Report to the CCRI section I on the activity carried out at ENEA-INMRI on photon and charged-particles dosimetry in the period 2011-2013

M.P. Toni, M. Pinto, M D'Arienzo, A.S. Guerra, M. Pimpinella, M. Bovi
Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti
ENEA, C. R. Casaccia
Mailbox 2400, 00100 AD Roma (Italy)

1. Introduction

The present report is a summary of the 2011-2013 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 /** Gy s^{-1}
Air Kerma (and dose-equivalent quantities)	Free-air ion chamber	10-50 kV x-ray	$1\ 10^{-6}$ - $7\ 10^{-3}$
	Free-air ion chamber	60-300 kV x-ray	$7\ 10^{-7}$ - $3\ 10^{-4}$
	Cavity ion chamber	^{60}Co gamma-ray	$2\ 10^{-4}$ - $7\ 10^{-3}$
	Calibrated ion chamber	^{137}Cs gamma-ray	$2\ 10^{-6}$ - $3\ 10^{-4}$
	Calibrated ion chamber	^{192}Ir gamma-ray	≅ $3\ 10^{-3}$
Absorbed Dose to water (external beams)	Graphite calorimeter	^{60}Co gamma-ray	$2\ 10^{-3}$ - $2\ 10^{-2}$
	Calibrated chemical dosimeters	^{60}Co gamma-ray	$8\ 10^{-3}$ - $3\ 10^{-1}$
Absorbed Dose to tissue-equivalent materials (1)	Extrapolation ion chamber	^{147}Pm, ^{85}Kr and ^{90}Sr/^{90}Y beta particles	$3\ 10^{-7}$ - $5\ 10^{-4}$

(1) The working activity with beta particles was temporarily suspended due to shortage of personnel.

2. National Standards Development

The following paragraphs pertain to the standards listed in Table 1 and describe the new activities that were carried out after the latest CCRI(I) meeting (2011). Some essential information regarding the standards are also provided.

2.1 Air-kerma standards

The air-kerma standards at ENEA-INMRI are (see Table I):

1. a parallel-plate free-air chamber for low-energy x-rays;
2. a cylindrical and telescopic free-air chamber (Attix-type) for medium-energy x-rays;
3. a graphite cylindrical cavity ionization chamber for ^{60}Co gamma rays, associated to a group of five chambers of the same type but different in geometry.

A 30 cm^3 ionization chamber (plastic walled) is available as secondary standard for air-kerma measurements with ^{137}Cs gamma rays calibrated by means of a linear interpolation procedure based on the chamber response for the ^{60}Co gamma rays and a 250 keV mean energy x-ray beam.
The above mentioned air-kerma standards also assure the traceability of measurements in terms of dose equivalent quantities in Italy.
A 1000 cm^3 ionization chamber (plastic walled) is also available as secondary standard for air-kerma measurements with ^{192}Ir gamma rays. This standard is currently calibrated against the air-kerma primary standards by means of an interpolation procedure based on the response curve as a function of energy, for several medium-energy x-ray qualities and ^{60}Co gamma rays.

Development on the Italian air-kerma standards

The first two national standards listed in Table I are currently being updated. Specifically, correction factors accounting for the effects attributable to the tungsten aperture diaphragm are being evaluated (Kurosawa and Takata 2005). These effects are estimated by Monte Carlo simulations. The calculations refer to correction factors for photon transmission through the aperture diaphragm (k_{dtr}), photon scatter in the diaphragm (k_{dsc}), fluorescence (k_{dfl}) and bremsstrahlung photons in the diaphragm (k_{dbr}) (see Burns and Kessler 2009 for a description of these factors) using the code PENELOPE 2011 (Salvat *et al* 2011) and an adaptation of the code penEasy (Sempau *et al* 2011). All Monte Carlo calculations are being performed for ideal mono-energetic x-rays with energy ranging from 300 keV to 2 keV, and are under completion. Correction factors for real x-ray beams will be obtained averaging the calculated mono-energetic factors over the actual photon fluence spectra of the beam experimentally determined at the ENEA-INMRI.

2.2 Absorbed dose to water standards (external beams)

The absorbed-dose to water standard operating at ENEA-INMRI (see Table I) is based on a graphite calorimeter and an ionometric transfer system (thick-walled graphite ionization chamber) for ^{60}Co gamma-ray beam.
A transfer standard system based on ferrous sulphate and dichromate dosimeters is also available for measurement at radiation-processing dose levels.

Development in the Italian absorbed-dose-to-water standards

At present, the measurement system associated to the primary standard is being upgraded on the basis of the automated data acquisition and temperature control system already developed for the brachytherapy graphite calorimeter. In particular, the lock-in amplifier of the measuring Weathstone bridges has been replaced by a Keithley 6220 DC precision current source and a Keithley 2182A DC nanovoltmeter. The new system will allow the automatic control of measurements and will likely improve the measurement reproducibility.

3. New Standards under development

The main characteristics of the new standards under development –and not yet commissioned as national standards– at the ENEA-INMRI in the field of radiation dosimetry are reported in Table II.

Table II. New standards under development at ENEA-INMRI in the field of photon and charged particle dosimetry

Quantity	**Standard**	**Radiation quality**	**Measurement range /** Gy s^{-1}	**Status**
Absorbed Dose to water (brachytherapy)	Well-shaped graphite calorimeter	^{192}Ir gamma-ray	2 10^{-3} - 5 10^{-2}	Completed, to be validated
Absorbed Dose to water (brachytherapy)	Large angle and variable volume ion chamber	^{125}I gamma-ray	≤ 5 10^{-5}	Completed, to be validated
Absorbed dose to water (medium energies x-rays)	Graphite calorimeter in water phantom	filtered x-rays, medium energies	2 10^{-3} - 5 10^{-2}	Design in progress
Absorbed Dose to water (Molecular Radiotherapy)	Feasibility study on graphite calorimeter	^{90}Y	to be determined	Study of feasibility

3.1 Absorbed-dose-to-water standards (brachytherapy)

ENEA-INMRI developed two new absorbed-dose-to-water standards for low dose rate (LDR) and high dose rate (HDR) brachytherapy (BT) sources within the framework of the EU joint research project "Brachytherapy" (Ankerhold and Toni 2012). The two standards are fully operational and will be commissioned following successful completion of an international comparison. In this regard the EURAMET Ionizing Radiation Technical Committee accepted the ENEA-INMRI preliminary proposal to organize a comparison for LDR and HDR absorbed dose to water BT standards. At present ENEA-INMRI, NPL and PTB agreed to participate in the comparison for ^{192}Ir HDR BT sources and ENEA-INMRI, LNHB and PTB agreed to participate in the comparison for ^{125}I LDR BT sources. The direct involvement of the BIPM in these intercomparisons will, naturally, be necessary.

3.1.a Low-dose-rate brachytherapy standard

The LDR BT standard LAVV-1 was designed to determine the absorbed dose to water due to ^{125}I LDR sealed BT sources. The standard consists in a large-angle, variable volume ionization chamber in a full scatter graphite phantom that measures the graphite kerma rate $\dot{K}_{g,d}$ at the measurement distance d of about 20 cm from the BT source. A Monte Carlo-based conversion procedure allows to determine the absorbed dose to water at 1 cm from the BT sources, $D_{w,1\,cm}$. All Monte Carlo-based correction and conversion factors were calculated using the EGSnrc code (Kawrakow *et al* 2011). The overall uncertainty associated to the ENEA-INMRI determination of $D_{w,1\,cm}$ was 2.6%, which includes also the type B relative standard uncertainty on the interaction cross sections that are used for the Monte Carlo simulations. Details of the standard construction and some measurement results have been published recently (Toni *et al* 2012).

The realization of the LAVV-1 standard also allowed an experimental determination of the dimensionless dose rate constant Λ_{1cm} traceable to both the $D_{w,1\,cm}$ and the low-energy air-kerma ENEA-INMRI standards (Selbach *et al* 2012). The result for a ^{125}I BEBIG I25.S16.C BT seed is Λ_{1cm} = 1.015 (u = 2.9%). This figure is consistent with the corresponding value derived from the international protocols consensus dataset (Rivard *et al* 2004) Λ_{1cm} = 1.012 (u = 4.8%), with the uncertainty appreciably reduced.

It is worth noting that the figure of the overall uncertainty associated to the LAVV-1 standard includes a rather large standard uncertainty associated to the value of the effective radius of the chamber measuring volume, as determined by mechanical and electrical measurements. A revision of the standard design was done to optimize this issue. The new standard LAVV-2 will allow the reduction of the overall uncertainty associated to the $D_{w,1\,cm}$ determination down to about 2.0%.

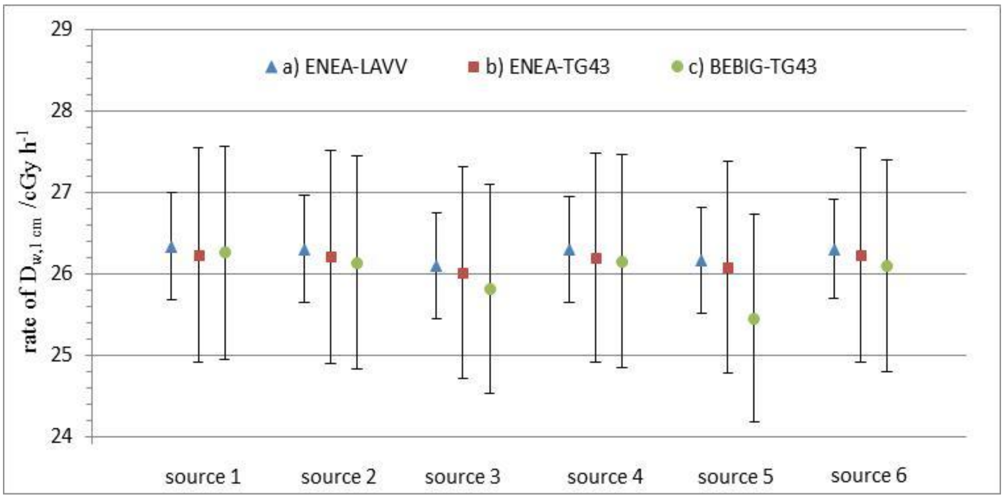

Figure 1. Comparison of three different determinations of $D_{w,1cm}$ obtained - for each of six BEBIG I25.S16.C seeds - by direct measurements with the ENEA LAVV-1 standard (a, u=2.6%, k=1) and by the conversion procedure of the TG-43 protocol applied starting from reference air kerma rate values measured at the ENEA-INMRI (b, u=5.0%, k=1) and values given by the manufacturer (c, u=5.0%, k=1). Reproduced from (Toni *et al* 2012)

3.1.b High-dose-rate brachytherapy standard

The ENEA-INMRI absorbed dose standard for HDR BT sealed sources (e.g. the ^{192}Ir capsules for remote afterloading) is a three-body (core, jacket and medium) portable graphite calorimeter for absorbed dose to graphite measurements. The calorimeter is designed for measuring the absorbed dose to graphite at 2.5 cm distance from the BT source. The calorimeter is inserted in a larger cylindrical graphite phantom having diameter and height equal to 30 cm to achieve the conditions of full backscattering at the measurement point (figure 2).

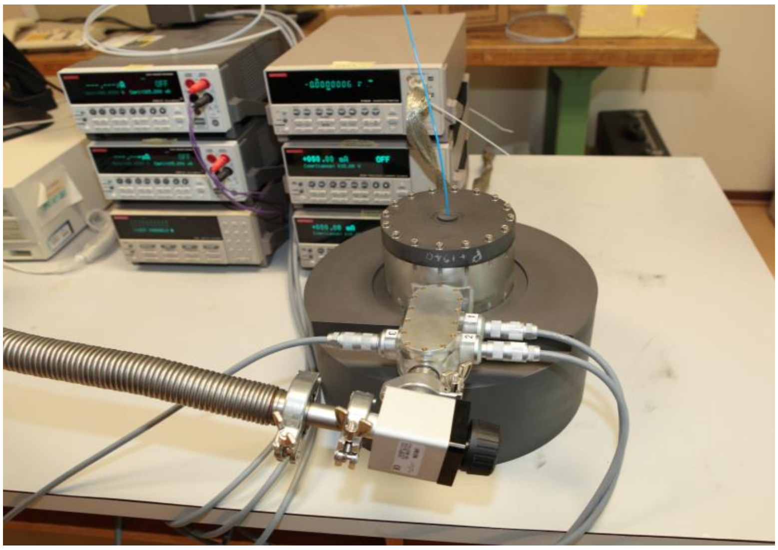

Figure 2. The HDR BT calorimeter embedded in the cylindrical graphite phantom. The phantom has diameter and height equal to 30 cm to achieve the conditions of full backscattering at the measurement point. The measurement system is also shown.

Using Monte Carlo calculations (Kawrakow *et al* 2011), the absorbed dose to graphite at 2.5 cm distance from the BT source is converted into absorbed dose to water at the reference distance of 1 cm from the source.

The correction factors relevant to calorimeter gaps, BT source geometry, finite size of the core, etc., have been also determined by Monte Carlo simulations. Correction factors were evaluated using both standard EGSnrc photon cross sections (Storm and Israel library) and most recent databases, i.e. XCOM and EPDL cross section libraries. The calculations performed indicate that there is almost no dependence on the cross section database used (observed deviations within 0.1%). Adopted Monte Carlo correction factors were determined using the EGSnrc standard library. After the electrical calibration at the ENEA-INMRI, the performance of the calorimeter was tested at the S. Andrea Hospital in Rome (figure 3), where $\dot{D}_{W1cm}$ measurements were executed for a MicroSelectron V2 ^{192}Ir source and compared with the $\dot{D}_{W1cm}$ value derived from reference air-kerma-rate measurements performed with the same source. Figure 4 shows two 120 s typical irradiation runs in the quasi-adiabatic mode obtained during $\dot{D}_{W1cm}$ measurements. The long term stability of the medium (10 hours) was experimentally assessed to be within $\pm 2 \cdot 10^{-4} K$, while the short term stability (20 minutes) resulted below 10^{-4} K. The relative standard uncertainty of $\dot{D}_{W1cm}$ was estimated to be about 1.4%. The absorbed dose rate value obtained from calorimetric measurements was compared with that obtained from RAKR formalism, using the ^{192}Ir dose rate constant, Λ, recommended in the ESTRO database, $1.108 \cdot 10^4$. The two $\dot{D}_{W1cm}$ values were in the ratio 1.005, well within the stated uncertainties. Further, from the experimental determination of *RAKR* for the same source, a value of $1.113 \cdot 10^4 \pm 1.8\%$ was derived for the ^{192}Ir dose rate constant, Λ. This value agrees with the values of $1.108 \cdot 10^4$ and $1.109 \cdot 10^4$ calculated by (Daskalov *et al* 1998) and by (Taylor and Rogers 2008),

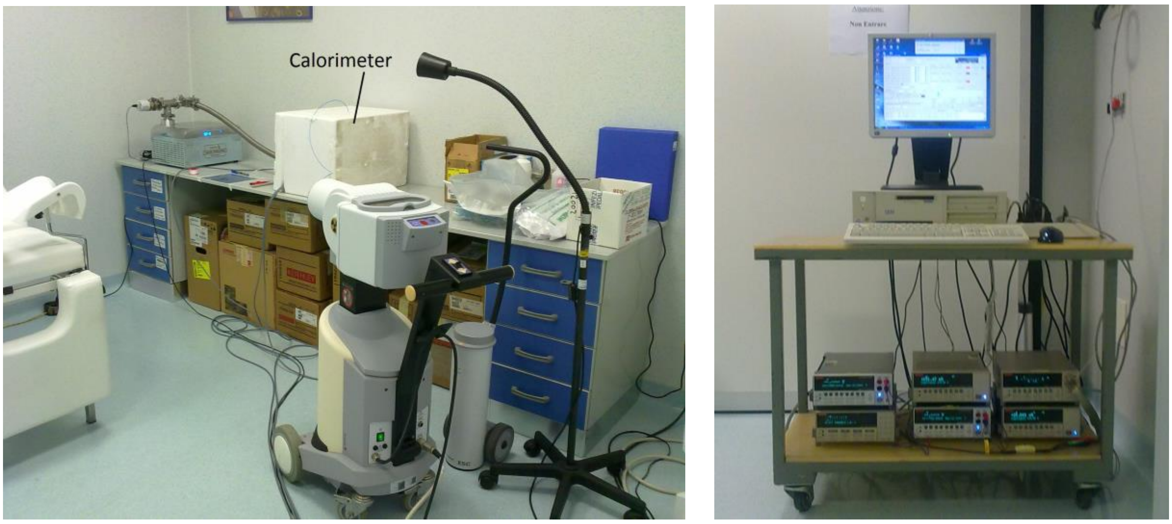

Figure 3. Left) Measurement set-up at the Sant'Andrea hospital for the determination of $\dot{D}_{W1cm}$ for a MicroSelectron V2 ^{192}Ir source. **Right)** Electronic equipment used for $\dot{D}_{W1cm}$ measurements. The calorimeter temperature controller is composed of a switching frame Keithley 7001, two precision Keithley 2400 power supplies. A precision current source Keithley 6220 coupled to a DC nanovoltmeter Keithley 2182A is used for thermistor resistance variation measurements.

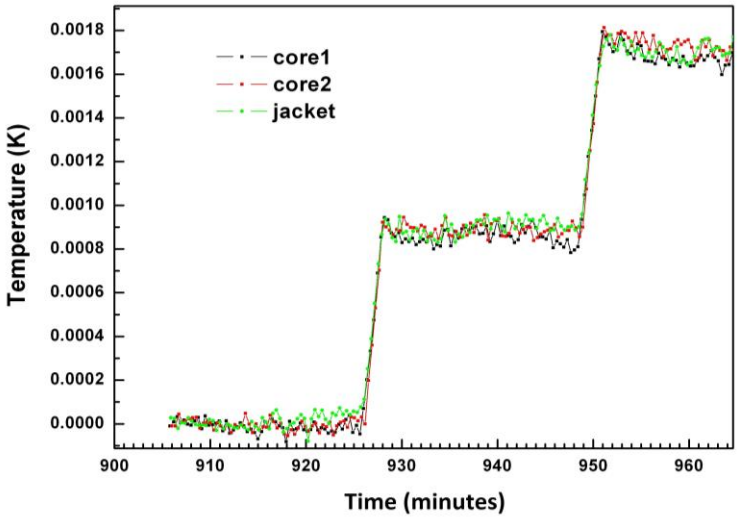

Figure 4. $\dot{D}_{W1cm}$ measurements with an ^{192}Ir Microselectron® HDR V2 source. Two 120 s typical irradiation runs in the quasi-adiabatic mode are shown. A pause of about 20 minutes follows each run.

respectively, and with the value measured by (Sarfehnia *et al* 2010), 1.10· 10^4. Further details of the standard, $\dot{D}_{W1cm}$ measurement results and determination of the dose rate constant Λ for a commercial BT ^{192}Ir seed can be found in (Selbach *et al* 2012, Guerra *et al* 2012).

3.2 Absorbed-dose-to-water standards (external beams)

A new absorbed dose to water standard, based on a miniature graphite calorimeter in a water phantom, is being developed for medium energy x-ray qualities in radiotherapy. This research is co-funded within the framework of the EURAMET EMRP project MetrExtRT (*Metrology for Radiotherapy Using Complex Radiation Fields, http://radiotherapy-emrp.eu/*). The calorimeter has been designed as a three bodies graphite calorimeter embedded in a PMMA envelope allowing for measurements in a water phantom at 2 g cm^{-2} depth (figure 5).

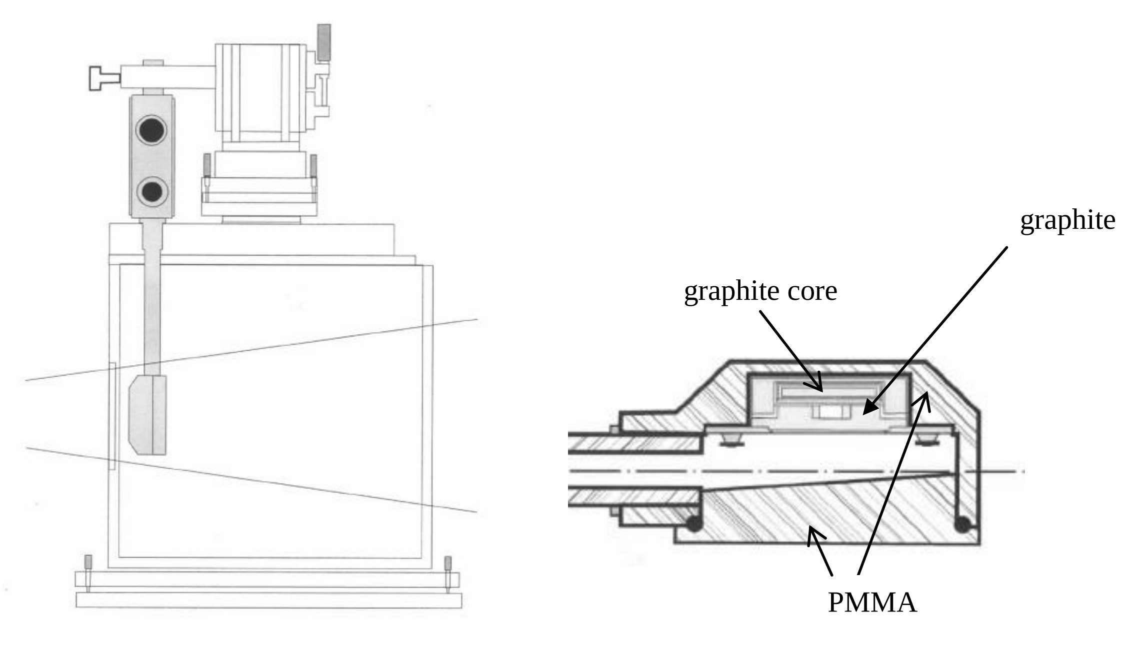

Figure 5. Schematic design, not to scale, of graphite calorimeter for medium energy x-rays under development at ENEA-INMRI. **Left)** The graphite calorimeter in water phantom; **Right)** Section of calorimeter showing design details.

Heat transfer calculations using the finite elements method are in progress in order to optimize the calorimeter design. In the meanwhile, preliminary Monte Carlo simulations have been run using EGSnrc code to evaluate the physical parameters and correction factors needed to convert absorbed dose to graphite into absorbed dose to water. An overall conversion factor is calculated as:

$$C_{w,g}(E) = D_w / D_g$$

where D_w is the calculated absorbed dose at 2 cm depth in homogeneous water and D_g the calculateed absorbed dose in the calorimeter core at the same depth in water. An expression of $C_{w,g}$ as product of specific physical parameters and correction factors determined through independent simulations is under validation. In this regard the mean value of mass-energy absorption-coefficient ratio of water to graphite was determined using the NIST database for mass-energy absorption coefficients (*http://www.nist.gov/pml/data/xraycoef/index.cfm*) and the simulated photon energy spectrum at 2 cm depth in water. Correction factors accounting for perturbation effects due to the presence of all calorimeter non water-equivalent materials, including graphite and vacuum gaps, were determined using DOSRZnrc and FLURZnrc Monte Carlo user codes. All Monte Carlo calculations were performed for ideal mono-energetic x-rays with energy in the range from 200 keV to 20 keV. Correction factors for real x-ray beams can be obtained averaging the calculated mono-energetic factors over the actual photon fluence (Φ) spectra of the beam as:

$$\overline{C_{w,g}(Q)} = \frac{\sum_i C_{w,g}(E_i)\Phi(E_i)}{\sum_i \Phi(E_i)}$$

Conversion factors, $C_{w,g}(E_i)$, ranging from 1.1 to 2.1 were obtained for x-ray energy from 200 keV to 20 keV. The largest contribution to $C_{w,g}(E_i)$ is from the mass-energy absorption-coefficient ratio of water to graphite being in general the overall perturbation correction factor below 5%.

3.3 Absorbed-dose-to-water standards (Molecular Radiotherapy)

Feasibility studies for the development of a primary absorbed dose to water standard for ^{90}Y (used in molecular radiotherapy) are currently being performed within the ongoing MetroMRT EURAMET EMRP project (*Metrology for Molecular Radiation Therapy, http://projects.npl.co.uk/metromrt/project-membership/npl/*). ENEA-INMRI is assessing the feasibility of developing a primary absorbed dose standard based on calorimetry. A draft of the calorimeter has been designed and is currently under study through Monte Carlo simulations. Preliminary results on the feasibility of the standard are expected by summer 2013.

4. International Comparisons

The international comparisons involving the ENEA-INMRI standards of air-kerma and absorbed dose are those listed below. Problems caused by the failure of the medium-energy x-ray tube and of the air conditioning system in the radiation protection level dosimetry laboratories hindered the completion of some of the intercomparisons originally planned. The current status of the intercomparisons is described in parentheses.

1- BIPM-ENEA comparison on absorbed-dose-to-water standards for ^{60}Co gamma rays (results published in 2011).

2- BIPM-ENEA comparison on low energy x-rays (results published in 2011).

3- BIPM-ENEA comparison on medium energy x-rays (started in January 2011 and still ongoing for the aforementioned reasons).

4- BIPM-ENEA comparison on mammography x-rays (started in January 2011 and still ongoing for the aforementioned reasons).

5- ENEA-LNHB-PTB comparison on absorbed dose to water due to LDR BT sources (to be organized in the framework of BIPM and EURAMET by 2013)

6- ENEA-NPL-PTB comparison on absorbed dose to water due to HDR BT sources (to be organized in the framework of BIPM and EURAMET by 2013)

5. Calibration activity

Calibrations of most protection-level and diagnostic dosimeters are traceable to the air-kerma standards for low/medium x-rays and ^{60}Co gamma rays. Calibrations of therapy-level, and industrial-level dosimeters are traceable to the absorbed-dose-to-water (D_w) standard operating at the ^{60}Co gamma ray quality. Calibrations in terms of D_w at low and medium energy x-rays are also available with traceability to the air-kerma standards.

5.1 Protection and diagnostic level calibration service

The dosimeters used in Italy for radiation protection and diagnostic purposes are currently calibrated both at the ENEA-INMRI and at seven secondary standard calibration laboratories accredited by the Italian National Accreditation Body, ACCREDIA. Diagnostic level dosimeter calibrations are made in terms of air kerma. Radiation-protection level dosimeters are calibrated in terms of air-kerma and dose-equivalent quantities. The reference radiation qualities used for calibrations are those internationally recommended.

5.2 Therapy-level calibration service

a) The therapy-level dosimeters used in the Italian radiotherapy centers are currently calibrated at ENEA-INMRI in terms of absorbed dose to water. Calibrations in terms of air kerma are also performed, however most of the customers require calibrations in terms of absorbed dose to water.

b) The service for direct calibration of the customer clinical beam (photon and electron beams) by chemical dosimetry based on ferrous sulphate solution (vial volume of about 1 cm^3) has been provided, as in the past. The service is particularly useful for calibrating electron beams with dose per pulse larger than 10 mGy per pulse as those produced by accelerators dedicated for intraoperative radiotherapy. The D_w measurements are traceable to the absorbed-dose-to-water standard for ^{60}Co gamma radiation.

5.3 Industrial-level calibration service

A calibration service for radiation processing dosimetry (dose levels in the range 5-50 kGy) had been provided by the ENEA-INMRI to industries until June 2012. D_w measurements are traceable to the therapy-level absorbed-dose-to-water standard through a transfer standard system based on ferrous sulphate and potassium dichromate transfer dosimeters. The service has been suspended due to shortage of personnel.

6. Dosimetry methods for radiotherapy beams

The activity related to CVD diamond dosimetry already undertaken in the framework of the EBCT EURAMET EMRP project (Ankerhold and Toni 2012) is being continued both experimentally and by Monte Carlo calculation.

Diamond dosimeters built at laboratories of Rome “Tor Vergata” University have been studied in order to be used as transfer dosimeters for absorbed-dose-to-water measurements in non-reference conditions. (Pimpinella *et al* 2012b). The dosimeters are based on a single crystal diamond detector acting as a Schottky-barrier photodiode with a sensitive volume 2 mm in diameter and 1 mm thick. They can be easily connected to commercial electrometers and automatic water phantom systems currently used for clinical dosimetry. The dosimeters show the best performance when operated in photovoltaic mode (i.e. with no external bias voltage applied).

Several prototypes, differing for minor fabrication details, were tested in the ENEA-INMRI reference ^{60}Co gamma beam. All the dosimeters showed fast dynamic response, linear response with dose and dose rate and long term reproducibility better than 0.5%. In order to use the dosimeter for absolute D_w measurements, energy and field size dependence of dosimeter response has been studied by Monte Carlo simulations in photon beams. Simulations were performed using the *egs_chamber/EGSnrc* Monte Carlo code and the EGSnrc C++ geometry package for modeling the detector including metal contacts, plastic envelope and triaxial cable (figure 6). Photon beams from 6 MV to 24 MV and field sizes from 10 cm x 10 cm to 0.5 cm x 0.5 cm were considered. A maximum variation below 2% in the

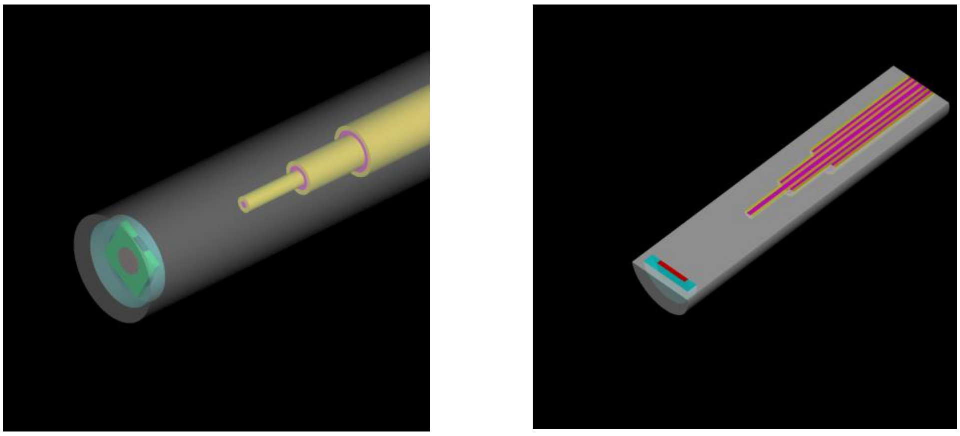

Figure 6. Model of of the diamond detector fabricated at Rome “Tor Vergata” University for Monte Carlo simulations.

dosimeter response in reference conditions (10 cm x 10 cm field size, 10 cm water depth) is observed in the range 6 MV to 24 MV. Monte Carlo calculations also show a dosimeter response independent of field size, within the Monte Carlo statistical uncertainty (0.4%, k=1), from 10 cm x 10 cm down to 2 cm x 2 cm field sizes. For even smaller field sizes the dosimeter response tends to increase giving rise to a significant perturbation. Figure 7 shows beam quality correction factors, k_Q, calculated as

$$k_Q = \left[D_w \middle/ D_d \right]_Q / \left[D_w \middle/ D_d \right]_{Co}$$

where D_d is the absorbed dose in the sensitive volume of the diamond detector at the reference measurement depth in water and D_w is the absorbed dose in homogeneous water at the same depth. The Monte Carlo results were experimentally verified through a comparison of D_w measurements in 6 MV and 10 MV beams by diamond dosimeter with those made using ionization chambers (field size down to 2 cm x 2 cm) and alanine dosimeters (field size 1 cm x 1 cm). Results have been published in (Pimpinella *et al* 2012a, 2012b). All the results demonstrated the feasibility of the use of this type of diamond dosimeter for traceable D_w measurements in radiotherapy photon beams with an uncertainty around 1%. The diamond detector accuracy in measuring D_w in small field sizes is similar to that of alanine dosimeters with the advantage of having a smaller sensitive volume and a real time reading.

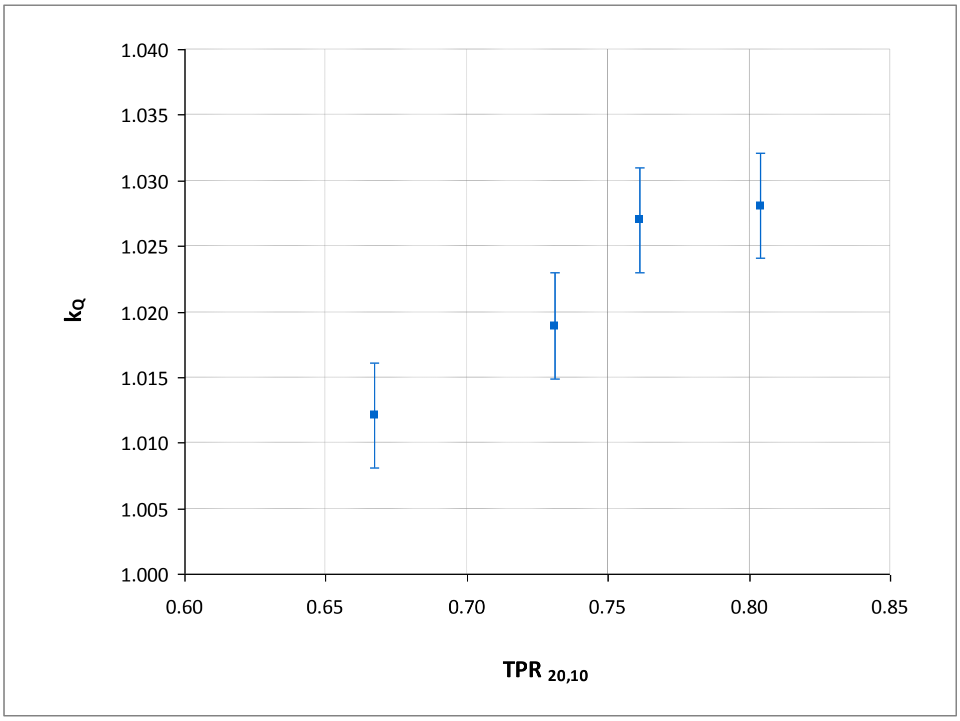

Figure 7. Beam quality correction factors in photon beams determined by Monte Carlo calculations for the diamond dosimeter fabricated at Rome "Tor Vergata" University. The uncertainty bars represent the type A standard uncertainty.

The dosimeter performance in radiotherapy electron beams is under study in the framework of the MetrExtRT project. Measurements of depth dose curves, beam profiles and output factors were performed in clinical electron beams with nominal energy from 6 MeV to 15 MeV and field size from 20 cm x 20 cm down to 6 cm x 6 cm produced, using standard applicators, by an Elekta Precise accelerator available at Rome "Tor Vergata" University. The measurements results from diamond dosimeter were compared to those obtained by ionization chambers and a p-type silicon diode obtaining an overall good agreement among results. In particular diamond dosimeters exhibited a spatial resolution better than ionization chambers and similar to that of the silicon diode (Di Venanzio *et al* 2013). Work is in progress to investigate the dosimeter performance in small and irregularly shaped electron beams and to calculate beam quality correction factors.

Monte Carlo simulations were also performed to study the overall influence of parameters such as diamond thickness, housing material, electrode material and thickness on the response of a generic diamond detector in photon beams. Manuscripts are in preparation.

7. Implementation of the Quality System

All the calibration activities carried out at the ENEA-INMRI are covered by Quality Management System (QMS). The QMS is self declared and was submitted for peer review at November 2012 in the framework of the EURAMET project n.1123. The reviewers assessed both the adequacy of the QMS and its implementation to demonstrate the conformity with the requirements of the CIPM-MRA. A number of findings were raised and actions were agreed to improve the QMS.

8. Participation in metrology and standardisation organizations

The ENEA-INMRI staff is currently involved in activities in metrological and standardisation organisations, including EURAMET, ICRM, BIPM/CCRI, IEC/TC45, ISO/TC85/SC2.

9. References

Ankerhold U and Toni M P 2012 European research projects for metrology in Brachytherapy and External Beam Cancer Therapy *Metrologia* **49** S161–7

Burns D T and Kessler C 2009 Diaphragm correction factors for free-air chamber standards for air kerma in x-rays *Phys Med Biol* **54** 2737–45

Daskalov G M, Löffler E and Williamson J F 1998 Monte Carlo-aided dosimetry of a new high dose-rate brachytherapy source *Med Phys* **25** 2200–8

Di Venanzio C, Marinelli M, Milani E, Prestopino G, Verona C, Verona-Rinati G, Falco M D, Bagalà P, Santoni R and Pimpinella M 2013 Characterization of a synthetic single crystal diamond Schottky diode for radiotherapy electron beam dosimetry. *Med Phys* **40** 021712

Guerra A S, Loreti S, Pimpinella M, Quini M, D'Arienzo M, Astefanoaei I, Caporali C, Bolzan C and Pagliari M 2012 A standard graphite calorimeter for dosimetry in brachytherapy with high dose rate 192Ir sources *Metrologia* **49** S179–83

Kawrakow I, Mainegra-Hing E, Rogers D W O, Tessier F and Walters B R B 2011 *The EGSnrc Code System:* (NRCC) Online: http://irs.inms.nrc.ca/software/egsnrc/documentation.html

Kurosawa T and Takata N 2005 Correction factors for free-air ionization chambers for x-rays transmitted through a diaphragm edge and scattered from the surface of the diaphragm aperture *Report to the CCRI(I)* **05** 1–6

Pimpinella M, Anton M, Rouijaa M and Stravato A 2012a Comparison of Dw measurements by alanine and synthetic diamond dosimeters in photon beams with 1 cm × 1 cm field size *Metrologia* **49** S211–4

Pimpinella M, Ciancaglioni I, Consorti R, Di Venanzio C, Guerra A S, Petrucci A, Stravato A and Verona-Rinati G 2012b A synthetic diamond detector as transfer dosimeter for Dw measurements in photon beams with small field sizes *Metrologia* **49** 207

Rivard M J, Coursey B, Dewerd L A, Hanson W, Huq M, Ibbott G S, Mitch M G, Nath R and Williamson J 2004 Update of AAPM Task Group No. 43 Report: A revised AAPM protocol for brachytherapy dose calculations *Med Phys* **31** 633

Salvat F, Fernandez-Varea J M and Sempau J 2011 PENELOPE-2011: A Code System for Monte Carlo Simulation of Electron and Photon Transport PENELOPE 2011 Workshop, Barcelona, Spain, 4-7 July 2011 pp 1–385

Sarfehnia A, Kawrakow I and Seuntjens J 2010 Direct measurement of absorbed dose to water in HDR [sup 192]Ir brachytherapy: Water calorimetry, ionization chamber, Gafchromic film, and TG-43 *Med Phys* **37** 1924

Selbach H-J, Bambynek M, Aubineau-Lanièce I, Gabris F, Guerra A S, Toni M P, Pooter J de, Sander T and Schneider T 2012 Experimental determination of the dose rate constant for selected 125I- and 192Ir-brachytherapy sources *Metrologia* **49** S219–22

Sempau J, Badal A and Brualla L 2011 A PENELOPE-based system for the automated Monte Carlo simulation of clinacs and voxelized geometries—application to far-from-axis fields *Med Phys* **38** 5887

Taylor R E P and Rogers D W O 2008 An EGSnrc Monte Carlo-calculated database of TG-43 parameters *Med Phys* **35** 4228–41

Toni M P, Pimpinella M, Pinto M, Quini M, Cappadozzi G, Silvestri C and Bottauscio O 2012 Direct determination of the absorbed dose to water from 125I low dose-rate brachytherapy seeds using the new absorbed dose primary standard developed at ENEA-INMRI *Metrologia* S193–7

ANNEX A.1

2011-2013 ENEA-INMRI ACTIVITY REPORT: ARTICLES PUBLISHED IN JOURNALS OR MEETING PROCEEDINGS IN THE FIELD OF PHOTON AND CHARGED PARTICLE DOSIMETRY

Ankerhold, U, Toni, M P, *European Research Projects for Metrology in Brachytherapy and External Beam Cancer Therapy*, Metrologia 49 (2012) S161-S167

Astefanoaei I., Bozan C., Caporali C., D’Arienzo M., Guerra A.S., Loreti S., Pagliari M., Pimpinella M. , Quini M. “Un calorimetro campione in grafite per la dosimetria nella brachiterapia con 192Ir” Presentazione orale VII Congresso Nazionale AIFM, Associazione Italiana di Fisica Medica, Squillace, 13-16 settembre 2011

Anton M., de Carlan L., Guerra A.S., Kapsch R.-P., Pimpinella M. “Capability of different types of dosimeters to ensure measurement traceability in photon beams with small field sizes”, Proceedings of an International Conference “Advanced Metrology for Cancer Therapy”, Braunschweig (Germany), 29th November - 1st December, 2011 PTB-Dos-56 ISBN 978-3-86918-187-5

Anzenberg Shaffer V, Boerma M, Buonanno M, Costes S, Criswell T, Gonon G, Pandey BN, Pinto M, Rockwell S., Broadcasting in the Airways: The Fifth Anniversary of the Radiation Research Podcast, Radiation Research 2012, Jul;178(1):99-100

Bagni O, D'Arienzo M, Chiaramida P, Chiacchiararelli L, Cannas P, D'Agostini A, Cianni R, Salvatori R, Scopinaro F. “90Y-PET for the assessment of microsphere biodistribution after selective internal radiotherapy”, Nucl Med Commun. (2012) Feb;33(2):198-204.

Bovi M., Capogni M, Caporali C, D’Arienzo M, De Felice P, Guerra A S, Pimpinella M, Pinto M, Toni M P, “Ionizing radiation metrology in cancer radiation therapy”, Energia, Ambiente e Innovazione 3/2012 (2012) pp 82-94

Burns D T, Allisy-Roberts P J, Desrosiers M F, Sharpe P H G, Pimpinella M, Lourenço V, Zhang Y L, Miller A, Generalova V, Sochor V, 2011, Supplementary comparison CCRI(I)-S2 of standards for absorbed dose to water in 60Co gamma radiation at radiation processing dose levels, Metrologia 48 (2011) Tech. Suppl. 06009 doi:10.1088/0026-1394/48/1A/06009

Burns D.T., Kessler C., Roger P., Toni M.P., Pinto M., Bovi M., Cappadozzi G., Silvestri C., Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the ENEA-INMRI, Italy and the BIPM in low-energy x-rays, Metrologia, 2011, 48, Tech. Suppl., 06010

Caporali C., Pimpinella M., Stravato A., “Monte Carlo calculation of correction factors for dosimetry in radiotherapy using the correlated sampling method” 1st Annual Conference of the Romanian Society of Hadrontherapy, Predeal, Romania, February 21-24, 2013

Cicone F, D’Arienzo M, Carpaneto A, Russo E, Coniglio A, Bischof Delaloye A, Scopinaro A, “Quantification of dose non-uniformities by voxel-based dosimetry in patients receiving 90Y-ibritumomab-tiuxetan”, Cancer Biother Radiopharm Cancer Biother Radiopharm. 2013 Jan 4

D'Arienzo M, Cicone F, Chiacchiararelli L, Coniglio A, Delaloye AB, Scopinaro F.,”Three-dimensional patient-specific dosimetry in radioimmunotherapy with (90)y-ibritumomab-tiuxetan”Cancer Biother Radiopharm. 2012 Mar;27(2):124-33.

D'Arienzo M, Chiaramida P, Chiacchiararelli L, Coniglio A, Cianni R, Salvatori R, Ruzza A, Scopinaro F, Bagni O, “90Y PET-based dosimetry after selective internal radiotherapy treatments”,Nucl Med Commun. 2012 Jun;33(6):633-40.

D’Arienzo M, Masciullo SG, De Sanctis V, Osti MF, Chiacchiararelli L, Maurizi Enrici R, “Integral dose and radiation-induced second malignancies: comparison between stereotactic body radiation therapy and three-dimensional conformal radiotherapy”, International Journal of Environmental Research and Public Health. 2012; 9(11):4223-4240.

D'Arienzo, M., Chiaramida, P., Chiacchiararelli, L., Salvatori, R., Ruzza, A., Scopinaro, F., Bagni., O., 90Y-PET based dosimetry after selective internal radiotherapy (SIRT) treatments [abstract]. Eur J Nucl Med Mol Imaging. 2011;38(Suppl 2):S93-S228, Birmingham, UK. Annual Congress of the European Association of Nuclear Medicine, October 15-19, 2011 (Selected for congress Highlight - Ranked within the best communications of all submitted papers)

D’Arienzo M, ENEA’s absorbed dose standard for the calibration of 192Ir sources used in high dose rate brachytherapy Trieste, V Alpe-Adria Medical Physics Meeting, 3-5 maggio 2012

D’Arienzo M., Guerra A.S., Loreti S., Pimpinella M., Quini M., Caporali C., “A graphite calorimeter for the measurement of the absorbed dose to water for 192Ir sources used in high dose rate brachytherapy”, World Congress of Medical Physics and Biomedical Engineering, Beijing, China, 26-31 May 2012

D’Arienzo M, “Metrology for Molecular Radiotherapy: an EMRP joint research project” Rome, IFO-IRE, Congress on Modern Clinical Radiobiology, June 7-8,2012

D’Arienzo M, “Dosimetry With ^{90}Y PET After Liver Radioembolization: The Role Of BED And EUD For The Assessment Of Non Uniform Activiy Distributions In Lesions”, [abstract]. Annual Congress of the European Association of Nuclear Medicine, October 27-31, 2012 Milan, IT.

D’Arienzo M, “Emission of β+ Particles Via Internal Pair Production in the 0+ – 0+ Transition of ^{90}Zr: Historical Background and Current Applications in Nuclear Medicine Imaging”, *Atoms*, 2013, 1 (in press)

De Sanctis V, Bolzan C, D'Arienzo M, Bracci S, Fanelli A, Cox MC, Valeriani M, Osti MF, Minniti G, Chiacchierarelli L, Maurizi Enrici R. “Intensity Modulated Radiotherapy in Early Stage Hodgkin Lymphoma Patients: Is It Better than Three Dimensional Conformal Radiotherapy?” Radiat Oncol. 2012 Aug 2;7(1):129.

Di Venanzio C., Marco M; Milani E., Prestopino G., Verona C., Verona-Rinati G., Falco M. D, Bagalà P., Santoni R., Pimpinella M. “Characterization of a synthetic single crystal diamond Schottky diode for radiotherapy electron beam dosimetry”, Med. Phys. 40, 021712 (2013)

Fabbri C, Mattone V, Casi M, De Lauro F, Agostini M, Bartolini N, D'arienzo M, Marchi G, Bartolomei M, Sarti G. “Quantitative evaluation on [90Y] DOTATOC PET and SPECT imaging by phantom acquisitions and clinical applications in locoregional and systemic treatments”, Q J Nucl Med Mol Imaging. 2012 Dec;56(6):522-8.

Filippi L, D’Arienzo M, Scopinaro F, Salvatori R, Bagni O, “Usefulness of Dual Time Point Imaging After Carbonated Water for the Fluorodeoxyglucose Positron Emission Imaging of Peritoneal Carcinomatosis in Colon Cancer”, Cancer Biother Radiopharm. 2013 Jan;28(1):29-33.

Gouriou J, Delaunay F, Le Roy M, Ostrowsky A, Sorel S, Pimpinella M, Guerra A S, Petrucci A “Current photon beams specifiers and small fields”, Proceedings of an International Conference “Advanced Metrology for Cancer Therapy”, Braunschweig (Germany), 29th November - 1st December, 2011 PTB-Dos-56 ISBN 978-3-86918-187-5

Guerra A.S., Loreti S., D’Arienzo M., Pimpinella M, Quini M., Astefanoaei I., C. Caporali, Bozan C., Pagliari M. “A graphite calorimeter as a standard for brachytherapy high dose rate 192Ir sources”, Proceedings of an International Conference “Advanced Metrology for Cancer Therapy”, Braunschweig (Germany), 29th November - 1st December, 2011 PTB-Dos-56 ISBN 978-3-86918-187-5

Guerra A.S., Loreti S., D’Arienzo M., Pimpinella M, Quini M., Astefanoaei I.,Caporali C., Bozan C., Pagliari M. “A graphite calorimeter as a standard for brachytherapy high dose rate ^{192}Ir sources”, Metrologia 49 (2012) S179-S183

Marinelli M., Consorti R., Falco M.D., Milani E., Petrucci A., Pimpinella M., Santoni R., Verona-Rinati G., “Dosimetric characterization of synthetic single crystal diamond diodes for radiotherapy application”, accepted as oral presentation, 2nd ESTRO Forum, Geneva, Switzerland , April 19-23, 2013

Pimpinella, M., Guerra, A.S., De Coste, V., Petrucci, A., Consorti, R.: “Caratterizzazione di due tipi di micro-camere per misure di dose assorbita in radioterapia”, Proceedings of the VII Congress “Metrologia & Qualità”, Turin, Italy, 13-15 April 2011

Pimpinella M., Guerra A.S., De Coste V, Petrucci., A., Consorti R. “Effetti di ricombinazione e polarità in microcamere per la dosimetria di fasci di fotoni per radioterapia” Presentazione orale VII Congresso Nazionale AIFM, Associazione Italiana di Fisica Medica, Squillace, 13-16 settembre 2011

Pimpinella M, Consorti R, Guerra A.S., Marinelli M., Milano E., Petrucci A, Stravato A, Verona-Rinati G, “A synthetic diamond detector as transfer dosimeter for Dw measurements in photon beams with small field sizes”, Proceedings of an International Conference “Advanced Metrology for Cancer Therapy”, Braunschweig (Germany), 29th November - 1st December, 2011 PTB-Dos-56 ISBN 978-3-86918-187-5

Pimpinella M, Kapsch R-P, Stravato A “Experimental determination of kQ factors for a synthetic diamond dosimeter in megavoltage photon beams”, Proceedings of an International Conference

"Advanced Metrology for Cancer Therapy", Braunschweig (Germany), 29th November - 1st December, 2011 PTB-Dos-56 ISBN 978-3-86918-187-5

Pimpinella M, Anton M, Rouijaa M, Stravato A "Comparison of Dw measurements by alanine and synthetic diamond dosimeters in photon beams with 1 cm x 1 cm field size", Proceedings of an International Conference "Advanced Metrology for Cancer Therapy", Braunschweig (Germany), 29th November - 1st December, 2011 PTB-Dos-56 ISBN 978-3-86918-187-5

Pimpinella M., Caporali C., Stravato A., Guerra A.S., "Investigation by Monte Carlo calculation of diamond detector response as a function of photon beam energy and field size", World Congress of Medical Physics and Biomedical Engineering, Beijing, China, 26-31 May 2012

Pimpinella M, Consorti R, Guerra A.S., Marinelli M., Milano E., Petrucci A, Stravato A, Verona-Rinati G, "A synthetic diamond detector as transfer dosimeter for Dw measurements in photon beams with small field sizes", Metrologia 49 (2012) S207-S210

Pimpinella M, Anton M, Rouijaa M, Stravato A "Comparison of Dw measurements by alanine and synthetic diamond dosimeters in photon beams with 1 cm x 1 cm field size", Metrologia 49 (2012) S211-S214

Pinto, M., Toni, M.P., Bovi, M., Cappadozzi, G., Quini, M., Silvestri, C., *"Misura diretta di kerma in aria di riferimento per la caratterizazione di sorgenti di 125I utiizzate per trattamenti brachiterapici in radioterapia"*, Atti del VII Congresso Nazionale AIFM Associazione Italiana di Fisica Medica, 13-16-09-2011 Porto Rhoca - Squillace – Catanzaro

Pinto, M., Bovi, M., Pimpinella, M., Cappadozzi, G., Quini, M., Silvestri, C., and Toni,M.P., *Traceability in terms of absorbed dose to water of low energy and low intensity photon sources used for brachytherapy radiotherapeutic treatments,* World Congress on Medical Physics and Biomedical Engineering in Beijing, China May 26 to 31, 2012.

Selbach H J, Aubineau-Lanièce I, Gabris F, Toni M P, de Pooter J and Sander T, *Experimental determination of the dose rate constant for selected* ^{125}*I and* ^{192}*Ir brachytherapy sources,* PTB report "Advanced Metrology for Cancer Therapy – Proceedings of an International Conference, Braunschweig, November 2011", p. 33, PTB-Dos-56, ISSN 0172-7095

Selbach, H.J., Bambynek, M., Aubineau-Lanièce, I., Gabris, F., Guerra, A.S., Toni, M.P., de Pooter, J., Sander, T, Schneider, T., Experimental determination of the dose rate constant for selected ^{125}I and ^{192}Ir brachytherapy sources, Metrologia 49 (2012) S219-S222

Sipilä P., de Pooter., J., Kapsch R-P., Pimpinella M., Kosunen A., Ankerhold U. "Testing of GafChromic EBT-2 film and diamond detector for IMRT TPS verification", Proceedings of an International Conference "Advanced Metrology for Cancer Therapy", Braunschweig (Germany), 29th November - 1st December, 2011 PTB-Dos-56 ISBN 978-3-86918-187-5

Spadaro S., Trucchi D. M., Conte G., Pimpinella M., Guerra A.S., Laitano R.F., "Dynamic response of diamond sensors to ionizing radiation", Sensors and Actuators A: Physical, 171(1), 2011, 43-47

Spadaro S., Pimpinella M., Guerra A.S., Trucchi D.M., Conte G. “Ottimizzazione del tempo di risposta di rivelatori a diamante sintetico per dosimetria in radioterapia” Poster VII Congresso Nazionale AIFM, Associazione Italiana di Fisica Medica, Squillace, 13-16 settembre 2011

Spadaro S., Conte G., Pimpinella M., Guerra A.S, “Electrical and dosimetric characterization of a CVD diamond detector with high sensitivity”, Radiation Measurement 48 (2013)

Toni M. P., Pinto M., Guerra A.S.., Pimpinella M., Bovi M., Loreti S. “Report to the CCRI Section I on the activity carried out at ENEA-INMRI on photon and charged particle dosimetry in the period 2009-2011”, Report CCRI(I) 11/29- CCRI(I) 20th meeting, 2011

Toni M P, Pinto M, Pimpinella M, Quini M, Cappadozzi G and Silvestri C “A primary standard developed at the ENEA-INMRI to measure the absorbed dose due to low dose rate brachytherapy sources emitting low energy photons, as 125I”, International Congress of Metrology, Paris (France), October 2011

Toni, M P, *The joint research project Brachytherapy to establish a more accurate metrological basis across Europe for absorbed dose determination in radiotherapy brachytherapy treatments,* PTB report “Advanced Metrology for Cancer Therapy – Proceedings of an International Conference, Braunschweig, November 2011”, p. 7, PTB-Dos-56, ISSN 0172-7095

Toni M P, Pimpinella M, Pinto M, Quini M, Cappadozzi G., Silvestri C. and Bottauscio O. “Determination of absorbed dose to water from 125I LDR brachytherapy seeds using the new primary standard developed at ENEA-INMRI”, Proceedings of an International Conference “Advanced Metrology for Cancer Therapy”, Braunschweig (Germany), 29th November - 1st December, 2011 PTB-Dos-56 ISBN 978-3-86918-187-5

Toni M P, Pinto M, Quini M, Bovi M, Pimpinella M, Cappadozzi G., Silvestri C., Quini M., “Traceability in terms of absorbed dose to water of low energy and low intensity photon sources used for brachytherapy radiotherapeutic treatments”, World Congress of Medical Physics and Biomedical Engineering, Beijing, China, 26-31 May 2012

Toni, M.P., Pimpinella, M., Pinto, M., Quini, M., Cappadozzi, G., Silvestri, C., Bottauscio, O., *Direct determination of the absorbed dose to water from* ^{125}*I low dose rate brachytherapy seeds using the new absorbed dose primary standard developed at ENEA-INMRI*, Metrologia 49 (2012) S193-S197

ANNEX A.2

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

Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti
ENEA, C. R. Casaccia
c.p. 2400, 00100 AD Roma (Italy)

Fax: ++39 06 3048 3558
Phone: ++39 06 3048 XXXX
E-mail: username@enea.it

STAFF	E-mail username	Phone extension
Head (Institute director)		
Dr P. De Felice	pierino.defelice	4580
Section co-ordinator		
Dr M. P. Toni	mariapia.toni	3957
Scientists		
Dr M. Bovi	maurizio.bovi	4524
Dr C. Caporali	claudio.caporali	6240
Dr. M D’Arienzo	marco.darienzo	4118
Dr A. S. Guerra	antonio.guerra	3552
Dr S. Loreti (20%)	stefano.loreti	4950
Dr M. Pimpinella	maria.pimpinella	6680
Dr M. Pinto	massimo.pinto	4662
Dr L. Silvi (from Dec 2012)	luca.silvi	3353
Technicians		
Mr GL Cappadozzi	gianluca.cappadozzi	4563

Mrs V. De Coste	vanessa.decoste	3831
Mr M. Quini (80%)	maurizio.quini	4563
Mrs C. Silvestri	claudia.silvestri	3354

Temporary staff		
n.1 Postgraduate fellow	Antonella.Stravato	3437
n.1 Ph.D Student (until Dec 2012)	Stefano.Spadaro	3437

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.