc = l L / 2*s)	10 µm
Beam size	120 x 4 mm^2

Absolute air-kerma measurements by the standard free-air chamber for low energy x-rays have been performed in synchrotron light beams to be used for high definition mammography in the framework of the SYRMA project (**SY**nchrotron **R**adiation for **MA**mmography) at the Synchrotron ELETTRA in Trieste, Italy. The energy of the monochromatic x-rays characterized was in the range from 8 keV to 30 keV and the relevant beam characteristics are in table II. Figure 1 shows a schematic diagram of the ELETTRA experimental set-up to obtain the monochromatic SYRMA light beam.
The reference point for measurements corresponded to the centre of the breast when the patient is on the support shown in figures 2 and the ENEA-INMRI standard chamber was positioned in this point as shown in the same figure. Because of the laminar shape of the synchrotron light beams, a specific 1.5 mm in radius diaphragm was made to be used with the standard chamber instead of the usual 4 mm in radius diaphragm.

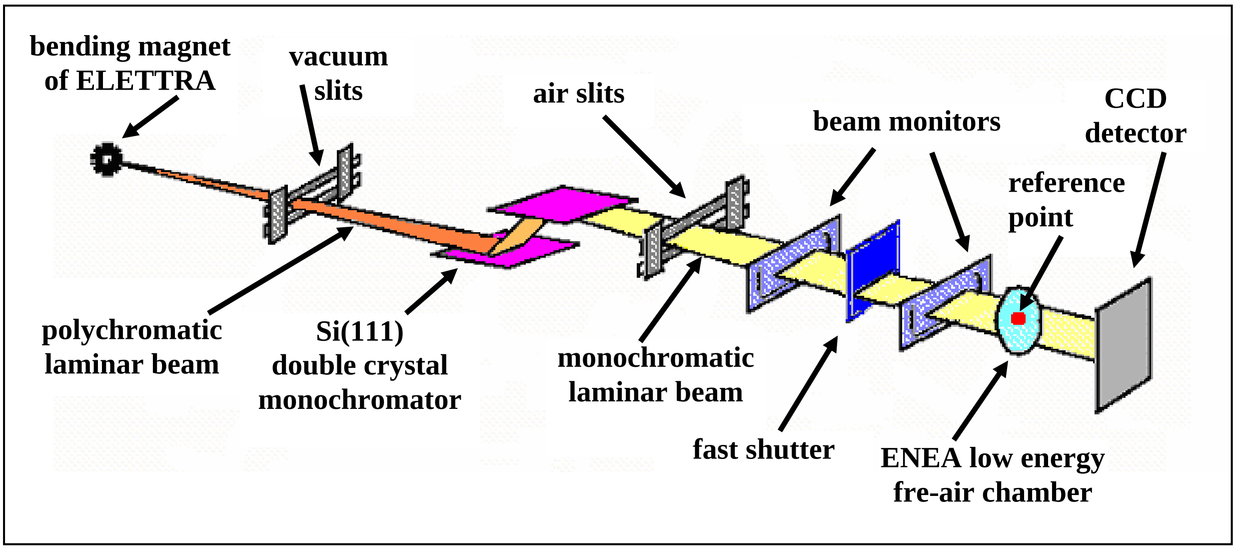

Figure 1. *Schematic diagram of the ELETTRA synchrotron light beam with laminar shape. The two beam monitors were calibrated directly against the ENEA-INMRI low-energy-free-air chamber. The monitors are transmission type ionization chambers specifically designed for measurement in photon beams with laminar shape.*

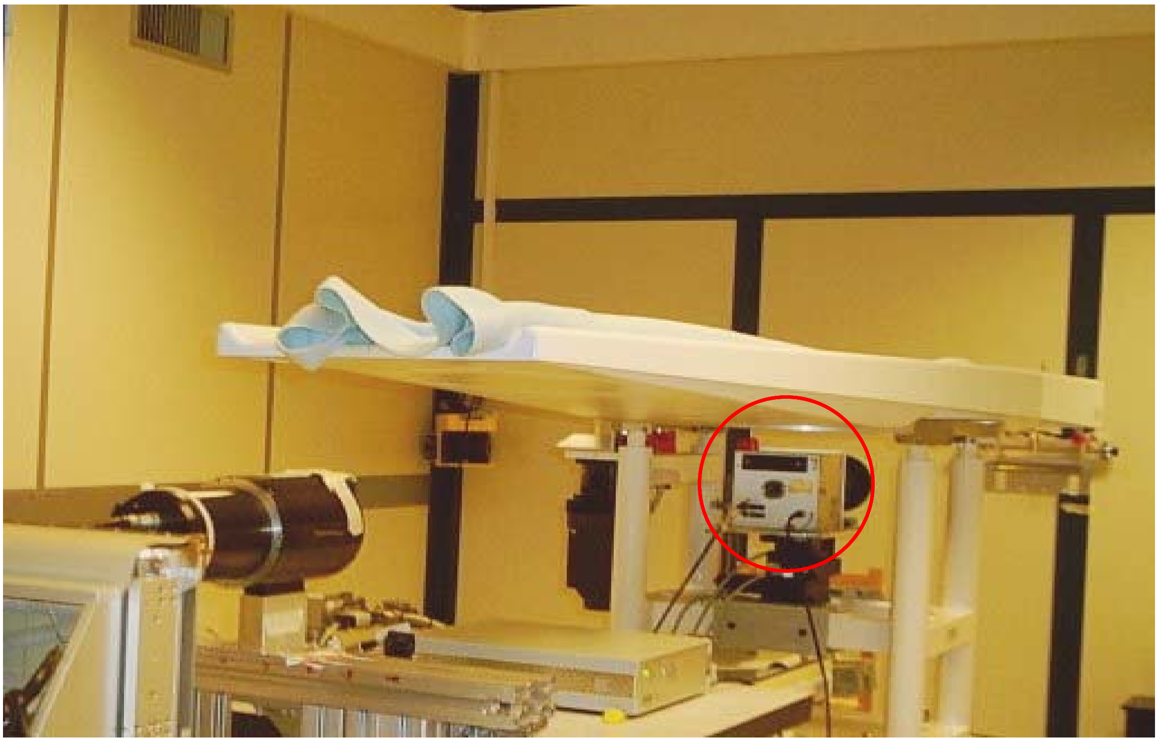

Figure 2. *The ENEA-INMRI standard free-air chamber for low energy x-rays at the reference measurement point (inside the red circle) under the patient support shown in figures 1, at the Synchrotron ELETTRA in Trieste, Italy.*

A re-determination of relevant correction factors has been made in this new chamber geometry. In particular, 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, were determined by the Monte Carlo code PENELOPE at the energies in the range from 8 keV to 30 keV. The calculation procedure is the same described in the report CCRI(I)/05-31 and the relative combined standard uncertainty estimated for the values of the $k_{fl}k_{sc}k_e$ product is within 0.1%. No significative difference was found in the $k_{fl}k_{sc}k_e$ values obtained for the smaller 1.5 mm in radius diaphragm or the usual 4.0 mm in radius diaphragm. In fact, the difference resulted in the range –0.012% to +0.005%, within the associated uncertainties.
Due to the low energy of the SYRMA photons beams and the distance travelled in air from the monitors and the standard chamber (about 3 m), the effect of photon attenuation in air was accurately investigated. The mass air attenuation coefficients, μ/ρ of these monochromatic x-rays were measured with the experimental apparatus associated to the ENEA-INMRI standard and based on a vacuum tube of 201 mm in length. Results are shown in figure 3 together with the values given by Hubbell and Seltzer (1995) for monoenergetic photons in the same range of energy. The percentage deviation of the values measured respect to the values given by Hubbell or by ICRU is in the range 0 to 3 %, corresponding to a percentage deviation of about 0.2 % in the correction factors applied. In figure 3 the experimental values determined at ENEA-INMRI for the series of filtered x radiation recommended by the ISO 4037 standard, are shown.
To be able to perform periodical calibration of the beam monitors a special ionization chamber was made at ENEA-INMRI. This chamber even if being a free-air chamber was not designed for absolute measurements. It was then calibrated against the standard free-air chamber directly in the monochromatic synchrotron light beams in the energy range from 8 keV to 30 keV.

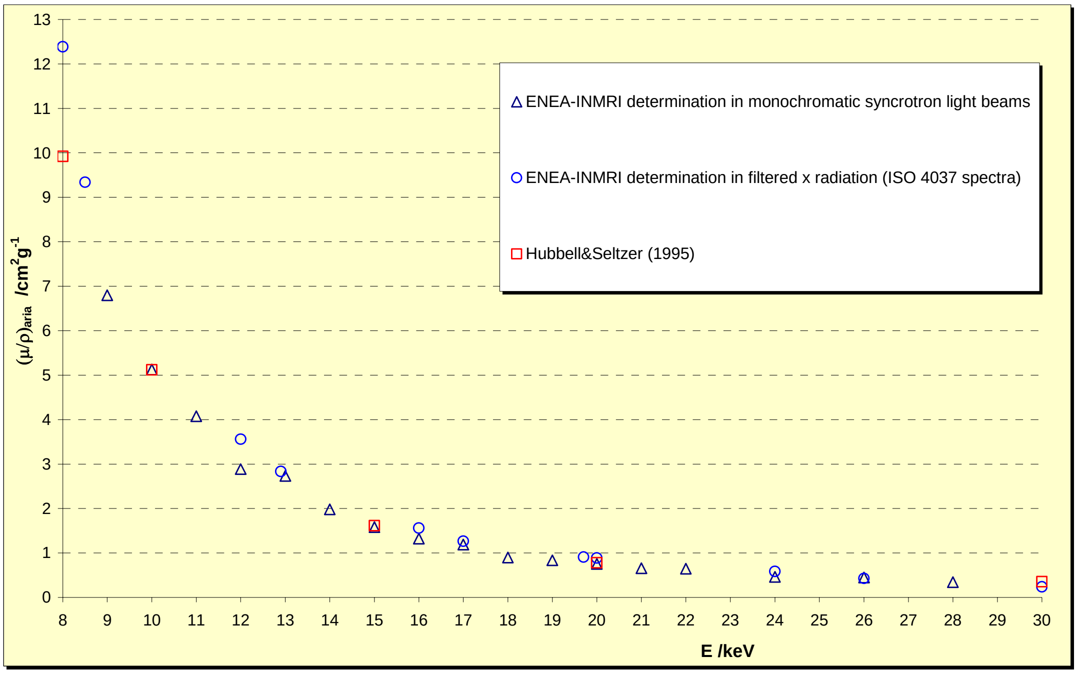

Figure 3. *Mass air attenuation coefficients, μ/ρ, measured in synchrotron monochromatic beams (triangles) and ISO 4037 filtered x-radiation (circles), in the energy range from 8 keV to 30 keV. Standard uncertainties were estimated to be within 0.5 %. The values given by Hubbell 95 (squares) and by ICRU 44 (diamonds) are also reported for comparison.*

2.1.b Air-kerma standard for Co-60 gamma-ray beam:

The characterization of new reference gamma radiations is going on for calibration of radiation protection dosemeters. These radiations are obtained from a collimated Co-60 gamma beam produced. by an high intensity therapy level source and a set of lead absorbers of different thickness placed close to the diaphragm, according to ISO [ISO 4037-I]. This experimental arrangement allows varying the intensity of the Co-60 beam using the same source and keeping constant the source-detector distance. This represents an undoubted advantage. Moreover, radiation protection measurements are often carried out with shielded radiation which spectral distribution is more similar to that of the attenuated beams than of the un-attenuated beam. The effect of lead attenuation on the beam characteristics were studied by Monte Carlo calculation using BEAMnrc, a general purpose Monte Carlo code for simulating radiotherapy beams from linear accelerators or Co-60 units. The spectral purity of the radiation resulted maintained, the mean energy approaches more and more that of the Co-60 radionuclide emission lines as shown in table III and figure 4.

Table III - K_{wall} correction factors for the ENEA-INMRI standard cavity chamber F determined by Monte Carlo calculation using photon spectra referring to Co-60 beams attenuated by lead absorbers of different thickness. The values calculated for the unattenuated beam and the mono-energetic photons (with energy 1.25 MeV) are reported for comparison. The statistical uncertainty is less than 0.01%.

Lead absorber thickness (cm)	*Photon mean energy* E (MeV)	*Correction factor* K_{wall}
0	1.107	1.02119
1	1.209	1.02035
5	1.246	1.02028
7	1.258	1.01969
--	1.250	1.02046

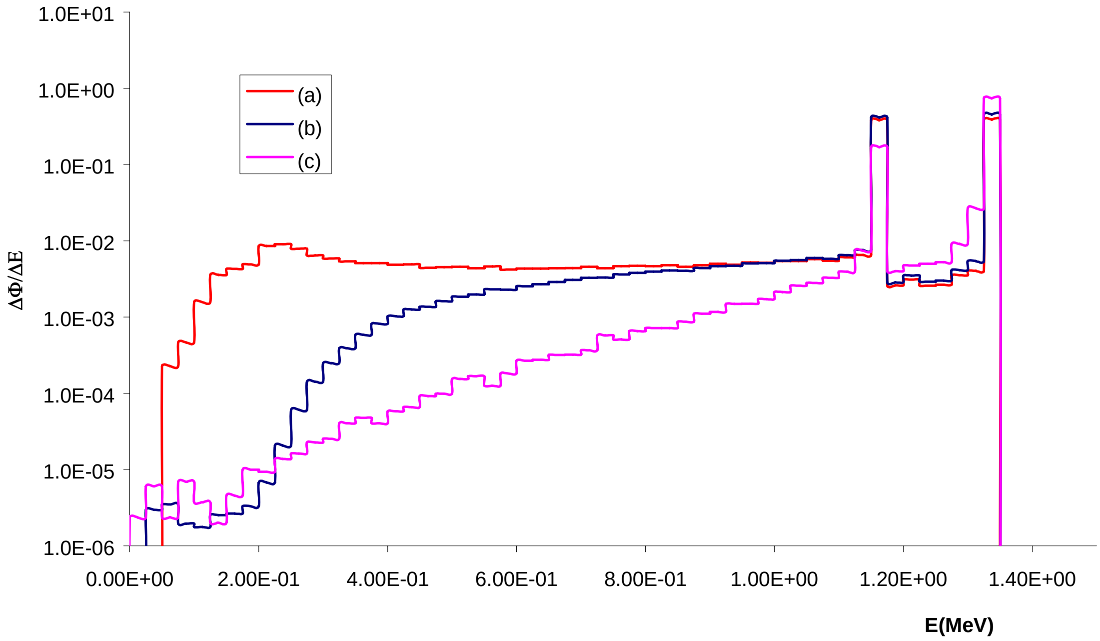

Figure 4. *Normalized spectral photon fluence distributions for the ENEA-INMRI Co-60 reference beam without absorber (a) and with lead absorbers of thickness 1 cm (b) and 22 cm (c). The distributions are calculated at SSD 200 cm for a field size of 20 cm x 20 cm.*

At present, a series of attenuated Co-60 beam reference qualities were already realized by using lead absorbers with thickness until 15.5 cm and the effects due to the radiation scattered by source and the filters were accurately investigated. The experimental set-up was optimized to minimize these effects. Air kerma measurements were carried out with the ENEA-INMRI primary standard cavity chamber and by calibrated standard chambers of different volume (from 30 cm^3 to 1000 cm^3), depending on the beam intensity. To this end, the relevant correction factors of the primary standard were re-determined for the actual energy spectral distributions.
In particular, the k_{wall} factor for the ENEA-INMRI standard cavity chamber F was calculated for spectral distributions referring to the attenuated beams, using the EGSnrc Monte Carlo code CAVRZnrc. The k_{wall} results are shown in the table III.

2.2 Absorbed dose standards

2.2.a <u>The absorbed-dose-to-water standard based on graphite calorimetry</u>

The ENEA-INMRI standard of absorbed dose to water for Co-60 gamma rays is based on a graphite calorimeter and an ionometric transfer system. A thick-walled graphite ionization chamber is used to transfer the absorbed dose from graphite to water (Fig. 5). The most important improvements on this standard regard the determination of the calorimeter gap correction, the assessment of the photon energy fluence perturbation due to the thick-walled graphite chamber in water and the calculation of the ratio of the mean mass energy-absorption coefficients of water and graphite, $\left(\bar{\mu}_{en}/\rho\right)_g^w$. The correction factors for the calorimeter vacuum gaps and for the energy fluence perturbation so far adopted were experimentally determined in the past with a relative uncertainty of about 0.14% and

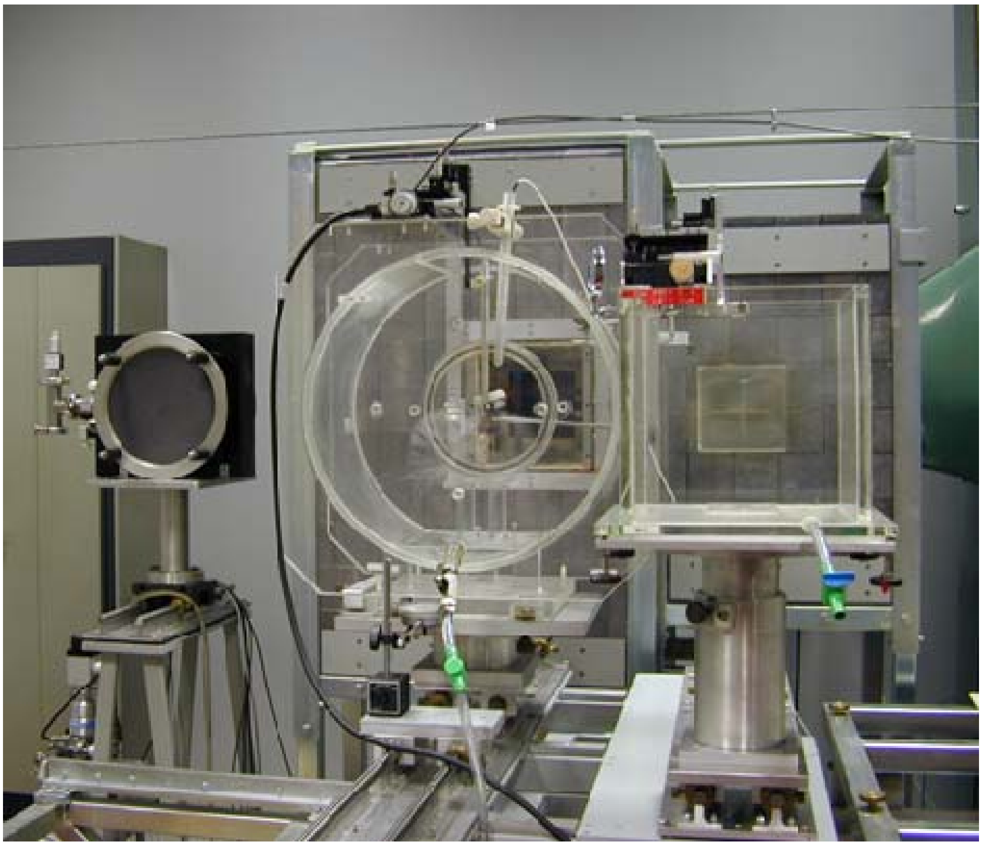

Figure 5. *The graphite calorimeter and the scaled cylindrical water phantom used for realizing the ENEA-INMRI absorbed dose to water standard.*

0.11%, respectively. By Monte Carlo calculation based on EGSnrc code a slightly improved accuracy was obtained on both the correction factors. The ratio $\left(\bar{\mu}_{en}/\rho\right)_g^w$ was re-calculated to take into account the photon spectrum describing the Co-60 gamma beam presently operating at ENEA. The Co-60 photon spectrum previously obtained by a Monte Carlo simulation of the ENEA beam has been used to describe the incident photon beam in all the simulations relevant to the absorbed dose to water standard. The gap correction factor was obtained by a Monte Carlo calculation of the absorbed dose in the calorimeter core (Fig. 6) and in an identical region (shape, dimension and graphite depth as for the calorimeter core) of a homogeneous graphite phantom. The calculation was performed with the EGSnrc code DOSRZnrc. The gap correction resulted equal to 1.0064 with a relative statistical uncertainty 0.05 %, at the measurement depth in graphite of 5.54 g cm^{-2} and with a field size of 6.25 cm x 6.25 cm.
The photon energy fluence correction, $(\Psi)_g^w$, was determined scoring the photon energy fluence both in water at the reference depth 5 g cm^{-2} and in a small mass of graphite placed in a water phantom with its center at the depth of 5 g cm^{-2}. The small mass of graphite had the same shape and dimensions as the thick-walled ionization chamber. The calculation was carried out using the EGSnrc code FLURZnrc that was modified to the end of simulating a cylindrical region (the small mass of graphite) in a cubic phantom. The correction resulted equal to 1.0068 0064 with a relative statistical uncertainty of 0.05 %.The correction factors determined by the Monte Carlo simulation are slightly different, within 0.1%, from those so far adopted. The EGSnrc/FLURZnrc code was also used to calculate the photon energy fluence spectra at the corresponding points in graphite and in water phantom with aim

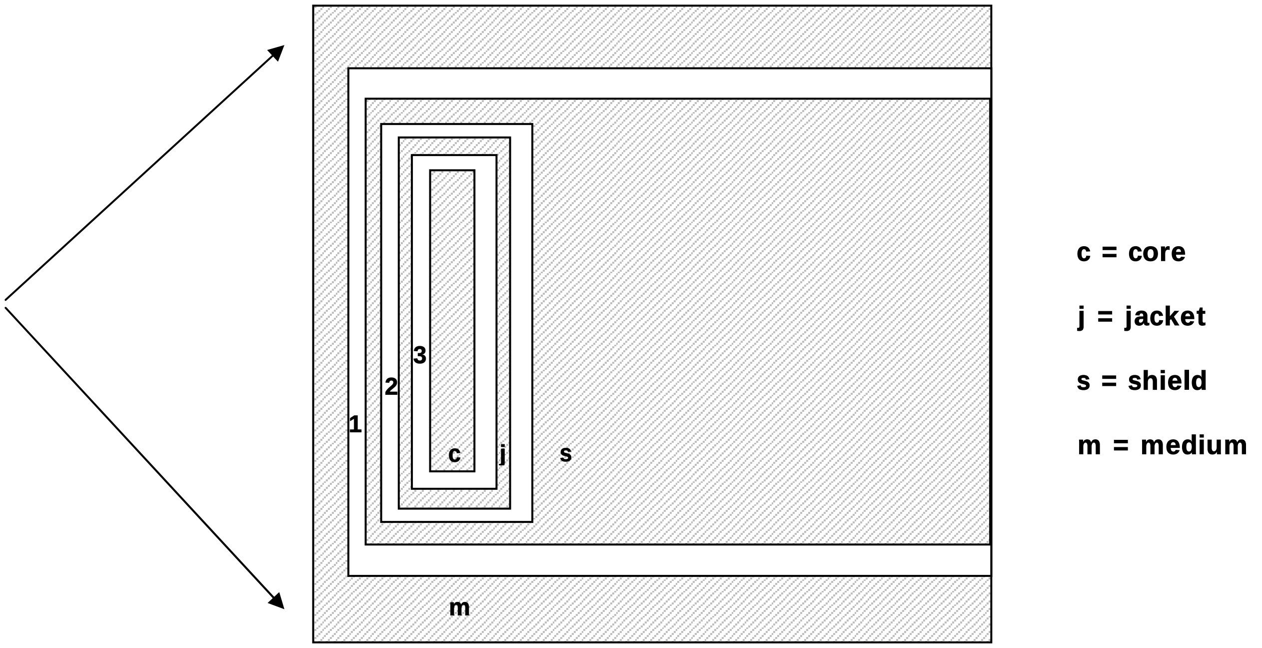

Figure 6. *Schematic configuration of the vacuum gaps in the ENEA-INMRI graphite calorimeter (not to scale). The gaps around the calorimeter core, a graphite disc of 20 mm diameter and 2.75 mm thickness, are denoted by 1, 2, 3. The gap width is 0.5 mm for all of the frontal gaps and for the annular gaps 2 and 3, 1 mm for the annular gap 1. The gap width is 1.2 mm and 0.65 mm for the posterior gaps 2 and 3, respectively.*

to check the similarity of the two spectra (Fig 7) and to calculate the $\left(\bar{\mu}_{en}/\rho\right)_g^w$ ratio. In the simulation the actual experimental conditions of measurement in graphite and in water (material, shape and dimensions of the phantoms, SSD and SDD distances, field sizes) were accounted for.

The new Monte Carlo values for the gap correction, the $(\Psi)_g^w$ factor and the ratio $\left(\bar{\mu}_{en}/\rho\right)_g^w$ have been adopted for the BIPM comparison scheduled in April 2007.

2.2.b Water calorimetry

The "sealed water" type calorimeter built many years ago at ENEA-INMRI for measurement in horizontal photon and charged particle beams, did not have significative improvements in 2006. The progress in this respect now depends primarily on the possibility of replacing some personnel retired.

2.3. International comparisons

The international comparisons involving the ENEA-INMRI standards of air-kerma and absorbed dose are those listed below. The current status of the intercomparisons is described in parentheses.

1 - EUROMET 605, “”Beam quality specification of high energy photon beams”

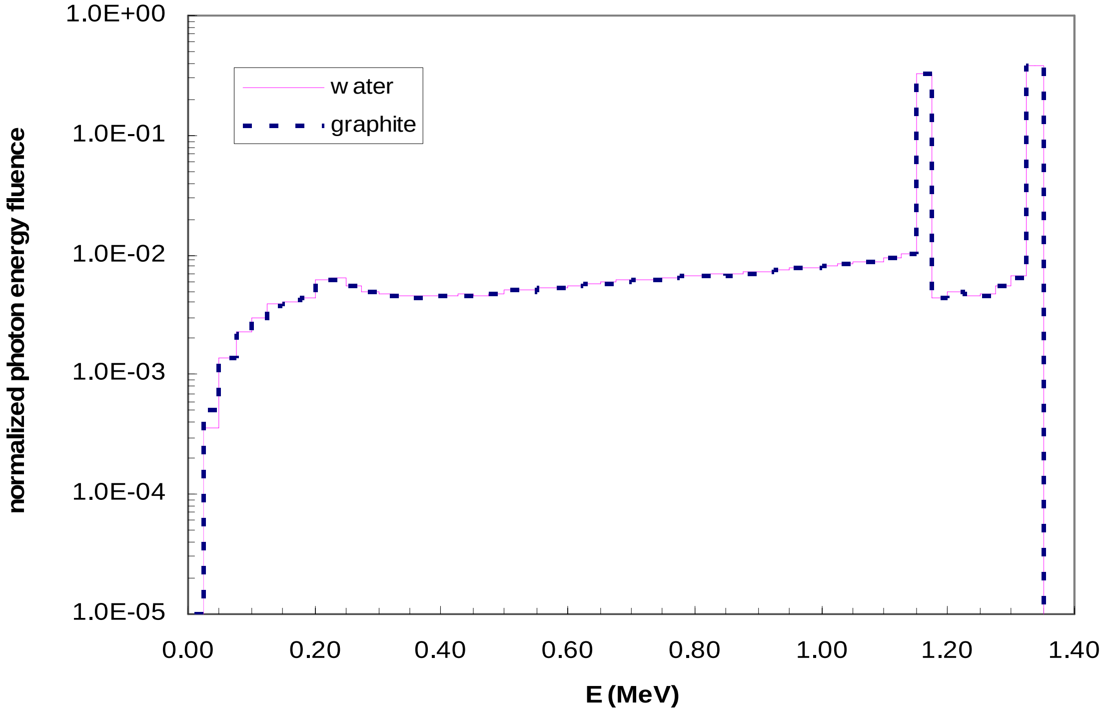

Figure 7. *Updated photon energy fluences differential in energy for the ENEA-INMRI Co-60 reference beam at the reference depth in water (5.0 g cm^{-2}, SDD=100 cm, field size 10 cm x 10 cm) and in graphite (5.54 g cm^{-2}, SDD=62.5 cm, field size 6.25 cm x 6.25 cm). The similarity of the two distributions is a measure of the validity of the corresponding depths in water and graphite.*

2- EUROMET P 739, KCDB Id: Supplementary comparison EUROMET.RI(I)-S2 "Intercomparison of the personal dose equivalent for beta radiation"

3- EUROMET P 628 "Direct comparison of primary standards of air kerma for medium energy (300 kV) X-rays“
(measurements to be carried out at ENEA-INMRI likely in a period of 2008 not yet specified)

4- EUROMET 813 “Measurement of air-kerma and absorbed dose to water due to Co-60 gamma radiation”
(measurements to be carried out at ENEA-INMRI in May 2007).

5- BIPM-ENEA bilateral comparison on absorbed-dose-to-water standards.

3. CALIBRATION ACTIVITY

Calibrations of most protection-level dosimeters are traceable to the air kerma standards for low/medium x rays and Co-60 gamma rays. The photon radiation qualities used for calibrations are shown in Table A.1. Calibrations of therapy-level, and industrial-level dosimeters are traceable to the absorbed-dose-to-water (D_w) standard presently operating only at the Co-60 gamma ray quality. Calibrations in terms of D_w at low and medium energy x rays are also available but only with traceability to the air-kerma standards.

3.1 Therapy-level calibration service

3.1.a Therapy-level dosimeters

The therapy-level dosimeters used in the Italian radiotherapy centres are calibrated in terms of air-kerma and/or absorbed dose to water. In the last two-three recent years most calibrations of ionization chambers are made in terms of absorbed dose to water.

3.1.b Clinical beam

The service for direct calibration of the customer clinical beam by chemical dosimetry has been operational, as in the past. The dosimeters consist of ferrous sulphate solution in sealed glass ampoules (volume of about 1 cm^3) with 0.5 mm wall thickness. A set of reference dosimeters (with their holder) is mailed to the customer for irradiation in water phantom. The combined standard uncertainty in D_w measurements in photon and electron beams by these reference dosimeters is estimated to be 1.6% including a 0.5% component due to neglecting the energy-dependence correction.

3.2 Protection-level calibration service

The dosimeters used in Italy for radiation protection purposes are currently calibrated both at the ENEA-INMRI and at the SIT calibration centres. The SIT centres are accredited secondary standards laboratories. At present there are 7 SIT centres operating in Italy and three more centres are in course of accreditation. Dosimeter calibrations at the SIT centres are traceable to the ENEA-INMRI national standards and are recognized at the international level in the framework of the EA and ILAC agreements. Protection-level dosimeter calibrations are made in terms of air-kerma and dose-equivalent quantities. The calibration qualities are those reported in Table A.1.

3.3 Industrial-level calibration service

A calibration service for high-dose dosimetry is provided by the ENEA-INMRI to industries working on radiation processing of materials for sterilization purposes.
Typically, industries ask to irradiate red-perspex dosimeters at certified dose levels in the range between 5 and 50 kGy. The irradiations are made in standard (Co-60) gamma cells calibrated in terms of absorbed dose to water by a set of ferrous sulphate and potassium dichromate transfer dosimetry standards.

4. DOSIMETRY METHODS FOR RADIOTHERAPY BEAMS

As in the past years the research activity at ENEA-INMRI was not confined just on primary standards but extended also to related areas of practical interest as dosimetry in radiotherapy. The work carried out in the period 2005-2007 is summarized below.

4.1 Charge recombination in ionization chambers for dosimetry in high-dose-per-pulse beams

A study on charge recombination was carried out for different plane-parallel ionization chambers exposed to clinical electron beams with low and high dose per pulse, respectively.
The electron energy was nearly the same (about 7 and 9 MeV) for any of the beams used. To determine the correction for ion losses, k_s, the presence of free electrons in the air of the chamber cavity was accounted for. The determination of k_s was made on the basis of the models for ion recombination proposed in the past years by Boag, Hochhäuser and Balk to account for the presence of free electrons. The absorbed dose measurements in both low-dose-per-pulse (less than 0.3 mGy/pulse) and high-dose-per-pulse (20–120 mGy/pulse range) electron beams were compared with ferrous sulphate chemical dosimetry, a method independent of the dose per pulse. The results of the comparison (Fig. 8) support the conclusion that one of the above models is adequate to correct for ion recombination, even in high-dose-per-pulse conditions, if the free electron fraction is properly assessed [Laitano et al, 2006]. In this respect the drift velocity and the time constant for attachment of electrons in the air of chamber cavity are rather critical parameters because of their dependence on chamber dimensions and operational conditions. A determination of the factors k_s was also made by zero extrapolation of the $1/Q$ vs $1/V$ saturation curves, leading to the conclusion that in high-dose-per-pulse beams this method does not provide consistent results.

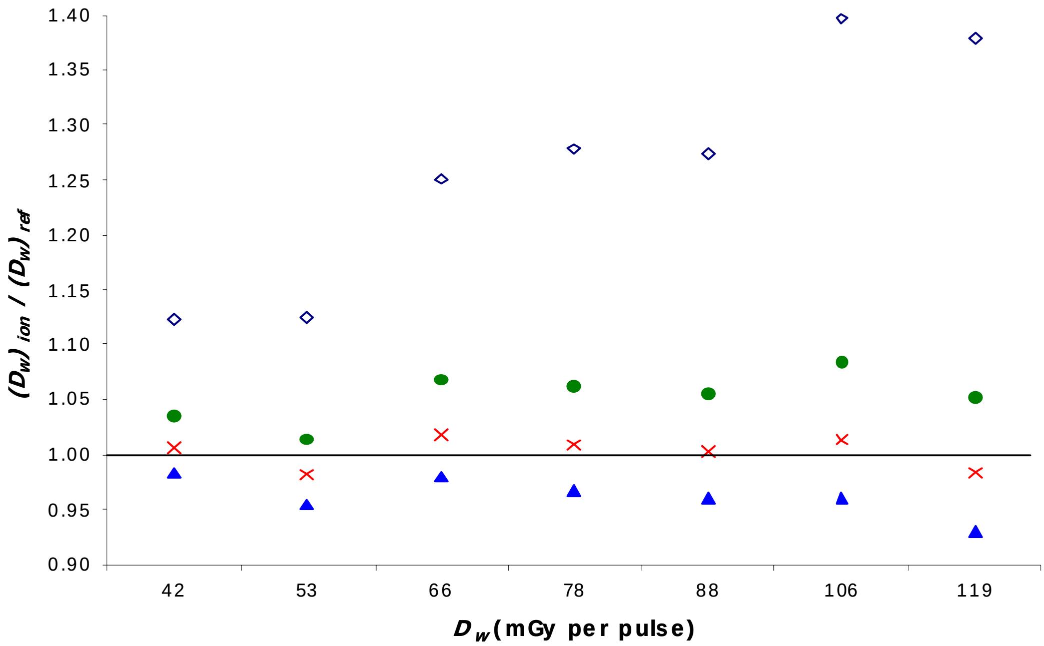

Figure 8. *The $(D_w)_{ion}$ /$(D_w)_{ref}$ ratios for a typical p-p chamber (Capintec type) as a function of dose per pulse in the range from about 40 to about 120 mGy dose per pulse. The symbols refer to the $(D_w)_{ion}$ values obtained using the correction factor k_s^i corresponding to the three different recombination models accounting for free electrons (circles, crosses and triangles) and to the conventional model not allowing for free electrons (diamonds). One of the recombination models (crosses) appears the most accurate at any dose per pulse in the above range. The chamber is operated at the voltage V_1 = 300 V. The relative uncertainty on the $(D_w)_{ion}$ /$(D_w)_{ref}$ values is 3.2% (1σ).*

4.2 Correction factors for reference ferrous sulphate dosimetry

The correction factor for the non water-equivalence of the reference ferrous sulphate dosimeter used for in situ calibration of clinical beams was determined by Monte Carlo simulation in electron and photon beams using realistic energy spectra. The calculation was performed modifying the EGSnrc/DOSRZnrc code to allow the simulation of a cylindrical dosimeter at various depths in a cubic phantom. The calculation was carried out for electron beams produced by accelerators of different type sampling the energy of the incident electrons from the spectral distributions describing the actual beams. The energy spectra were taken from literature or determined by simulating the actual beams with BEAMnrc code (this was made for the NOVAC7 IORT accelerator). For comparison the correction factors were also determined for monoenergetic electrons in the energy range from 3 MeV to 24 MeV. The relevant correction factors in the R_{50} range from 1.12 g cm^{-2} to 8.5 g cm^{-2} are now available (Figs. 9). The results show that the correction factors are weakly dependent on the energy distribution for electron beams with R_{50} values in the range from 2.5 g cm^{-2} to 8.5 g cm^{-2}. In this range the correction factors obtained using realistic spectral distributions differ by no more than 0.5% from those obtained using monoenergetic electrons with nearly the same R_{50} value. For R_{50} values less than 2.5 g cm^{-2} the correction factor tends to increase and a difference up to 1% was obtained for electron beams with nearly the same R_{50} value. The calculation was performed also for Co-60 gamma beam and

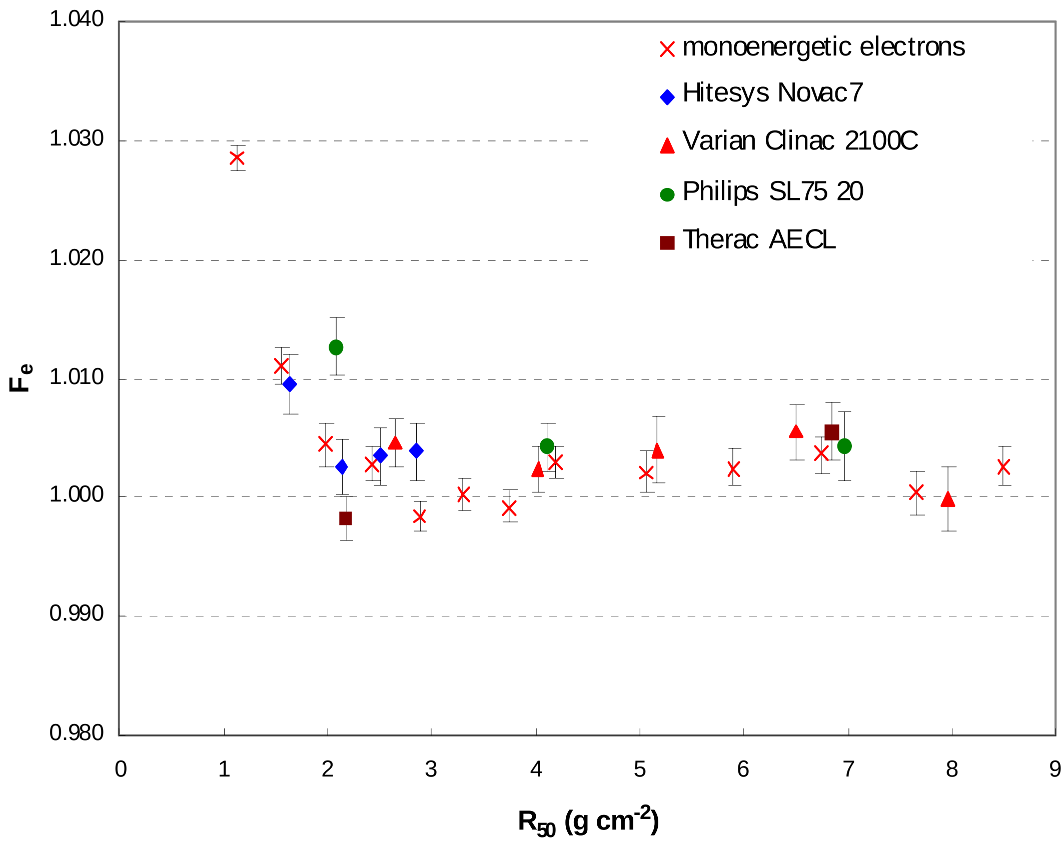

Figure 9. *Correction factors, F_e, taking into account the non-water equivalence of the ENEA-INMRI ferrous sulphate dosimeters in electron beams as a function of the R_{50} parameter. The factors were determined by Monte Carlo calculation for electron beams produced by accelerators of different type. The correction factors were calculated at the depth of maximum dose in water sampling the energy for the incident electrons from the realistic spectral distributions. For comparison the calculation was also carried out for monoenergetic electrons with energy in the range from 3 MeV to 24 MeV.*

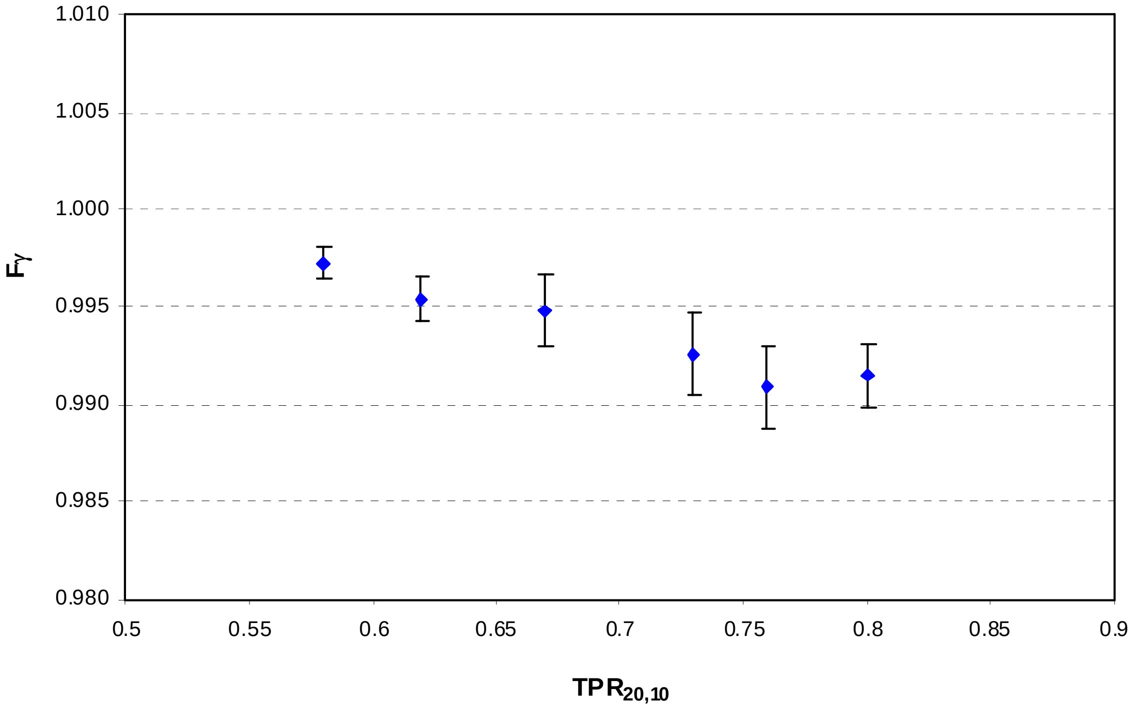

Figure 10. *Correction factors, F_γ, taking into account the non-water equivalence of the ENEA-INMRI ferrous sulphate dosimeters in photon beams. The factors were determined by Monte Carlo calculation based on the EGSnrc code and refer to the reference depth in water of 5 cm or 10 cm according to the IAEA TRS 398.*

for photon beams of 6 MV, 10 MV, 15 MV and 24 MV (Fig. 10). For Co-60 beam the energy spectrum relevant to the ENEA-INMRI beam was used. The energy spectra for accelerator beams were taken from literature. The correction factor value decreases from 0.9973 in Co-60 beam to 0.991 in photon beams with $TPR_{20,10}$ of about 0.8.

5. IMPLEMENTATION OF THE QUALITY SYSTEM

In the recent years part of the activity at the ENEA-INMRI has been aimed at implementing the Quality System according to the MRA and EUROMET requirements. In 2006 the Quality Manual was updated in some aspects by writing some technical procedures on the calibration service. A number of internal audits were made as well as the management review.

6. PARTICIPATION IN METROLOGY AND STANDARDS ORGANISATIONS

The ENEA-INMRI staff is currently devoted to activities in metrological and standardisation organisations, such as: EUROMET, ICRM, BIPM/CCRI, IEC/TC45, ISO/TC85/SC2.

ANNEX A.1

REFERENCE RADIATIONS FOR CALIBRATION IN TERMS OF AIR-KERMA AT THE ENEA-INMRI

Code(1)	H.V. (2) (kV)	Filtration (3) (mm)	E_m (4) (keV)	HVL (mm) (5) Al	Cu	Air kerma rate (6) (Gy s^{-1})	u% (7)
L1	60	4.0 Al + 0.28 Cu	44.5	*4.7*	0.18	5.4 10^{-5}	0.5
L2	80	4.0 Al + 0.46 Cu	56.3	*7.2*	0.35	1.0 10^{-4}	0.5
L3	110	4.0 Al + 2.04 Cu	78.5	*14.1*	0.96	6.4 10^{-5}	0.5
L4	150	4.0 Al + 1.0 Sn	104.0	-	1.85	1.5 10^{-4}	0.5
L5	200	4.0 Al + 2.0 Sn	136.4	-	3.07	2.7 10^{-4}	0.5
L6	250	4.0 Al + 4.0 Sn	171.7	-	4.18	3.4 10^{-4}	0.5
L7	300	4.0 Al + 6.5 Sn	199.0	-	5.10	4.2 10^{-4}	0.5
S1	10	0.30 Al	8.4	0.05	*.002*	6.8 10^{-7}	1.0
S2	15	0.91 Al	12.4	0.15	*.004*	2.2 10^{-6}	1.0
S3	20	1.90 Al	16.6	0.35	*.009*	3.5 10^{-6}	1.0
S4	25	2.0 AL	20.0	0.66	*.017*	3.5 10^{-6}	1.0
S5	30	5.50 Al	25.3	1.2	*.032*	5.3 10^{-6}	1.0
S6	40	4.0 Al + 0.21 Cu	3.,5	*2.7*	0.09	5.0 10^{-6}	0.8
S7	60	4.0 Al + 0.6 Cu	48.0	*5.5*	0.24	1.6 10^{-5}	0.8
S8	80	4.0 Al + 2.1 Cu	65.4	*10.9*	0.59	8.2 10^{-6}	0.8
S9	100	4.0 Al + 5.0 Cu	82.7	-	1.16	4.6 10^{-6}	0.8
S10	120	4.0 Al + 5.0 Cu + 1.0 Sn	99.0	-	1.73	5.0 10^{-6}	0.8
S11	150	4.0 Al + 2.5 Sn	116.6	-	2.46	3.5 10^{-5}	0.8
S12	200	4.0 Al + 2.0 Cu + 3.0 Sn + 1.0 Pb	161.2	-	3.90	1.4 10^{-5}	0.8
S13	250	4.0 Al + 2.0 Sn + 3.0 Pb	202.5	-	5.20	1.5 10^{-5}	0.8
S14	300	4 Al + 3.0 Sn + 5.0 Pb	249.6	-	6.20	1.5 10^{-5}	0.8
A1	10	-	7.4	0.03	*.001*	2.0 10^{-4}	0.5
A2	20	0.15 Al	12.4	0.11	*.003*	7.5 10^{-4}	0.5
A3	30	0.52 Al	18.9	0.35	*.009*	5.5 10^{-4}	0.5
A4	60	3.2 Al	36.4	*2.4*	0.08	4.0 10^{-4}	0.5
A5	100	3.9 Al + 0.2 Cu	57.3	*6.9*	0.30	5.1 10^{-4}	0.5
A6	200	4.0 Al + 1.2 Cu	102.4	-	1.70	1.1 10^{-3}	0.5
A7	250	4.0 Al + 1.6 Cu	124.7	-	2.47	1.8 10^{-3}	0.5
A8	300	4.0 Al + 2.5 Cu	152.4	-	3.40	2.1 10^{-3}	0.5
B1	10	0.3 Al	8.5	0.06	*.002*	1.0 10^{-6}	1
B2	20	2.0 Al	17	0.42	*.010*	1.0 10^{-6}	1
B3	30	0.18 Cu + 4.0 Al	26	1.46	*.040*	1.0 10^{-6}	1
B4	35	4.O Al + 0.25 Cu	30.0	2.38	*.070*	1.0 10^{-6}	0.8
B5	55	4.0 Al + 1.2 Cu	47.9	*5.77*	0.25	1.5 10^{-6}	0.8
B6	70	4.0 Al + 2.5 Cu	61.1	*9.12*	0.48	1.3 10^{-6}	0.8
B7	100	4.0 Al + 0.5 Cu + 2 Sn	87.0	-	1.28	1.4 10^{-6}	0.8
B8	125	4.0 Al + 1.0 Cu + 4 Sn	109.2	-	2.14	1.3 10^{-6}	0.8
B9	170	4.0 Al + 1.0 Cu + 3 Sn + 1.5 Pb	149.4	-	3.67	1.1 10^{-6}	0.8
B10	210	4.0 Al + 0.5 Cu + 2 Sn + 3.5 Pb	184.6	-	4.91	1.3 10^{-6}	0.8
B11	240	4.0 Al + 0.5 Cu + 2 Sn + 5.5 Pb	212.4	-	5.89	7.8 10^{-7}	0.8

(§)

Table A.1 (continued)

Code [1]	H.V. [2] (kV)	Filtration [3] (mm)	E_m [4] (keV)	HVL (mm) [5] Al	Cu	Air kerma rate [6] (Gy s^{-1})	u% [7]
RQR2	40	3 Be+2.5 Al	27.8	1.41	*.039*	3.2 10^{-4}	0.5
RQR3	50	3 Be+2.5 Al	31.9	1.76	*.050*	3.2 10^{-4}	0.5
RQR4	60	3 Be+2.5 Al	35.6	2.09	*.062*	5.3 10^{-4}	0.5
RQR5	70	3 Be+2.5 Al	39.0	2.35	*.069*	5.3 10^{-4}	0.5
RQR6	80	3 Be+2.5 Al	42.5	2.66	*.084*	1.1 10^{-3}	0.5
RQR7	90	3 Be+2.5 Al	45.8	2.99	*.100*	1.1 10^{-3}	0.5
RQR8	100	3 Be+2.5 Al	48.9	3.30	*.110*	1.7 10^{-3}	0.5
RQR9	120	3 Be+2.5 Al	54.5	3.92	*.147*	1.7 10^{-3}	0.5
RQR10	150	3 Be+2.5 Al	61.6	4.88	*.195*	2.5 10^{-3}	0.5
RQA3	50	2.5 Al + 10 Al	37.4	3.78	*.142*	2.1 10^{-5}	0.5
RQA4	60	2.5 Al + 16 Al	-	5.26	-	2.0 10^{-5}	0.5
RQA5	70	2.5 Al + 21 Al	50.7	6.85	*.315*	2.2 10^{-5}	0.5
RQA6	80	2.5 Al + 26 Al	-	8.04	-	3.3 10^{-5}	0.5
RQA7	90	2.5 Al + 30 Al	62.1	9.39	*.494*	3.3 10^{-5}	0.5
RQA8	100	2.5 Al + 34 Al	-	10.06	-	5.6 10^{-5}	0.5
RQA9	120	2.5 Al + 40 Al	75.6	11.92	*.719*	5.6 10^{-5}	0.5
RQA10	150	2.5 Al + 45 Al	87.3	13.58	*.819*	4.8 10^{-5}	0.5
MO1	23	0,060 Mo	-	0.33	-	4 10^{-4}	0.5
MO2	28	0,060 Mo		0.36	-	4 10^{-4}	0.5
MO3	35	0,060 Mo	-	0.39	-	4 10^{-4}	0.5
MO4	40	0,060 Mo		0.41	-	4 10^{-4}	0.5
MOA1	23	0,060 Mo + 2 mm Al	-	0.56	-	1 10^{-5}	0.5
MOA2	28	0,060 Mo + 2 mm Al	-	0.63	-	1 10^{-5}	0.5
MOA3	35	0,060 Mo + 2 mm Al	-	0.90	-	1 10^{-5}	0.5
MOA4	40	0,060 Mo + 2 mm Al	-	1.17	-	1 10^{-5}	0.5
P1	10	-	7.4	0.03	*.001*	2.0 10^{-4}	0.5
P2	25	0.43 Al	15.7	0.25	*.006*	4.0 10^{-4}	0.5
P3	30	0.26 Al	15.4	0.18	*.005*	1.5 10^{-3}	0.5
P4	50	1.07 Al	27.4	1.04	*.027*	7.5 10^{-4}	0.5
P5	50	4.72 Al	33.1	2.27	*.067*	1.2 10^{-4}	0.5
P6	100	3 Be + 3.48Al	50.9	4.00	0.15	9.7 10^{-4}	0.5
P7	135	3Be + 4.08Al + 0.18Cu	68.9	8.70	0.50	8.5 10^{-4}	0.5
P8	180	3Be + 4.06Al + 0.51Cu	86.0	*15.0*	1.00	1.3 10^{-3}	0.5
P9	250	3Be + 4.02Al + 1.72Cu	126.1	-	2.50	1.7 10^{-3}	0.5
Am-241		gamma radiation	59	from 1.2 10^{-8} to 7.55 10^{-8}			0.7
Cs-137		gamma radiation	662	from 2.4 10^{-10} to 2.4 10^{-7}			0.7
Co-60		gamma radiation	1253	from 2.4 10^{-9} to 5.7 10^{-3}			0.5

Photon and electron beams from a 4-20 MeV Microtron are available but are not yet used for calibration.

(1) The P series includes the CCRI x-ray reference qualities. The L, S, A and B series include the reference x-ray qualities recommended by ISO 4037 (i.e., wide and narrow spectrum, high and low rate). The RQR and RQA series are the x-ray reference qualities recommended by IEC 1267 for radiodiagnostics. The MO and MOA series are the x-ray reference qualities recommended by IEC 61223-3-2 for mammography.

(2) X-ray tube tension.

(3) The additional filtration is approximately 2.5 mm of Be for the x-ray qualities with H.T.$\leq$ 50 kV and 3 mm Be + 3 mg cm^{-2} of aluminized mylar for the x-ray qualities with H.T.> 50 kV.

(4) Mean energy values calculated from the experimental energy spectrum.

(5) The Al or Cu HVL values *in italics* are not directly measured and are reported here only for comparison with the experimental Cu or Al corresponding values.

(6) Typical air kerma rates for a tube current of 10 mA and a SDD of 100 cm. The field size has a diameter of 15 cm and 10 cm for x-ray qualities generated at H.T.$\leq$ 50 kV and at H.T.> 50 kV, respectively.

(7) Rounded value (%) of the combined standard uncertainty (as recommended in the "Guide to the Expression of Uncertainty in Measurement" ISO(1993)) on the air kerma determination at ENEA.

ANNEX A.2

ENEA-INMRI 2005-2007 Activity Report:
Articles published in journals or meeting proceedings in the field of photon and charged particle dosimetry

1- P.J. Allisy-Roberts, D.T. Burns, C.Kessler, R.F. Laitano, M.P. Toni, M. Bovi, M. Pimpinella: *"Comparison of the standars for air-kerma of the ENEA-INMRI and the BIPM for Co-60 gamma rays"*, Rapport BIPM-2003/10, Bureau International des Poids et Mesures, Sèvres, 2005.

2- M. Bovi, K. Pasciuti, M. Quini, C. Silvestri, M.P. Toni, *"La riferibilità' in radioprotezione nel caso di dose dovuta ad irradiazione esterna con radiazione beta" ";* – AIRP Convegno Nazionale di Radioprotezione; – Catania 15-17 settembre 2005;

3- M. Bovi, *"La riferibilità nelle misurazioni di kerma in aria ed equivalente di dose ambiente o personale: i campioni nazionali";* – Giornata di studio AIRP, CEI, CESNEF; Milano 23 giugno 2005;

4- N. Dell'Arena, *Il Controllo dei dati nella ISO/IEC 17025.* Tutto_Misure Anno V n° 1 pagg 83-85, 2005.

5- N. Dell'Arena, *Una guida per i laboratori di prova*. Tutto_Misure Anno V n° 2 pagg 173, 2005.

6- N. Dell'Arena, *La gestione delle apparecchiature secondo la norma ISO 17205. Parte 1 Apparecchiature e Specifica di prova,* Tutto_Misure Anno V n° 3 pagg 243-245, 2005

7- N. Dell'Arena, *La nuova edizione della norma ISO 17025.* ANGQ NEWS n° 18 pagg 3-5, 2005.

8- N. Dell'Arena, *La gestione delle apparecchiature secondo la norma ISO 17205. Parte II Taratura e Conferma,* Tutto_Misure Anno V n° 4 pagg 329-331, 2005.

9- N. Dell'Arena, *Norme per la gestione della strumentazione e dei laboratori di misura*. IV Congresso Metrologia & Qualità Torino 22-24 febbraio 2005.

10- N. Dell'Arena, M. Bovi, M.P. Toni, "*Valenza dei confronti di misura interlaboratorio ai fini dell'accreditamento dei laboratori di prova e taratura"*. IV Congresso Metrologia & Qualità Torino 22-24 febbraio 2005.

11- N. Dell'Arena, "*Variazioni introdotte nella nuova edizione della norma ISO 17025*". IV Congresso Metrologia & Qualità Torino 22-24 febbraio 2005.

12- A.S. Guerra, R.F. Laitano, M. Pimpinella, L. Begnozzi, A. Bufacchi, S. delle Canne, T. Malatesta, "*Effetti di ricombinazione ionica sulla determinazione degli indici di qualità per fasci di fotoni ($TPR_{20,10}$) e di elettroni (R_{50}) mediante camere a ionizzazione",* Atti del IV Congresso Nazionale AIFM, Verona 14-17 giugno 2005, Vol. II pp 884-888.

13- A.S. Guerra, R.F. Laitano, M. Pimpinella, E. Busatti, A. Petrucci, "*Confronto nella misura di dose assorbita in fasci di elettroni con camera a ionizzazione Wellhöfer PPC05 e con sistemi dosimetrici di riferimento."* Atti del IV Congresso Nazionale AIFM, Verona 14-17 giugno 2005, Vol. II pp 821-824.

14- R.F. Laitano, M. Pimpinella, M.P. Toni, "*Report to the CCRI Section I on the activity carried out at ENEA-INMRI on photon and charged particle dosimetry in the period 2003-2005",* Report CCRI(I)/05-32- CCRI(I), BIPM, Sèvres, 17th meeting 18-20 Maggio 2005.

15- R.F. Laitano, M. Pimpinella, M.P. Toni, "*Influence of photon energy spectra on k_{wall} factor and related uncertainty in Co-60 air-kerma measurement by cavity ionization chambers",* Workshop(I)/05-22, BIPM Workshop, Uncertaities in Dosimetry, BIPM, Sèvres, 17 Maggio 2005.

16- R.F. Laitano, M. Pimpinella, M.P. Toni, "*Influence of x-ray spectra on* k_{sc}*,* k_e*,* k_{fl} *correction factors and related uncertainties in air-kerma measurement by FACs",* Workshop(I)/05-23, BIPM Workshop, Uncertaities in Dosimetry, BIPM, Sèvres, 17 Maggio 2005.

17- R.F. Laitano, M. Pimpinella, M.P. Toni, M. Quini, M. Bovi, "*Uncertainties in volume determination for standard ionization chambers to measure air-kerma in Co-60 gamma-ray beams",* Workshop(I)/05-17, BIPM Workshop Uncertaities in Dosimetry - 17 Maggio 2005.

18- M.P. Toni, M. Bovi, L. Ceravolo, C. Silvestri,*"La riferibilità in campo medico nelle valutazioni radioprotezionistiche di dose impartita al paziente per l'effettuazione di esami mammografici"; –* AIRP Convegno Nazionale di Radioprotezione; – Catania 15-17 settembre 2005.

19- M.P. Toni, M. Bovi, R.F. Laitano, M. Pimpinella, M. Quini, C. Silvestri, *"Revisione del valore di riferimento del kerma in aria per la taratura di dosimetri usati in campo radioprotezionistico"; –* AIRP Convegno Nazionale di Radioprotezione; – Catania 15-17 settembre 2005

20- M.P. Toni, *"La rete dei Centri SIT"; –* Giornata di studio AIRP, CEI, CESNEF; – Milano 23 giugno 2005;

21- M.P. Toni, "*La misura in qualità: stima delle incertezze di misura e conferma metrologica per le misurazioni in campo"; –* Giornata di studio AIRP, CEI, CESNEF; – Milano 23 giugno 2005

22- D. Mihăilescu, M. Pimpinella, A.S. Guerra, R.F. Laitano, "Monte Carlo calculation of stopping-power ratios for electron beams produced by a linac for IORT", 2006, Rom. Journ. Phys. vol.51 N 5-6 pp 583

23- D. Mihăilescu, M. Pimpinella, A.S. Guerra, R.F. Laitano, *"Comparison of measured and Monte Carlo calculated dose distributions for the NOVAC7® linear accelerator",* 2006, Rom. Journ. Phys. vol 51 N 7-8 pp 729-739

24- R F Laitano, A S Guerra, M Pimpinella, C Caporali, A Petrucci **"***Charge collection efficiency in ionization chambers exposed to electron beams with high dose per pulse",* 2006, Phys. Med. Biol.. (51) pp 6416-6436

25 M. Bovi, M.P. Toni, L. Ceravolo, A. Fidanzio, K. Pasciuti, A. Piermattei, L. Avario, N. Capote, F. Perrone "*Estensione alla dosimetria clinica del campo di misura del campione nazionale di dose assorbita dovuta a radiazione beta di bassa energia*", - Atti del V Congresso "Metrologia & Qualità", Torino 14-16 Marzo 2007

26 M. Pimpinella, M.P. Toni, R.F. Laitano, A.S. Guerra, "*L'uso del metodo di simulazione Monte Carlo nello sviluppo di alcuni campioni primari per la dosimetria delle radiazioni ionizzanti"*, - Atti del V Congresso "Metrologia & Qualità", Torino 14-16 Marzo 2007

27 A.S. Guerra, R.F. Laitano, M. Pimpinella, C. Caporali, "*Analisi delle diverse fonti d'incertezza nelle dosimetria di base in radioterapia"*, - Atti del V Congresso "Metrologia & Qualità", Torino 14-16 Marzo 2007

28 M. Pimpinella, R.F. Laitano, A.S. Guerra, S. La Civita, *"Caratterizzazione metrologica dei fasci di elettroni ad alte dosi per impulso prodotti negli acceleratori dedicati per radioterapia di tipo IORT",* - Atti del V Congresso "Metrologia & Qualità", Torino 14-16 Marzo 2007

ANNEX A.3

ENEA-INMRI STAFF INVOLVED IN THE ACTIVITY ON PHOTON AND CHARGED PARTICLE DOSIMETRY STANDARDS

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STAFF*	**E-mail username**	**Phone extension**
Scientists		
Dr. M. Bovi	bovi	4524
Dr. C. Caporali	caporali	6240
Dr. A. S. Guerra	guerra	3552
Dr. R.F. Laitano (50%)[+]	laitano	3559
Dr. M. Pimpinella	pimpinella	6680
Dr. M. P. Toni	toni	3957
Dr. N. Dell'Arena(+)	dellarena	3555
Technicians		
Mr. L. Ceravolo	ceravolo	3576
Mr. GL Cappadozzi	cappadozzi	4563
Mr. M. Moscati	moscati	6028
Mr. M. Quini (80%)[+]	quini	4563
Mrs. C. Silvestri	silvestri	3354

(*) Some programs have been carried out in collaboration with guests (postgraduate fellowships) and students (stagers for thesis).
Personnel for administrative services and technical assistance for maintenance and repair are supplied by the CR Casaccia central service and are not included in the ENEA-INMRIstaff.

(+) Due to the shortage of personnel some technicians share their activity (e.g., mechanical workshop) among the different sections of the Institute.
The activity of R.F. Laitano include the institute management (50%) and the scientific work on dosimetry standards (50%). The activity of N. Dell'Arena deals only with the INMRI-ENEA Quality System.