REPORT TO THE CCRI SECTION I ON THE ACTIVITY CARRIED OUT AT ENEA-INMRI ON PHOTON AND CHARGED PARTICLE DOSIMETRY IN THE PERIOD 2007 – 2009

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1. INTRODUCTION

The present report is a summary of the 2007-2009 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}
	- Calibrated ion chamber	^{192}Ir gamma-ray	$3\ 10^{-3}$ 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

In the following just the new actions made after the latest CCRI(I) meeting (2007) are described.

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;
- a cavity ionization chamber for Co-60 gamma rays;

The following transfer standards are also currently operating:
- a 30 cm^3 ionization chamber (plastic wall) for Cs-137 gamma rays;
- a 1000 cm^3 ionization chamber (plastic wall) for Ir-192 gamma rays.

These transfer standards are calibrated against the medium-energy x-ray and Co-60 air-kerma standards and their response curve as a function of energy, for the Cs-137 and for the Ir-192 gamma rays, is derived by an interpolation procedure.

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

The extensive renovation works in the low and medium-energy x-ray irradiation rooms, as requested by the control authority for radiological protection, were completed in December 2008. The functionality of the low and medium-energy x-ray irradiation rooms was for the most part restored. The research and calibration activity in this field will resume at full capacity by the year, after the verification of the measurement reproducibility for each standard system.

2.2 Absorbed dose standards

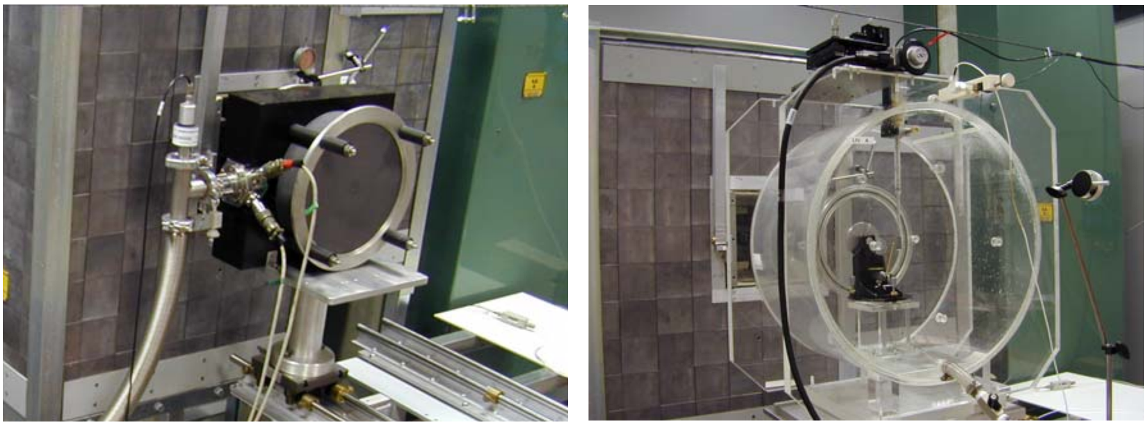
The absorbed-dose standards at ENEA-INMRI are:

- a graphite calorimeter for Co-60 gamma- ray absorbed dose to graphite,
- a graphite calorimeter and an ionometric transfer system (thick-walled graphite ionization chamber) for Co-60 gamma- ray absorbed dose to water.

A transfer standard system based on ferrous sulphate and dichromate dosimeters is currently operating for calibration in the industrial-level irradiation range. This transfer standard is calibrated against the absorbed-dose-to-water standard at the Co-60 gamma-ray quality.

2.2.a Absorbed-dose-to-water standard for Co-60 gamma radiation

Since the time of its first comparison at BIPM (1994) the absorbed-dose-to-water standard (a picture of which is shown in figure 1) has been revised in various aspects such as the correction factors for gap effects, etc..
In April 2007 the standard was compared with the BIPM absorbed dose to water standard and the comparison results are in course of publication. For the comparison new values have been adopted for some quantities entering the expression of absorbed dose to water. The new and old values for the parameters that have been revised are reported in Table 2. Due to the lower uncertainty of the new values the combined relative standard uncertainty on the absorbed dose to water decreases from 0.45% to 0.36%.



(a) ***(b)***

Figure 1. *The graphite calorimeter (a) and the scaled cylindrical water phantom (b) used for realizing the ENEA-INMRI absorbed dose to water standard.*

Table 2. Physical costants and correction factor revised in the period 1994 to 2007 for the absorbed dose to water standard in Co-60 gamma radiation.

	1994		2007	
	value	Relative standard uncertainty	value	Relative standard uncertainty
$(\bar{\mu}_{en}/\rho)_{w,c}$ water to graphite mass energy-absorption coefficient ratio	1.1124	0.2	1.1124	0.14
k_{gap} gap correction	1.0051	0.14	1.0064	0.08
$\Psi_{w,c}$ energy fluence correction	1.0072	0.11	1.0068	0.08

2.2 b Absorbed dose to water transfer standard system for radiation-processing dose levels

In July 2008 the traditional gammacell for industrial-level irradiations was no longer used. A new Co-60 irradiation facility was characterized in terms of absorbed dose rate and has been operative for the high-dose calibration service since January 2009. The new irradiation facility (Calliope irradiation plant) is a pool-type Co-60 irradiation plant built at ENEA. The source consists of a double annular array of 48 source bars (Figure 2 and Figure 3). The diameter of the inner array, consisting of 24 sources, is 32 cm. The diameter of the outer array, consisting of 24 sources, is 38 cm. The source bar height is 21 cm or 27.5 cm. The pool is 2 m x 4.5 m x 8 m, with a water depth of 7 m. The irradiation is performed by raising the whole source annular array from the bottom of the water pool up to the source top position. The source to dosimeter distance is expressed in terms of distance from the centre of the dosimeter to the centre of the double annular array of Co-60 sources.
The overall activity of the source is about 400 TBq on January 1st, 2009.
The source was calibrated in terms of absorbed dose to water by a set of ferrous sulphate and potassium dichromate transfer dosimetry standards. The ferrous sulphate solution is used in the dose rate range from 30 Gy/h to 1 kGy/h. The potassium-silver dichromate solution is used in the dose rate range from 1 kGy/h to 10 kGy/h. The absorbance reading of ferrous sulphate and dichromate solutions are made by a Varian Cary 400 U/V spectrophotometer at 304 and 440 nm, respectively.
The calibration procedure includes the following steps:

A - Calibration of the ferrous sulphate dosimeter against the ENEA-INMRI primary standard of absorbed dose to water, D_w, in the reference Co-60 gamma beam (Irradiation Unit 1, I.U. 1) at a dose rate of about 30 Gy h^{-1}.

B - Calibration of the dichromate dosimeter against the ferrous sulphate dosimeter in the Calliope plant (I.U. 2) at a dose rate of about 1 kGy h^{-1} (irradiation condition 1, I.U. 2).

C - Determination of D_w by the dichromate dosimeter (calibrated in step B) in the I.U. 2 at the centre of the double annular array of 48 sources (irradiation condition 2, I.U. 2). In the irradiation condition 2 the dose rate is about 4.4 kGy h^{-1} on January 1st, 2009.

The combined relative standard uncertainty on the absorbed dose to water rate is 1.7% (Table 3).

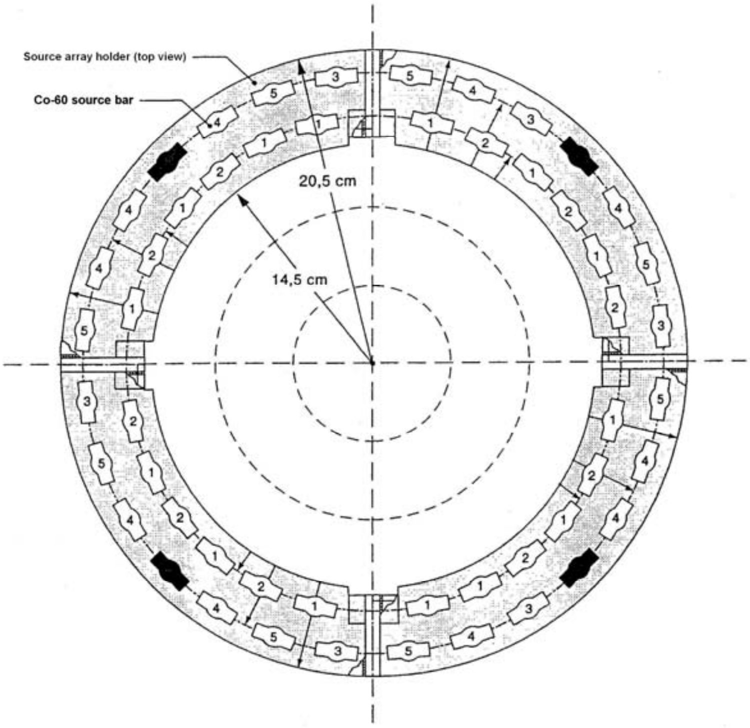


Figure 2. *Top view (schematic) of the Co-60 source array in the ENEA pool-type irradiation plant for irradiation at radiation-processing dose level.*

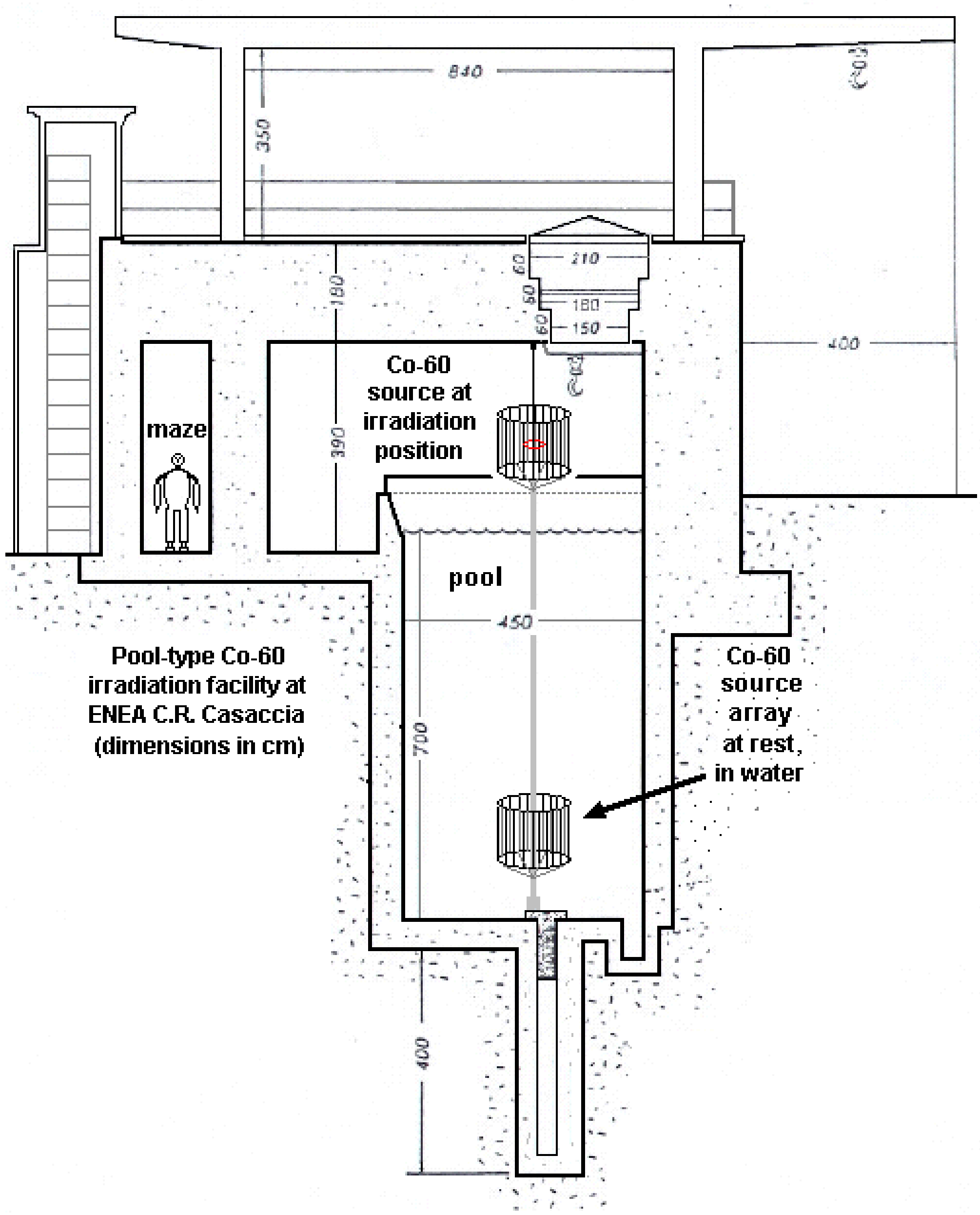


Figure 3. *The pool-type irradiation facility used at ENEA-INMRI for irradiation at radiation-processing dose level.*

Table 3. Uncertainties in absorbed dose to water rate for the ENEA-INMRI pool-type Co-60 irradiation facility.

	Relative standard uncertainty	
Component of uncertainty	Type A (%)	Type B (%)
Step A: ferrous sulphate dosimeter calibration in the reference Co-60 gamma beam (I.U. 1)		
Primary standard (D_w)		
Reference D_w at 5 g cm^{-2}		0.4
Ferrous sulphate dosimeter		
Dosimeter positioning		0.2
Absorbance reading	0.2	0.3
Irradiation temperature		0.2
Absorbance reading temperature		0.1
Stability of ferrous sulphate solution		0.2
Transfer dosimeter intra-batch variability	0.4	
Step B: dichromate dosimeter calibration in the pool-type Co-60 irradiation facility (irradiation condition 1, I.U. 2)		
D_w determination by ferrous sulphate dosimeter		
Dosimeter and source positioning		0.5
Absorbance reading	0.2	0.3
Irradiation temperature		0.3
Absorbance reading temperature		0.2
Transfer dosimeter intra-batch variability	0.4	
Irradiation time	0.2	
Dichromate dosimeter		
Dosimeter and source positioning		0.5
Absorbance reading	0.2	0.3
Irradiation temperature		0.2
Absorbance reading temperature		0.1
Stability of dichromate solution		0.1
Dosimeter intra-batch variability	0.4	
Irradiation time	0.1	
Step C: D_w measurements by dichromate dosimeter in the pool-type Co-60 irradiation facility (irradiation condition 2, I.U. 2)		
Dosimeter and source positioning		0.5
Absorbance reading	0.2	0.3
Irradiation temperature		0.2
Absorbance reading temperature		0.1
Stability of dichromate solution		0.1
Dosimeter intra-batch variability	0.4	
Irradiation time	0.1	
Field non-uniformity		0.5
Quadratic sum	0.9	1.4
Combined relative standard uncertainty	1.7	

3. NEW STANDARDS IN COURSE OF CONSTRUCTION

In the recent years the ENEA-INMRI started a research project to develop two new absorbed dose standards for low dose rate (LDR) and high dose rate (HDR) brachytherapy sources, respectively. The design of these two standards is already completed and the construction of the mechanical components is at its final stage. This project is also supported by the joint research project “Increasing cancer treatment efficacy using 3D Brachytherapy” in the framework of the Grant Agreement No. 217257 between the EC and EURAMET under the Seventh Framework Programme. The coordination of the “Brachytherapy” project has been entrusted to the ENEA-INMRI.

3.1 Low dose rate brachytherapy Standard

The low dose rate brachytherapy standard is designed to measure LDR brachytherapy sealed sources, e.g. I-125 seeds. It consists of a large volume ionization chamber the length of which can be varied. The chamber components are made of solid water and graphite. The entrance window of the chamber is equivalent to 1 cm of water. The rear window of the chamber is equivalent to 5 cm of water and such to allow the full backscatter condition for the maximum photon energy considered (40 keV). The absorbed dose is determined at 1 cm depth in water by a kerma-to-absorbed-dose conversion procedure and and Monte Carlo calculations.

Monte Carlo simulations were carried out to confirm the basic design of the standard and the electric field inside the ionization chamber was investigated by calculations performed on the basis of the 3D Boundary Element Method (BEM). A preliminary assembly of the in-graphite version of the new ENEA-INMRI chamber has been mechanically built up.

3.2 High dose rate brachytherapy Standard

In the framework of the EURAMET/EC joint research project “Increasing cancer treatment efficacy using 3D Brachytherapy” the ENEA-INMRI is involved in developing a prototype of an absorbed dose standard for High Dose Rate (HDR) brachytherapy sealed sources, e.g. the Ir-192 capsules for remote afterloading machines, welded to the end of flexible steel wires. The standard will be a graphite calorimeter for absorbed dose to graphite measurements. The work has been started performing Monte Carlo and heat transfer simulations to optimize the design of the calorimeter. Monte Carlo calculations by EGSnrc were done to optimize the core dimensions and radius. Heat transfer simulations were performed by Finite Element Method (Comsol Multiphysics), to optimize the gap number, the gap size and the coating of the internal surfaces of the calorimeter, needed to minimize the heat transfer by radiation. Heat transfer calculations were initially made in 2D, but a 3D approach was later needed to find the best arrangement of the heaters in the 3 bodies of the calorimeter. The heaters are needed for the electrical calibration of the calorimeter. The calibration is made in terms of the heating energy per fractional change of the core thermistor resistance. The heaters are also needed for the operation of the calorimeter both in the quasi-adiabatic or the quasi-isothermal mode of operation. The graphite calorimeter has a cylindrical symmetry, like the well-type ionization chambers widely used for the characterization of HDR brachytherapy sealed sources. The calorimeter is disc-shaped, designed for being inserted in a suitable larger graphite phantom, having about 20 cm diameter and 20 cm height. This is to achieve the conditions of full backscattering at the measurement point (Figure 4 and 5). The calorimeter is intended to be a portable three-body (core, jacket and medium) graphite calorimeter. The core, the jacket and the shield are surrounded by 0.5 mm vacuum gaps to minimize heat loss by conduction. The enclosure to obtain high vacuum around the core, the jacket and the medium is in PMMA.

The annular core has a diameter 25 mm, height 2 mm, and is surrounded by the jacket and the medium having similar shape. The temperature variation in the core and in the jacket is measured by 0.3 mm diameter NTC microthermistors and a precision AC powered Wheatstone bridge. In the medium, larger size NTC thermistors are used.

It is planned to convert by Monte Carlo calculations the absorbed dose to graphite at 2.5 cm distance from the brachytherapy source into absorbed dose to water at 1 cm distance from the source. The correction factors relevant to calorimeter gaps, brachytherapy source geometry, finite size of the core, etc., will be also determined by Monte Carlo simulations.

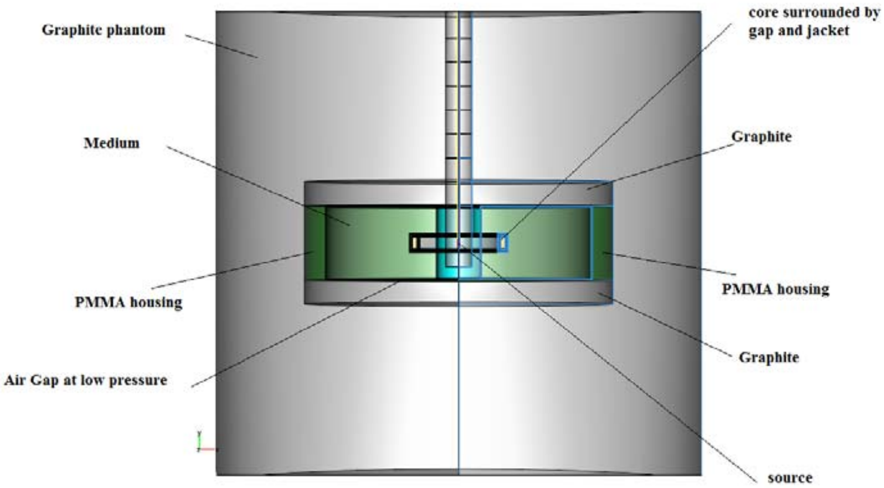


Figure 4. Section of the disc-shaped graphite calorimeter inside the 20 cm height graphite phantom.

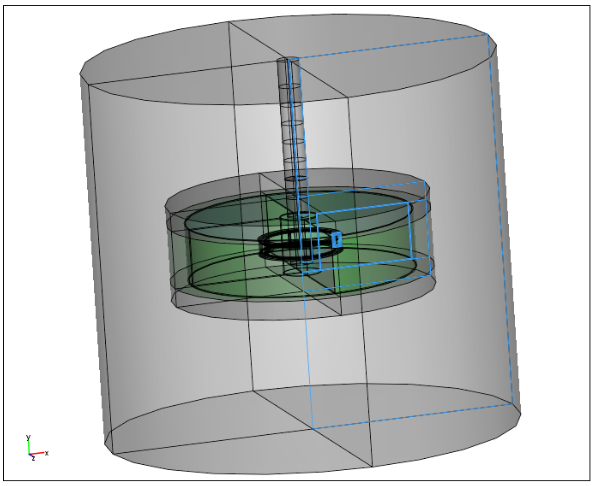


Figure 5. 3D thermal modeling by finite element method of the graphite calorimeter

4. 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”
(results in course of publication)

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 2009 not yet specified)

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

5- BIPM-ENEA comparison on absorbed-dose-to-water standards for Co-60 gamma rays (measurements carried out in April 2007, report in course of publication).

6- CCRI(I)-S2 “Comparison of standards for absorbed dose to water for Co-60 gamma radiation at radiation-processing dose levels”
(NPL and NIST alanine dosimeters irradiated at ENEA-INMRI in February 2009)

5. 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.

5.1 Therapy-level calibration service

a) 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 years the largest part of the calibrations of ionization chambers has been made in terms of absorbed dose to water.

b) 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.

5.2 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. 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.

5.3 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. At present the irradiations are made in the pool-type Co-60 irradiation facility described above (Section 2.2 b). Until July 2008 the irradiations were 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.

6. 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 2007-2009 is summarized below.

6 1. Dosimetry in accelerator beams for IORT (intraoperative radiation therapy)

The use of movable accelerators for electron beam based IORT has been increasing in Italy over the last ten years. The long plastic applicators used in these accelerators give rise to a strong scattered component in the electron beam. Therefore the spectral distributions of electrons at phantom surface are somewhat different from those produced by usual clinical linacs. To improve the accuracy of ionization chamber dosimetry in the electron beams produced by these accelerators the water-air stopping power ratios, $s_{w,air}$, were specifically determined by Monte Carlo calculation. The IORT electron beams with nominal energy 9 MeV, 7 MeV, 5 MeV and 3 MeV were simulated by the Monte Carlo code BEAMnrc. The calculated electron distributions in energy, angle and position at the water phantom surface were used to calculate the $s_{w,air}$ values as a function of field size (field diameter from 10 cm to 4 cm) and depth in water. The calculation was carried out by the EGSnrc/SPRRZnrc Monte Carlo code. The calculated $s_{w,air}$ values slightly decrease with field size for all the beam nominal energies. The variation is within 0.4% as shown in Figure 6 for the 9 MeV electron beam. The $s_{w,air}$ values calculated for the IORT beams at the reference depths differ from the corresponding $s_{w,air}$ values recommended by the TRS-381 and TRS-398 IAEA less than $\pm$ 0.4%. The differences increase up to about 1.3% along the depth dose curve as shown in Figure 7 for the 9 MeV electron beam. These differences should be accounted for in the uncertainty budget when using, for the IORT beams dosimetry, the $s_{w,air}$ data reported for conventional beams by the IAEA dosimetry protocols.

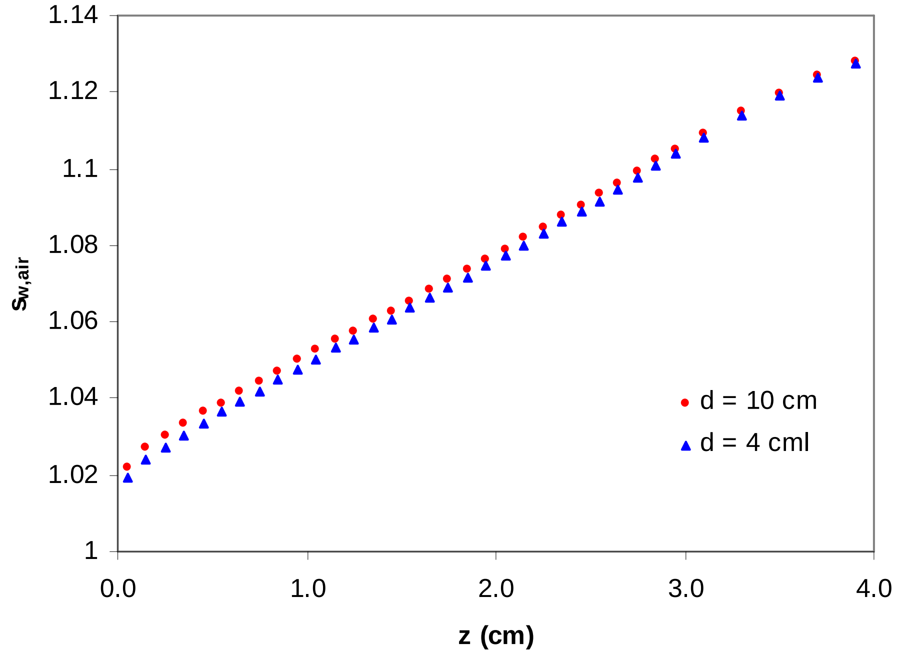


Figure 6. *Water-air stopping power ratios calculated by Monte Carlo for 9 MeV electron beam produced by the NOVAC7 IORT mobile accelerator with field diameter of 10 cm and 4 cm, respectively.*

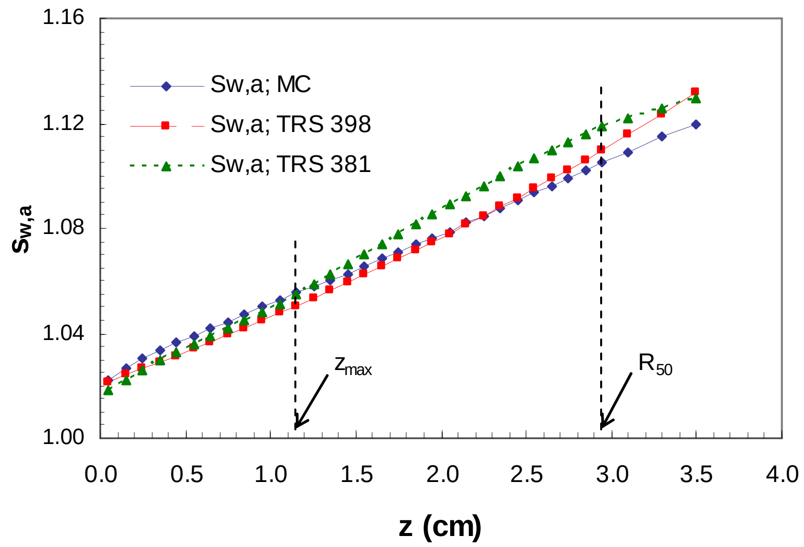


Figure 7. *Comparison among water-air stopping power ratios calculated by Monte Carlo for the IORT electron beams and the* $s_{w,a}$ *values reported by the TRS-398 and TRS-381 IAEA dosimetry protocols. The data refer to the IORT electron beam produced by the NOVAC7 mobile accelerator with nominal energy 9 MeV.*

6 2. Traceability of absorbed dose measurements in small field size photon beams used in radiotherapy

The ENEA-INMRI is developing a new dosimetric system capable to perform absorbed-dose-to-water measurements traceable to the D_w primary standard in radiotherapy photon beams with small field sizes. The dosimetric system is based on a in-house CVD diamond detector produced in collaboration with the Department of Electronic Engineering of the Roma Tre University. A first detector prototype has been manufactured using a single crystal diamond. Silver electrodes (200 nm thick) were thermally evaporated on both sides of the diamond having dimensions 3 mm x 3 mm x 0.5 mm. The schematic drawing and a picture of the detector prototype are shown in Figure 8 and Figure 9 respectively. The stability of the detector response has been studied in the ENEA-INMRI Co-60 gamma beam with dose rate in the range from 0.3 Gy min^{-1} to 1.38 Gy min^{-1}. The results show that an acceptable signal reproducibility (about 0.5%) is obtained if

a) a daily pre-irradiation with an absorbed dose in the range from 5 Gy to 10 Gy is made;
b) the detector is continuously kept polarized;
c) After starting the detector irradiation some time is needed before starting data acquisition (charge or current). As a rule of thumb this time must correspond to an integrated absorbed dose between 0.5 Gy and 3 Gy depending on the beam dose rate.

In figure 10 the current measured during subsequent irradiations with dose of 3 Gy (5 minutes) followed by a pause of 3 minutes is reported. As shown in the figure 10 the signal rise time in the first irradiation is longer than in the following irradiations. When the signal is stabilized the repeatability is 0.3% and the reproducibility 0.5%.

Monte Carlo simulations have been done to evaluate the diamond detector response as a function of beam quality and field size. The irradiation of the diamond detector at the reference depths in a cubic water phantom with side of 30 cm was simulated by the DOXYZnrc/EGsnrc code. The user code was modified to implement the dose calculation by correlated sampling method. The detector response was calculated as ratio of the absorbed dose to diamond (D_d) to the absorbed dose to water (D_w) in the same volume of the sensitive diamond. Up to now the results showed a variation of the diamond response of about 1.5% from Co-60 quality to a 10 MV photon beam. As regarding the field size the results showed a field size dependence of the diamond detector response only for field size less than 3 cm x 3 cm.

The research project on CVD diamond detectors is also supported by the joint research project “External Beam Cancer Therapy” in the framework of the Grant Agreement No. 217257 between the EC and EURAMET under the Seventh Framework Programme..

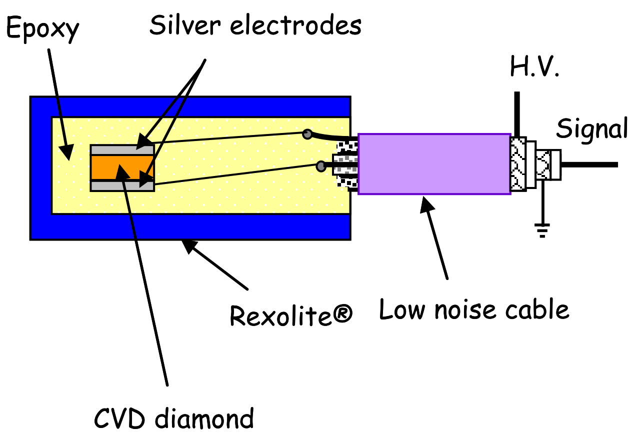


Figure 8. *Schematic drawing of the ENEA-INMRI diamond detector (not to scale).*

Figure 9. *Prototype of the ENEA-INMRI diamond detector.*

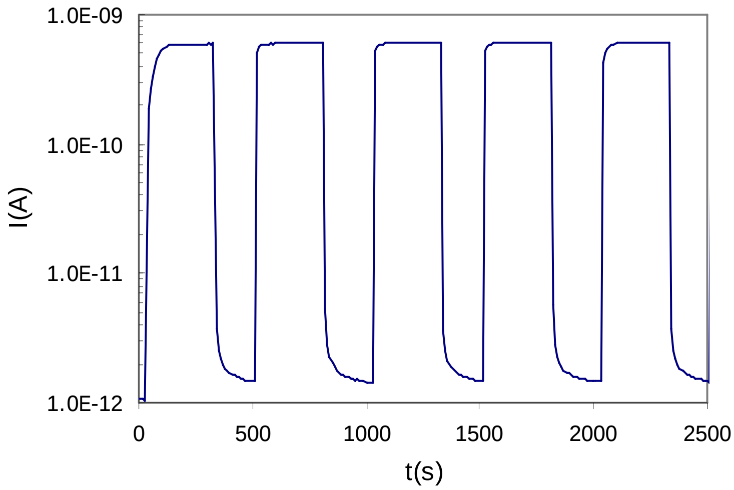


Figure 10. *Diamond detector current measured during subsequent irradiations with 3 Gy (irradiation time 5 minutes) followed by a pause of 3 minutes. The data refer to a Co-60 beam with dose rate of 0.5 Gy min^{-1}. The polarizing voltage was 50 V.*

7. IMPLEMENTATION OF THE QUALITY SYSTEM

According to the CIPM MRA and EURAMET requirements the Quality Manual of ENEA-INMRI was updated in some aspects. A number of internal audits were made as well as the management review.

8. PARTICIPATION IN METROLOGY AND STANDARDISATION ORGANISATIONS

The ENEA-INMRI staff is currently devoted to activities in metrological and standardisation organisations, such as: EURAMET, 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	1107	from 2.4 10^{-9} to 5.7 10^{-3}			0.5
Co-60	attenuated by lead absorbers	gamma radiation	1209 to 1250	from 4 10^{-6} to 3 10^{-3}			0.7

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

2007-2009 ENEA-INMRI activity report: articles published in journals or meeting proceedings in the field of photon and charged particle dosimetry

1- M. Pimpinella, D. Mihailescu, A.S. Guerra, R.F. Laitano: *"Dosimetric characteristics of electron beams produced by a mobile accelerator for IORT"*; Phys. Med. Biol. 52 (2007) pp 6197–6214

2- A.S. Guerra, R.F. Laitano, M. Pimpinella: *"Dosimetria con camere a ionizzazione in fasci di elettroni ad alta dose per impulso";* V Congresso Nazionale AIFM, Castelvecchio Pascoli, 17 - 20 settembre 2007

3- M. Pimpinella, S. La Civita, A.S. Guerra, R.F. Laitano: *"Determinazione dei fattori di perturbazione per i dosimetri di riferimento a solfato ferroso dell'INMRI-ENEA in fasci di elettroni e fotoni per radioterapia"*; V Congresso Nazionale AIFM, Castelvecchio Pascoli, 17 - 20 settembre 2007

4- M. Pimpinella, D. Mihailescu, A.S. Guerra, R.F. Laitano: *"Rapporti dei poteri frenanti acqua-aria per fasci di elettroni prodotti da acceleratori del tipo NOVAC7"*; V Congresso Nazionale AIFM, Castelvecchio Pascoli, 17 - 20 settembre 2007

5- M. Pimpinella, A.S. Guerra, S. La Civita and R.F. Laitano: *"Procedures for absorbed dose to water determination in high energy photon and electron beams by ferrous sulphate dosimeter at INMRI-ENEA"*; Workshop on "Absorbed Dose and Air Kerma Primary Standards" Paris, 9-11 May, 2007

6- A. S. Guerra, C. Caporali, R.F. Laitano, M. Pimpinella: *"Improvements in absorbed dose standards at INMRI-ENEA (Italy)";* Workshop on "Absorbed Dose and Air Kerma Primary Standards" Paris, 9-11 May, 2007

7- M. Bovi, R.F. Laitano, M. Pimpinella, M. P. Toni, F. Arfelli, K. Casarin, D. Dreossi, R. H. Menk, E. Quai, G. Tromba, A. Vascotto: *"Absolute air-kerma measurement in a synchrotron radiation beam by ionizing free-air chamber"*; Workshop on "Absorbed Dose and Air Kerma Primary Standards" Paris, 9-11 May, 2007

8- M. Mancuso, E. Pasquali, S. Leonardi, M. Tanori, S. Rebessi, V. Di Majo, S. Pazzaglia, M. P. Toni, M. Pimpinella, V. Covelli, A. Saran: *"Oncogenic bystander radiation effects in Patched heterozygous mouse cerebellum"*; PNAS (2008) 105:12445-12450; doi:10.1073/pnas.0804186105; http://www.pnas.org/content/105/34.toc

9- M. Bovi, A.S. Guerra, R.F. Laitano, M. Pimpinella, M.P. Toni; *"La metrologia delle radiazioni ionizzanti nell'ambito dell'"European Metrology Research Programme" (EMRP) del 7° Programma Quadro"*; AIRP Convegno Nazionale di Radioprotezione; – Pisa 5-6 giugno 2008

10- M. Pimpinella: *"Metrology for medical applications of ionizing radiation in the framework of the EC-EURAMET Research projects"*; IMEKO TC8 Workshop "Traceability to support CIPM MRA and other international arrangements" Torino, 6-7 Novembre 2008

11- M. Pimpinella: "*Il calcolo Monte Carlo nella metrologia delle radiazioni ionizzanti per radioterapia";* Workshop Nazionale della Rete di collaborazione MARS "Metodi numerici per Applicazioni in Radioprotezione e Sanità", Bologna 3-4 Dicembre 2008

12 S. Baccaro, C. Caporali, A.S. Guerra, R.F. Laitano, A. Pasquali, M. Pimpinella: *"Il campione di riferimento dell'INMRI-ENEA per la dosimetria ad alte dosi in applicazioni industriali"*; - Atti del VI Congresso "Metrologia & Qualità", Torino 7-9 Aprile 2009

13 M. Pimpinella, A.S. Guerra; R.F. Laitano, G. Conte, "*La riferibilità ai campioni primari nella dosimetria in radioterapia con fasci di radiazione a intensità modula-ta (IMRT)"*, - Atti del VI Congresso "Metrologia & Qualità", Torino 7-9 Aprile 2009

14 M. Bovi, R.F. Laitano, M. Pimpinella, M.P. Toni, K. Casarin, G. Tromba, A. Vascotto: *"Misure assolute di kerma in aria del fascio di luce di sincrotrone prodotto presso l'impianto Elettra di Trieste per applicazioni nella diagnostica medica ad alta risoluzione"*;- Atti del VI Congresso "Metrologia & Qualità", Torino 7-9 Aprile 2009

15 M. Bovi, A.S. Guerra, R.F. Laitano, M. Pimpinella, M.P. Toni: *"La riferibilità nelle misure di dose assorbita dal paziente nei trattamenti di brachiterapia",* - Atti del VI Congresso "Metrologia & Qualità", Torino 7-9 Aprile 2009

16- M. Bovi, F. Campanella: *"Specifiche dei "Rapporti di prova" richiesti ai fini autorizzativi per l'impiego delle radiazioni ionizzanti nei luoghi di lavoro"* Atti del VI Congresso "Metrologia & Qualità", Torino 7-9 Aprile 2009

17- 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 2005-2007",* Report CCRI(I)/07-29- CCRI(I), BIPM, Sèvres, 18th meeting 14-16 Maggio 2007

18- G. Qian, S. Baccaro, A. Guerra, L. Xiaoluan, Y. Shuanglong, G. Iurlaro, G. Chen "*Gamma irradiation effects on ZnO-based scintillating glasses containing CeO_2 and/or TiO_2",* Nucl. Instr. Meth. Phys. Res. B 262 (2007) pp.276-280

19- N. Dell'Arena, *"La gestione delle apparecchiature seconda la norma ISO/IEC17025.Utilizzo, identificazione e procedure"*, Tutto_Misure Anno IX n° 1 pagg. 82-83, 2007

20- N. Dell'Arena, *"La gestione delle apparecchiature seconda la norma ISO/IEC17025.Targhetta di conferma e miscellanea"*, Tutto_Misure Anno IX n° 3 pagg. 233-235, 2007

21- N. Dell'Arena, "*Confronto tra le norme ISO 9001, ISO 14001 e ISO 17025 per la gestione di una organizzazione nei riguardi delle problematiche ambientali".* V Congresso Metrologia & Qualità, Torino 14-15 marzo 2007

22- N. Dell'Arena, *"Il rapporto tra cliente e laboratorio nella norma ISO/IEC 17025. Parte II"* Tutto_Misure News Anno IX n° 2 2007

23- N. Dell'Arena, "*Approvvigionamento e subappalto nella norma ISO/IEC 17025. Parte I*" Tutto_Misure News Anno X n° 1 pagg. 4 Aprile 2008

24- N. Dell'Arena, "*Approvvigionamento e subappalto nella norma ISO/IEC 17025. Parte II*" Tutto_Misure News Anno X n° 2 pagg. 8 Luglio 2008

25-. N. Dell'Arena, "*Luogo di lavoro e condizioni ambientali. Attrezzature e condizioni ambientali".* Tutto_Misure Anno X n° 1 pagg. 85-87, 2008

26- N. Dell'Arena, "*Luogo di lavoro e condizioni ambientali. Monitoraggio e controllo delle condizioni ambientali".* Tutto_Misure Anno X n° 2 pagg. 172-174, 2008.

27- N. Dell'Arena, "*Luogo di lavoro e condizioni ambientali. Accesso, utilizzo e buon governo".* Tutto_Misure Anno X n° 3 pagg. 249-250, 2008

28- N. Dell'Arena, "*La norma ISO 17025: Aspetto gestionali e tecnici".* Workshop: La metrologia nell'acustica subaquea. CNR Istituto O.M. Corbino Roma 16 Maggio 2008

29- N. Dell'Arena, "*Campionamento nella ISO/IEC 17025 Parte I".* Tutto_Misure Anno X n° 4 325-326, 2008

30- N. Dell'Arena, "Campionamento nella ISO/IEC 17025 Parte II. Documentazione per il campionamento". Tutto_Misure Anno XI n° 1 pagg. 77-79, 2009

31- M.P. Toni et al, "*The project -Increasing cancer treatment efficacy using 3D brachytherapy- in the framework of the action iMERA-Plus of the European Metrology Research programme*" 2009 Metrology Congress, Paris (Fr), 22-25 June 2009

ANNEX A.3

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

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Mr GL Cappadozzi	gianluca.cappadozzi	4563
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Mr M. Quini (80%)+	maurizio.quini	4563
Mrs C. Silvestri	claudia.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-INMRI staff.

(+) 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 includes the institute management (50%) and the scientific work on dosimetry standards (50%). The activity of N. Dell'Arena deals only with the ENEA-INMRI Quality System.