Equivalent detector models for the simulation of efficiency response of an HPGe detector with PENELOPE code

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INTRODUCTION

- Monte Carlo simulation of response of an HPGe detector is a widely used technique to evaluate counting efficiencies.
- It is particularly useful when calibration standards with the same shape and composition of the sample under examination are not available.
- The result of the simulation depends on the more or less detailed knowledge of the characteristics of the detector, able to define a "model" of the same detector.
- To highlight parts not well defined in the manufacturer's certification, a detector X-ray analysis is usually performed, except in cases when it is not possible.

INTRODUCTION

- In this work, in absence of some data on the detector and a being unworkable to perform a X-ray graph, some "equivalent" models have been studied and adopted.
- The main feature was to attribute the uncertainties of the model to only one of the parameters, in this case the dead layer (DL) of the detector, keeping the other data provided by the manufacturer unchanged.
- Adopting this model and using the Monte Carlo PENELOPE code, the efficiency response of a spettrometric system based on an ORTEC GEM-50195S detector, installed inside a "low-background" (LLD) bunker in the Department of Engineering of the University of Palermo, was evaluated.

INTRODUCTION

- A similar activity had already been carried out with the use of the MCNP code (MC N-particle Transport Code) version 5 (Maurotto et al., REDS, 2009), with appreciable results both from the operational point of view and numerical evaluations that can, therefore, be considered a reference point for evaluating the data obtained with the PENELOPE code.
- To compare the results obtained with the two codes, the same HPGe detector of the analysis with code MCNP5 was taken into consideration, i.e. an ORTEC GEM-50195S, keeping unchanged shielding and measurement spectrometric system inside LLD bunker.

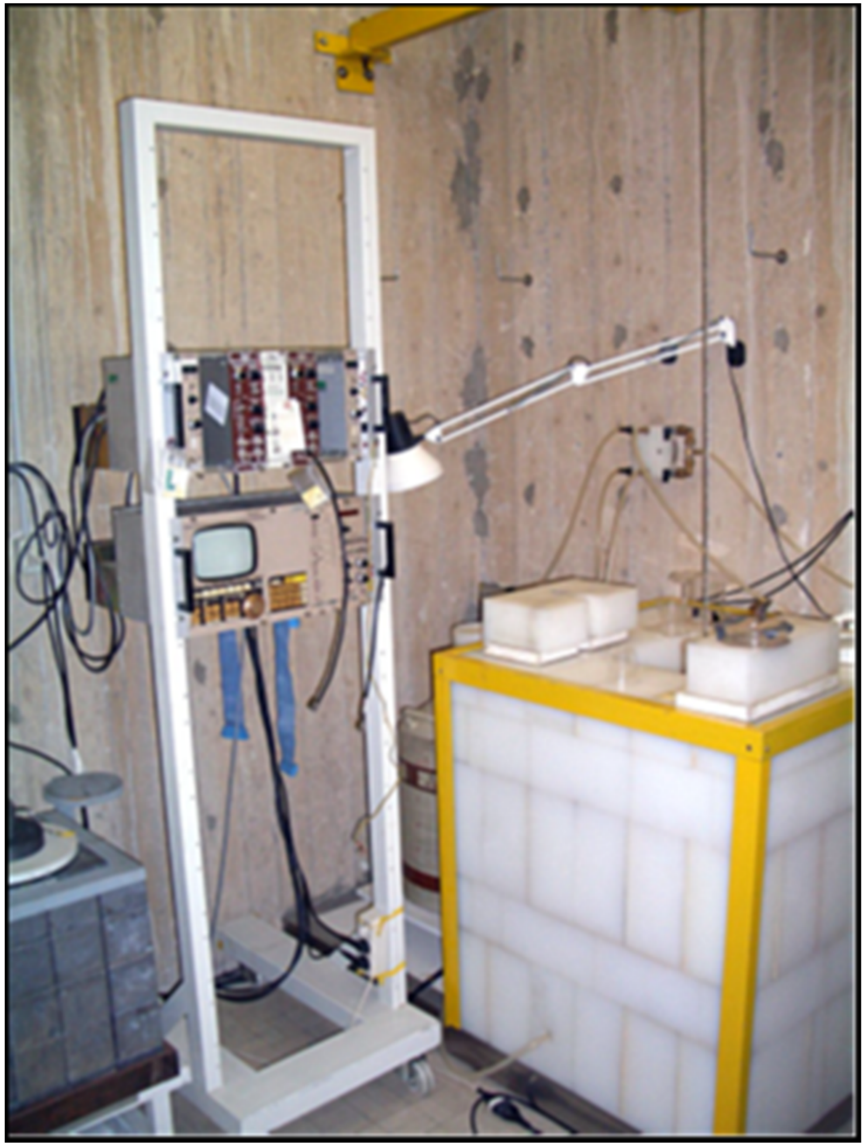
MATERIALS AND METHODS
THE GEM50195S HPGe DETECTOR

- The measuring instrument taken into consideration in this study is a p-type HPGe coaxial detector, with a cryostat in HV (Low Background) configuration, manufactured by ORTEC model GEM-50195S. Germanium crystal has a straight cylinder shape with a diameter of 69.4 mm and a height of 69.3 mm, with a dead layer of about 0.7 mm and a 1.5 mm thick magnesium cap.
- Its efficiency, compared to that of a NaI (TI) 3"x3" crystal at 1.33 MeV for a ^{60}Co source measured at a distance of 25 cm, was 60.8%. The FWHM (Full Width at Half Maximum) at 1.33 MeV results 1.75 keV. The background of the spectrometric system was attenuates to very low levels with the adoption of various levels of shielding.

MATERIALS AND METHODS
THE GEM50195S HPGe DETECTOR

- A first shielding, the innermost one, consists of a rectangular paralpepid made of OFHC (Oxygen Free High Conductivity) copper, 30 mm thick, followed by a second layer of 120 mm thick lead bricks, a third solid HBO_3 shielding with a thickness of 30 mm contained in large Plexiglas boxes, having the function of absorbing the thermal neutrons, and finally a covering in polyethylene bricks of 150 mm of thickness having also the function of thermalizing the fast neutrons associated with the radiation of natural background.
- In order to further attenuate the environmental radiation of cosmic origin and limit as much as possible the temperature changes, the complex is located inside a concrete bunker with walls no less than 70 cm thick, including the roof, with a labyrinth entrance (Cannizzaro et al., NIMA,1997).

MATERIALS AND METHODS
THE GEM50195S HPGe DETECTOR



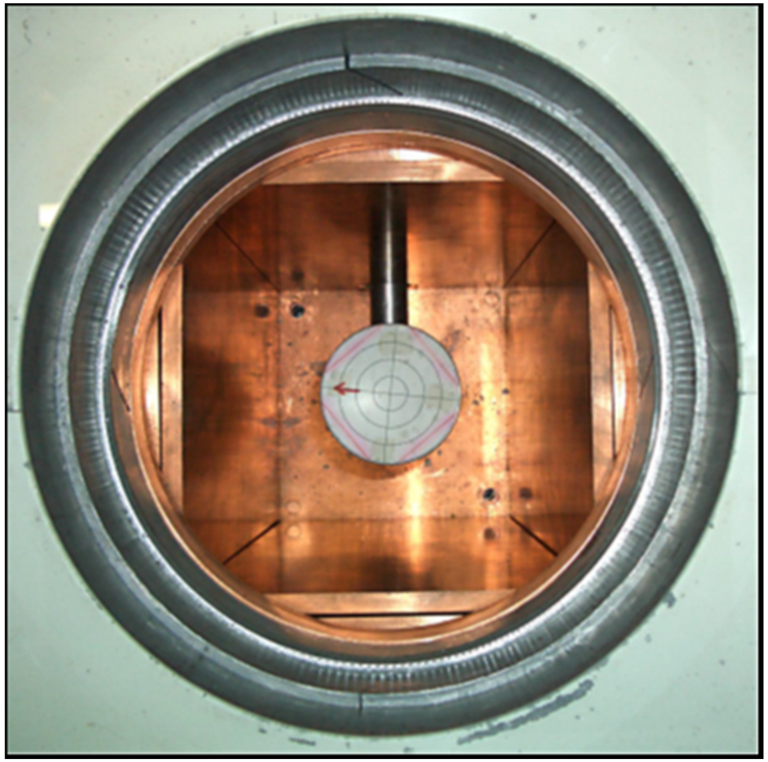


Fig.1 shows a photograph of the Polyethylene detector-shielding complex and the associated spectrometric system units, as well as a photograph of the inside of the measurement cavity with the detector and the OFHC copper coating that acts as attenuation of the fluorescence radiation of lead.

MATERIALS AND METHODS
THE PENELOPE MC CODE

- The code used, PENELOPE (2011 and 2014 versions), was developed entirely in Fortran 77 by Salvat et al. (2011) in order to have a simple, fast and relatively easy to manage tool for the simulation of the interactions of photons and electrons in material systems.
- The interaction models adopted by the program and the associated databases allow the simulation photon transport for energies in the range 1 keV ÷ 1 GeV.
- The program can also be implemented in Windows environment and therefore the most common personal computers can be used, even if the speed of execution of the various routines and associated programs is significantly reduced with simulation times, according to cases, even rather prohibitive.
- For the simulations described in this work, the code was implemented in a Windows environment in a suitable portable PC with a parallel CPU architecture..

MATERIALS AND METHODS
EQUIVALENT MODELS

- In order to elaborate a detector model it is necessary to provide characteristic data of the detector with a good precision.
- Sometimes, despite having the manufacturer's certification, a radiograph of the measuring instrument is used to accurately determine the size of the various constituents and their mutual position.
- Since it is not possible, due to the structure of the shielding described above, to carry out an X-ray of the detector and not knowing with precision some geometrical characteristics of the detector, it was decided to adopt a model of the detector defined by incorporating all uncertainties within the dead layer (Dead Layer, DL), assuming for the remaining parameters the values supplied by the manufacturer.

MATERIALS AND METHODS
EQUIVALENT MODELS

It was decided to use the main program of the code, PENMAIN, which allows to simulate not only the detector and sources but is able to directly output the quantity of our interest, namely the photoelectric efficiency. The modeling of the detector can be easily carried out with the GVIEW2D program, whose results can be appreciated in fig. 2.

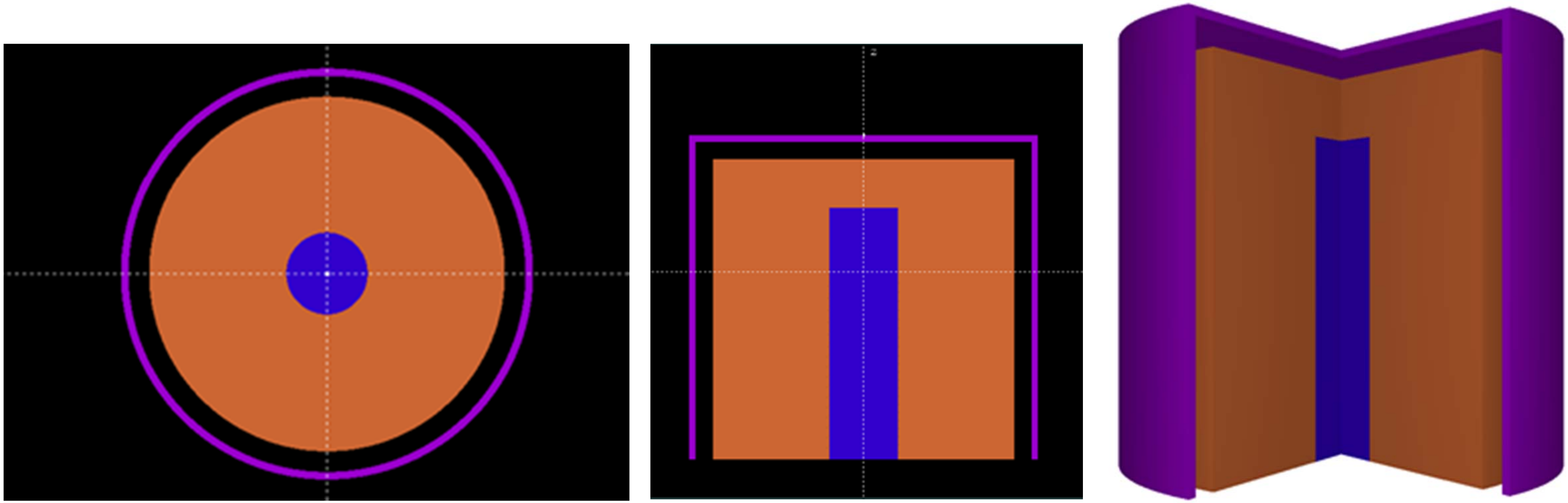


Fig. 2 . Two-dimensional sections and a 3D section of the simulated detector.

MATERIALS AND METHODS
EQUIVALENT MODELS

- The resulting model can therefore be defined as "**equivalent**", since it takes into account the interaction properties of the radiations in the same detector, even though the DL parameter is substantially different from that indicated by the manufacturer.
- The verification of the efficacy of use of this modeling is one of the purposes of the present work.
- For this aim and for the validation of MC models, it is need to have reliable experimental efficiency data obtained from spectrometric measurements of calibrated sources.
- FEPE (Full-Energy Peak Efficiency) efficiency data for point-type gamma sources and for two volumetric sources, the classic 1L Marinelli beaker filled with $CaCO_3$ matrix and the "packet-sample" geometry were available (Tomarchio, 2006, 2013).

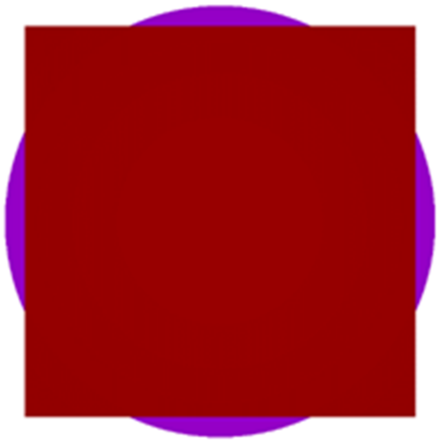
Gamma point sources

- The experimental measurements used to define the models refer to point sources certified by the "Commissariat à l'Énergie Atomique" (CEA) with an uncertainty on activity of less than 2% (1σ).
- These were part of a kit of single-line sources - that is, with a single gamma emission - reliable for determining efficiencies. The sources consist of radionuclides ^{241}Am, ^{109}Cd, ^{57}Co, ^{139}Ce, ^{51}Cr, ^{113}Sn, ^{85}Sr, ^{137}Cs, ^{54}Mn, ^{65}Zn and, in addition, a source of ^{88}Y.
- These sources were measured at different distances in axis from the detector cap up to 30 cm to have a FEPE efficiency data set for point sources.

MATERIALS AND METHODS
CALIBRATED GAMMA-RAY SOURCES

The packet-sample geometry

- Adopted for several years (Cannizzaro et al., 1995.1999, 2004; Rizzo and Tomarchio, 2007, 2013) for the spectrometric measurement of atmospheric particulate filters collected during a night-time air filtration. The cellulose filter, size 45x45 cm, is reduced to 16 strips, stacked and pressed to obtain a "package" of the dimensions 6cmx6cmx0.7cm, named "Packet-sample". Fig.3 shows a section and a top view of the simulation model



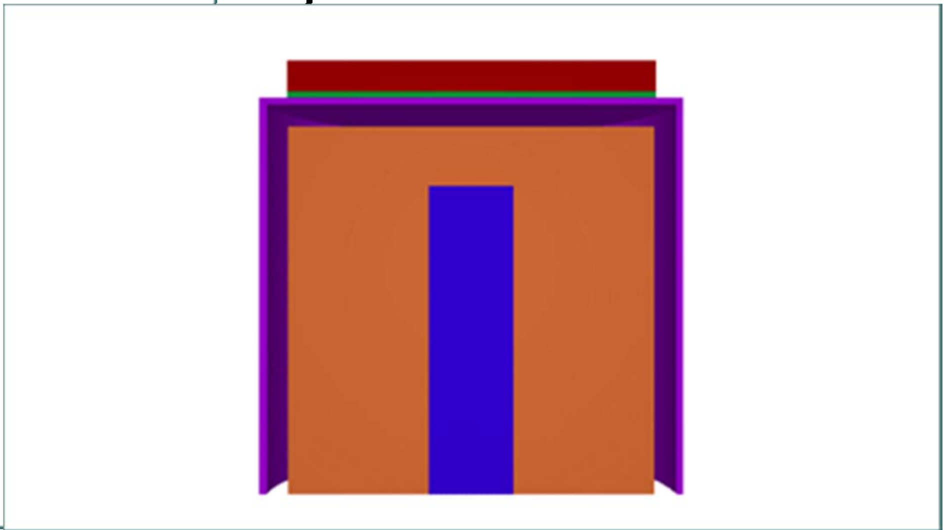


Fig. 3. GVIEW3D representation of «packet-sample» model, including 1 mm of a Plexiglas plate where the filter for the measurement is placed.

MATERIALS AND METHODS
CALIBRATED GAMMA-RAY SOURCES

<u>The Marinelli geometry (1 L)</u>

Other experimental efficiency data were obtained using the known Marinelli geometry (volume 1 L) filled with a pure inert, calcium carbonate, $CaCO_3$, supplied by Merckx with 99% purity, and a small amount of ThO_2.

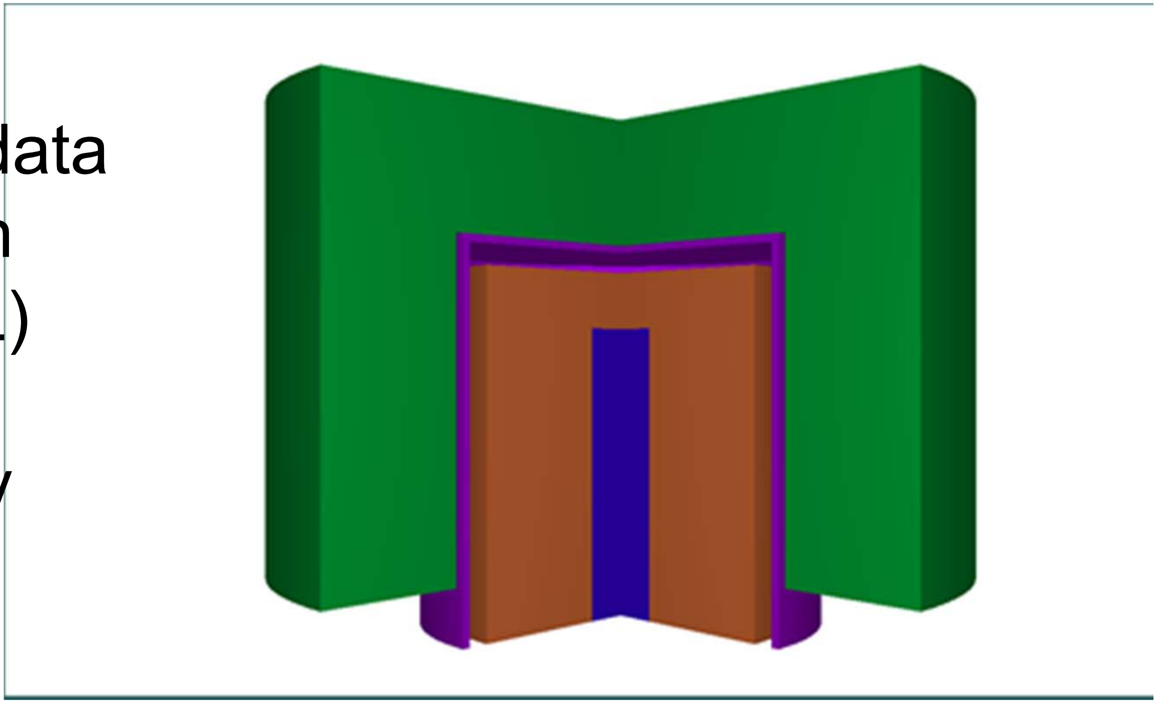


Figura 4 – Section of simulation model: detector and Marinelli beaker.

Fig. 4 shows a 3D section of the configuration of the detector model and of the Marinelli beaker. Details on the preparation of the standards and the results obtained can be found in (Tomarchio, 2006a, 2013).

RESULTS AND DISCUSSION

- Once the detector model was defined, also in comparison with the previous MCNP5 modeling (Maurotto et al, 2009), the simulation results were verified and the equivalent models defined. Fig. 5 shows the experimental trends of FEPE for some measurement geometries for point sources.

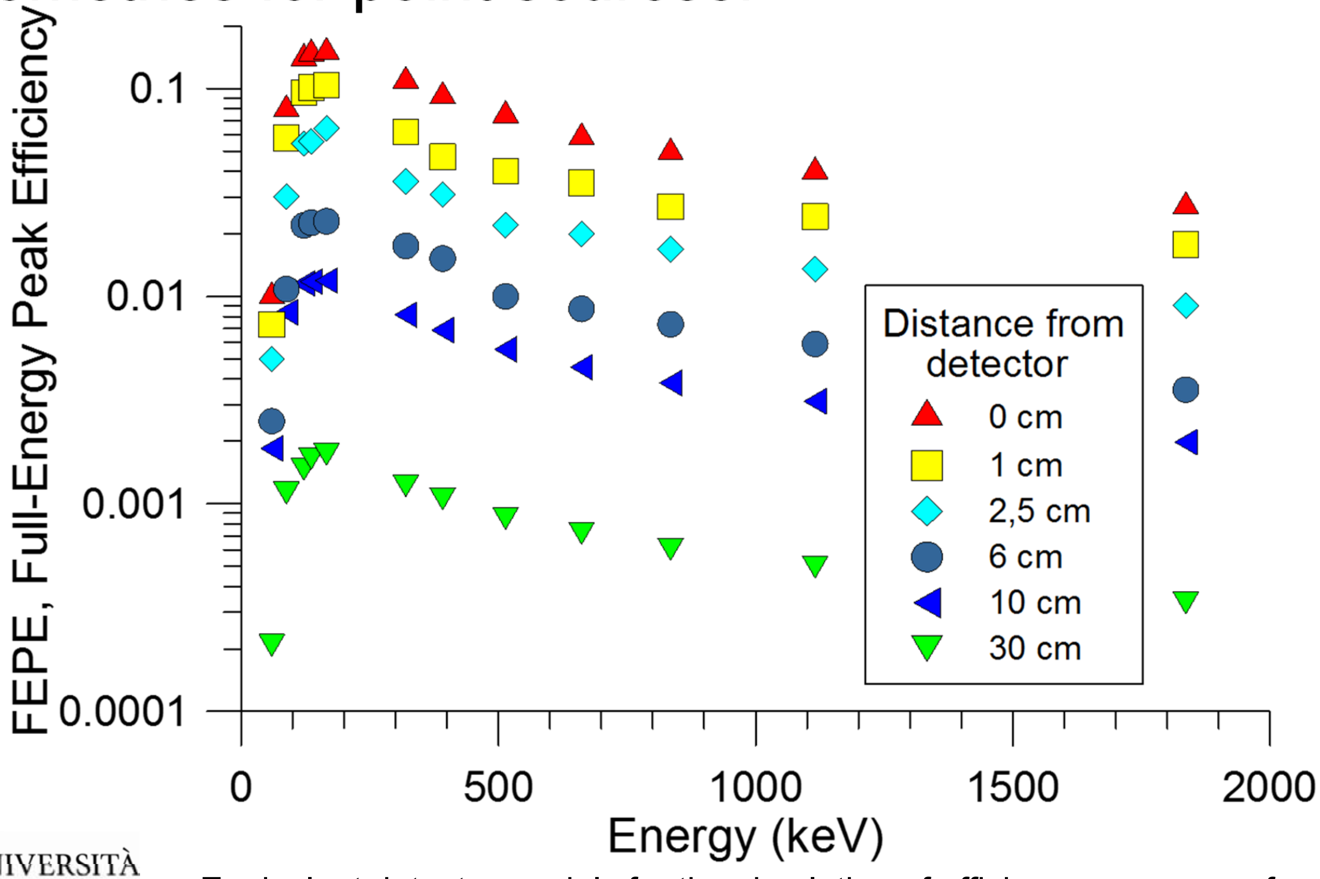


Fig. 5 – Experimental FEPE data for point sources put at different distances from the cap of detector.

RESULTS AND DISCUSSION

- The efficiency values measured at 0 cm (i.e. on the top of the cap), 10 cm and 30 cm were obtained from measurements carried out a few years earlier than those for distance measurements 1 cm, 2.5 cm and 6 cm.
- This can lead to some differences in the assessment of the DL of the equivalent model as will be seen better below. Simulation were carried out for 0, 10 and 30 cm distances, each with a different DL value and, from the comparison of all the results obtained with the experimental data, a possible optimal DL value was identified for the equivalent model equal to 0.23 cm (Figg. 6 and 7).
- This determination was in line with the conclusions reported in (Maurotto et al., 2009) in which the DL value was assumed equal to 0.21-0.22 cm (Fig. 8).

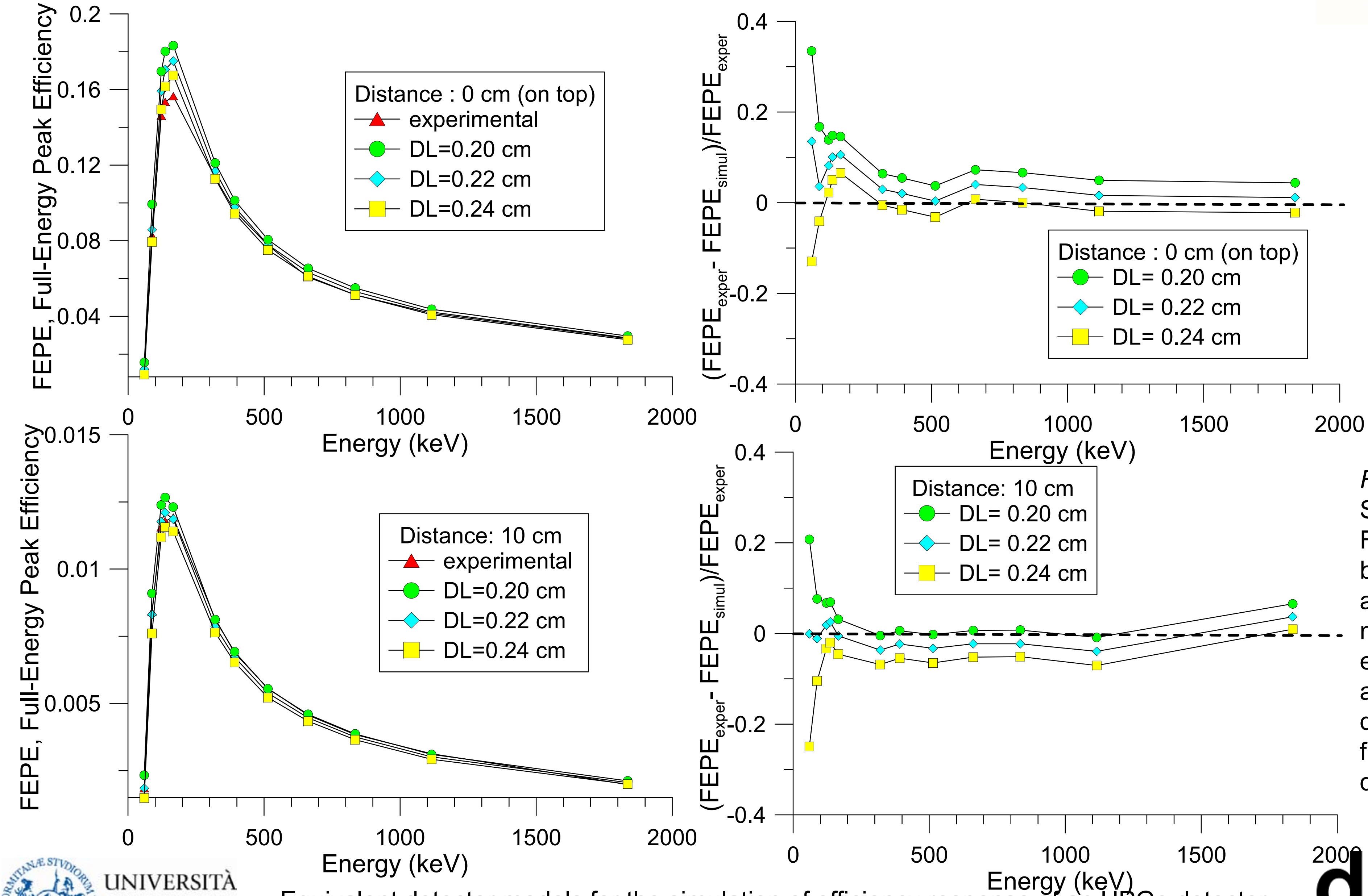
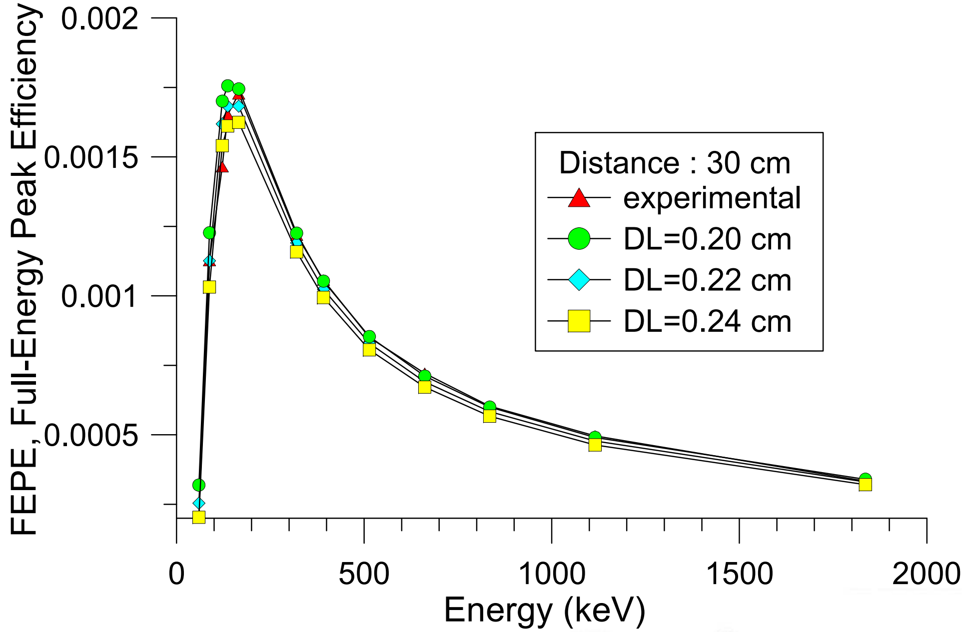


Fig. 6 – Simulated FEPE behaviours and normalized errors for 0, and 10 cm distances from top of detector.



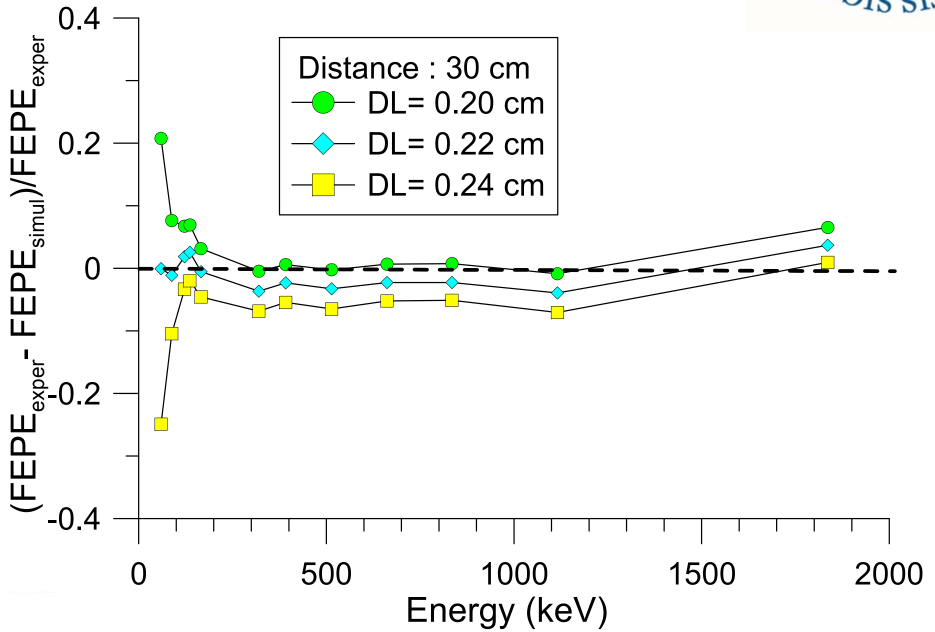


Fig. 7– Simulated FEPE behaviours and normalized errors for 30 cm distance from top of detector.

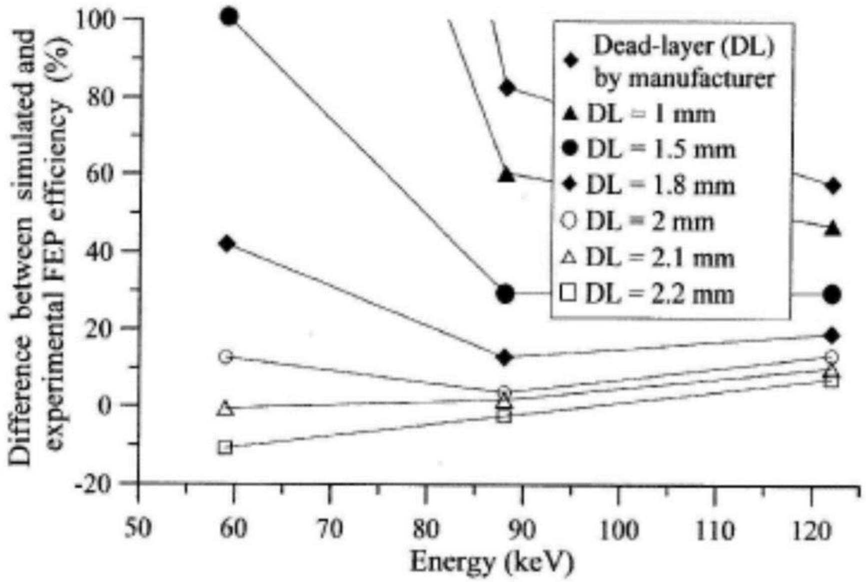


Fig. 8 – Evaluation of DL value with MCNP code performed in 2009.

Maurotto, Rizzo and Tomarchio, Radiation Effects and defects in Solids, 164,5-6 (2009), 302-306.

RESULTS AND DISCUSSION

- Subsequently, for 1, 2.5 ad 6 cm distances, simulations were carried out, with different DL values and, from the comparison of the results obtained with the experimental data, a possible optimal DL value was identified for the equivalent model in about 0.30 cm (Fig. 9).
- This result, a little surprising, leads us to say that the characteristics of the detector have changed in the period of time elapsed between the two set of measurements and that consequently the equivalent model must also change.
- This result leads to affirm, quite logically, that since the characteristics of the detector (but also of the measurement system as a whole) change, both the experimental values of efficiency, the models and the same simulation must be periodically verified and, most probably, re-evaluated.

RESULTS AND DISCUSSION

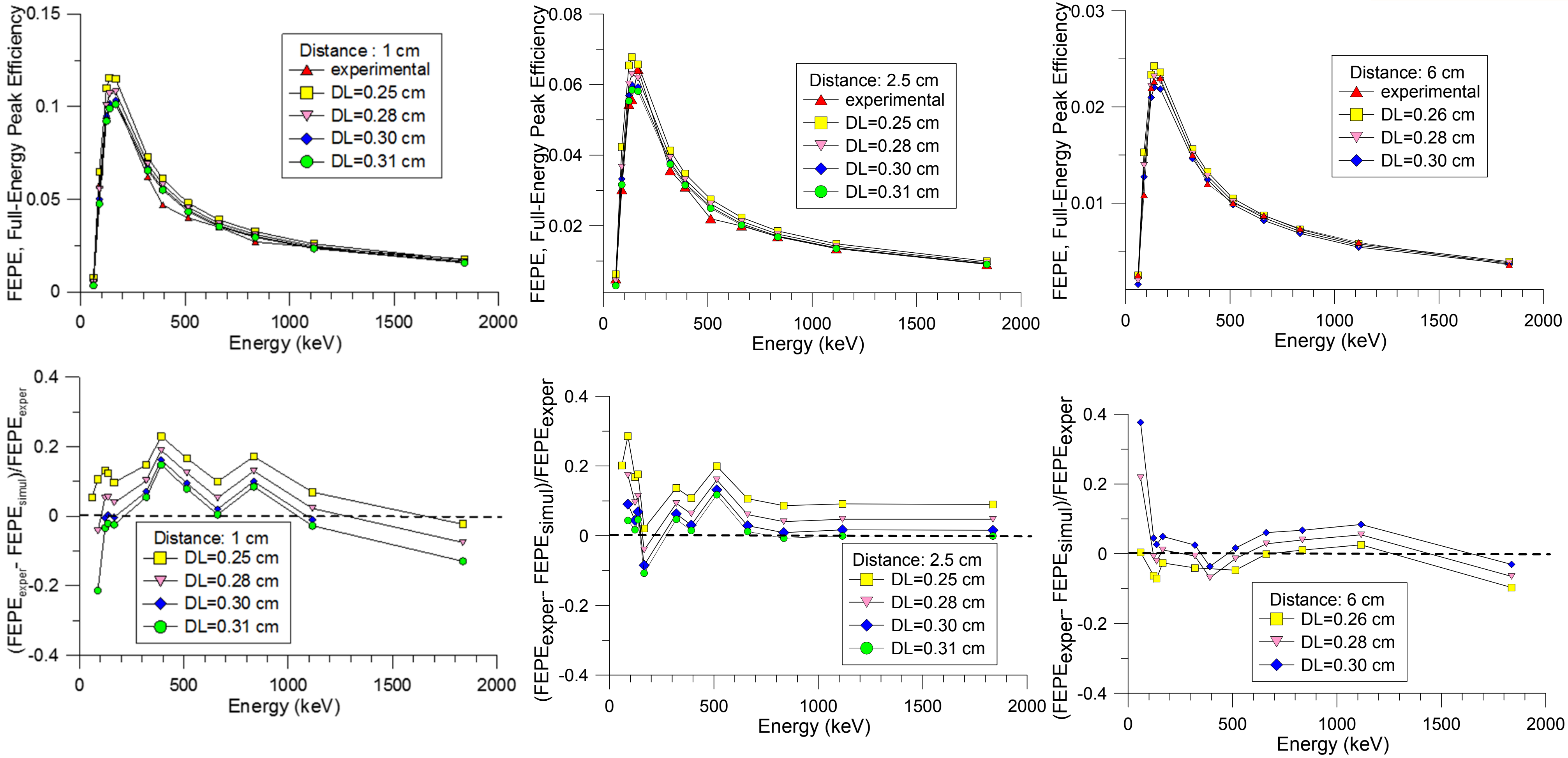


Fig. 9– Simulated FEPE behaviours and normalized errors for 1, 2.5 and 6 cm distances from top of detector.

RESULTS AND DISCUSSION

- After the validation of the simulation code for point sources, we tried to define models to evaluate the detection efficiency for two volumetric sources: the “packet-sample" source and the "Marinelli" beaker source. The results are shown in Fig. 10.
- Even in this case, although it has reported only three values of DL, it seems that the value of DL = 0.40 cm evaluated for the "packet-sample" can also be adopted in Marinelli geometry even with an error of about 10% compared to the experimental values of (Tomarchio, 2006b).
- As can be seen from the exam of the "packet-sample" curves, simulations lead, in the worst cases, to deviations of the order of 20%. This difference is justifiable, in addition to the aforementioned differences in the characteristics of the detector, if taking into account that cellulose was used as the material making up the filter, since the paper, whose chemical composition is rather complex, does not appear among the materials envisaged in the code.

RESULTS AND DISCUSSION

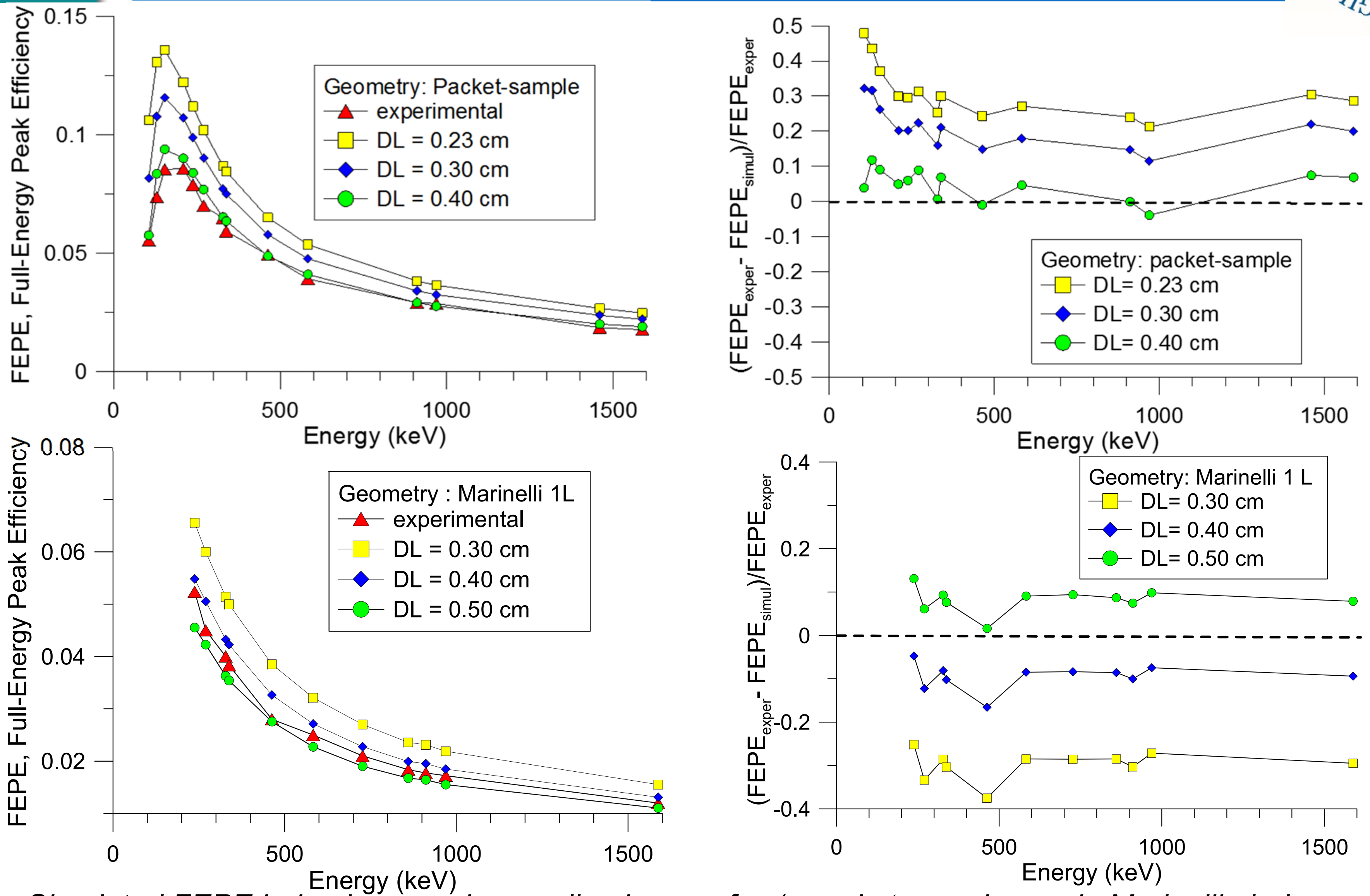
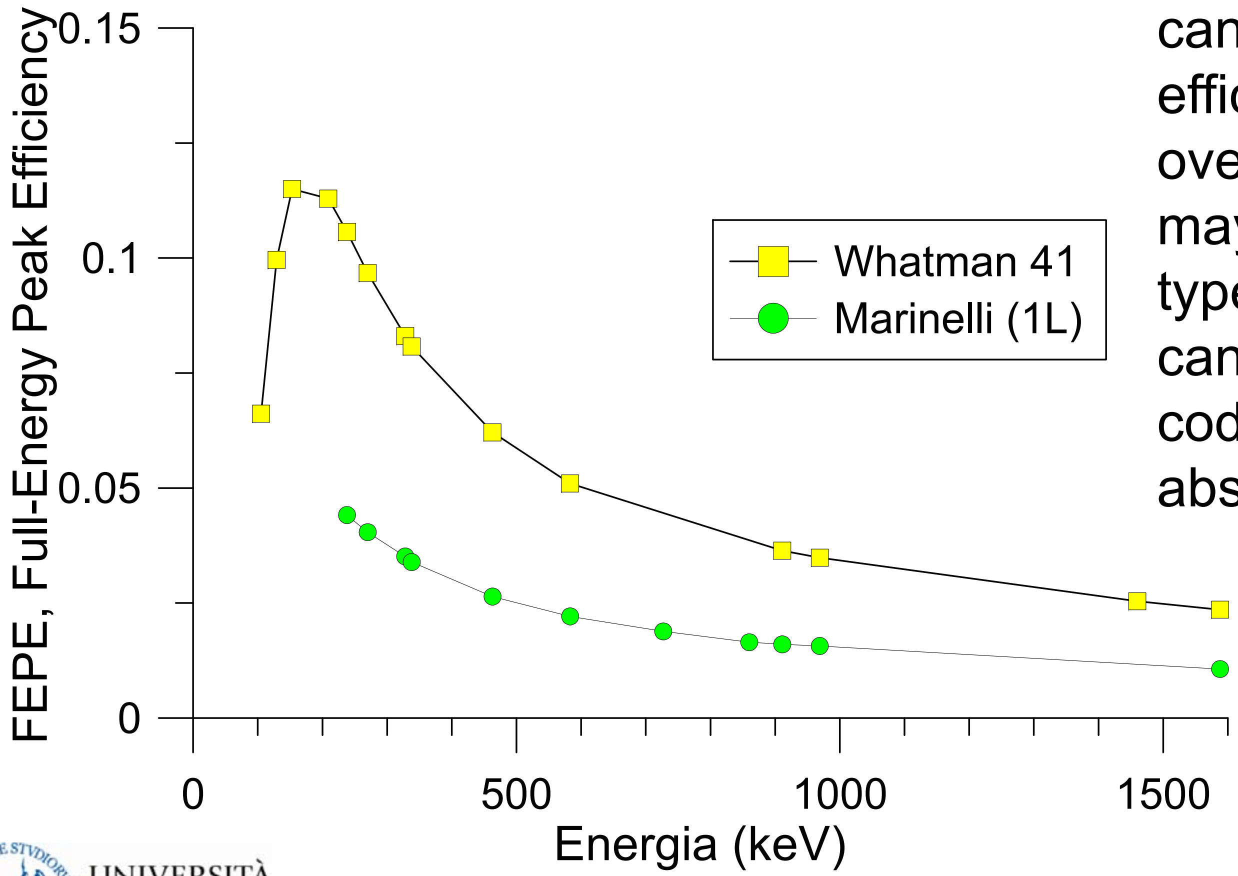


Fig. 10– Simulated FEPE behaviours and normalized errors for 1»packet-sample» and «Marinelli» baker geometries.

RESULTS AND DISCUSSION

Finally, assuming the value DL = 0.40 cm, the efficiencies have been evaluated for a Marinelli container filled with a liquid solution and for the well-known "Whatman 41" filter, a device most used in contamination monitoring (Fig. 11).



With the above considerations, it can be considered that the Marinelli efficiencies are assessed with an overall error lower than 20%, which may be acceptable in relation to the type of measure, and in any case it can be observed that the use of the code allow to evaluate the FEPE in absence of calibrated standards,

Fig. 11 – Simulated efficiencies for a 1 L Marinelli beaker filled with liquid solution and Whatman 41 filter.

CONCLUSIONS

- The use of the PENELOPE code and the equivalent models defined with the comparison with the experimental data, assuming a fictitious value of DL, made it possible to obtain evaluations of efficiencies for the geometries examined with various materials and different densities.
- To evaluate the quality of the simulations performed in this work, a comparison was made between the results obtained with the PENELOPE code and the analogous ones obtained with the code MCNP5, deriving from simulations carried out in a previous work. In this way, it was possible to verify that the evaluations of the two codes are comparable for measurements carried out a few years ago. Moreover, PENELOPE seems easy to implement and quite fast, so that it can be used with a normal “PC", at least for rather simple geometries.

CONCLUSIONS

- Differences were observed with efficiency data obtained from more recent measurements.
- It was possible to verify that the characteristics of the detector actually change over time - as already indicated by the manufacturer - so the models to be used in the simulations for the calculation of the efficiency must be continuously re-evaluated, and the experimental measurements of efficiency they must be periodically repeated also for the same measurement geometry.
- Finally, the use of equivalent models, with the attribution of all the uncertainties of description of the detector on a parameter, makes the modeling itself and the realization of the simulation much simpler.

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THANK YOU FOR YOUR ATTENTION !

QUESTIONS?

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