DUAL ENERGY MATERIAL RECOGNITION: PRELIMINARY RESULTS OBTAINED WITH THE RADIO-TOMOGRAPHIC SYSTEM HOSTED IN MESSINA

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Abstract

Dual energy technique is a very powerful tool for material recognition. It typically involves X-ray energy below 1 MeV, thus limiting to few mm the thickness of the inspected heavy materials. However, it would be interesting to investigate the chance to extend this technique to higher energies, to allow recognition of thick heavy samples too.
Encouraging preliminary tests performed by means of the radio-tomographic system based on a 5 MeV electron linac have suggested to develop a dual energy technique for high energy X-ray beams. This can be done because first experimental tests have confirmed the chance to vary the electron beam energy in a continuous way. As a consequence, bremsstrahlung beams with different end-points can be produced thus allowing to work with different X-ray transmissions. The composition of two different energies X-ray transmission results, allows to perform material recognition.
By means of the MCNP4C2 code, simulations have been performed to evaluate the theoretical X-ray transmission in different materials and thickness. These results allow us to choose two X-ray energies providing the best results in order to perform material recognition.

EXPERIMENTAL SETUP

The work discussed in what follows consists of preliminary results obtained in the framework of the DARMA experiment, supported by INFN.
The X-ray source considered in the experiment has been designed by the INFN - Gruppo Collegato di Messina, basing on the 5 MeV, S-band, electron linac hosted at the Dipartimento di Fisica, Università di Messina, and which main features have been widely discussed in previous papers [1, 2].
Electrons are extracted from the accelerating structure through a 50 μm thick Ti foil, as a focused beam of a 2 mm diameter. The e-γ converter, placed at 2 mm distance from the Ti window, has been entirely designed by means of the MCNP4C2 (Monte Carlo N Particle, version 4C2) code [3] to obtain the highest bremsstrahlung X-ray production [4].
A properly designed collimation system provides a X-ray spot of about 16 cm diameter at the sample position, and a beam aperture of about 3.8 degrees.
For radiographic purposes, the X-ray source has been coupled to an image acquisition system consisting of a CCD camera and a scintillator screen.
A 768x512 pixels resolution, a square pixel of 9x9 μm^2 and a dark current lower than $10pA/cm^2@25^oC$ are the main features of the CCD camera. The screen converting X-rays in visible light consists of a GOS scintillator, 300x400 mm^2 wide and 1.1 mm thick.
In order to preserve the CCD camera from radiation damage, it has been set at a 90° angle with respect to the beam direction, and 100 cm far from the mirror, reflecting the image from the scintillator screen to the camera.

SIMULATION RESULTS

Given the possibility to vary the electron beam energy, a huge simulation work has been performed to evaluate the corresponding bremsstrahlung beams.
The experimental setup has been entirely reproduced by means of the MCNP4C2 code.
Several simulations have been performed to evaluate both bremsstrahlung beams, as produced by the electron linac for different electron beam energies, and the corresponding transmission values through different materials and thicknesses.
As all the Monte Carlo codes, MCNP4C2 requires high computing power and long cpu times which can be successfully reduced by using the code together with the parallel computing environment PVM (Parallel Virtual Machine). At the Dipartimento di Fisica, Università di Messina, MCNP4C2 runs in parallel modality, on a linux cluster accounting for 16 processors.
Bremsstrahlung spectra have been simulated for energies in the range 1.0 to 5.5 MeV, with 500 keV step. The choice of the energy range follows from the results discussed in [5]: these show the chance to produce electron beams with energy up to 8 MeV (not considering power losses) by means of variations of the magnetron power, electron current and other linac parameters.
The simulated spectra have been obtained setting up bins of

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250 keV width. The choice of the bin width is a compromise between the accuracy of simulation results and computing times.
A comparison among the produced bremsstrahlung spectra is shown in Fig. 1. The shown results provide statistic errors lower than a few percent.

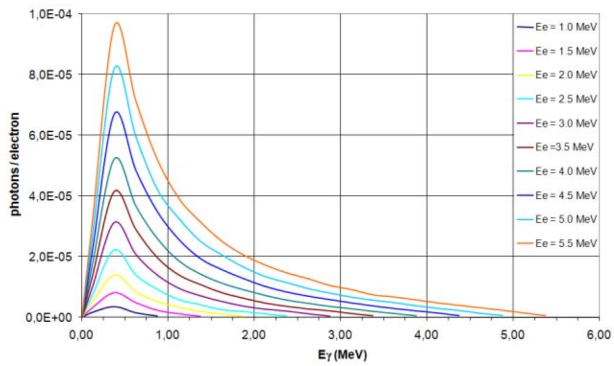

Figure 1: Bremsstrahlung spectra produced by different energy electron beams.

As one can easily see, low energy bins (in the range 250-500 keV) show the highest photon population, whatever the electron beam energy is. This means that although bremsstrahlung spectra with different end-points can be produced, because of the low energy spectrum components, the X-ray transmission is essentially driven by Photoelectric and Compton Scattering processes. In fact, the high energy components, contributing with Pair Production, are characterized by low X-ray fluxes, especially above 2 MeV. The balance between low and high energy components determines the X-ray transmission.
This evidence, typical of a bremsstrahlung spectrum, will be a predominant feature of all our further study, and it has to be taken into account very carefully.
As a further step, simulations have been performed providing the transmission values of all the simulated spectra in different materials.
Our purpose is to investigate Pb, Cu, Al, W, and Fe. The maximum thickness investigated is 10 cm.
For computing time saving reasons, simulations have been thought consisting of two steps. The first one accounts for X-ray production: X-rays are produced in the e-γ converter, then pass through the collimation system and are stored on a surface just behind the second collimator.
The second step accounts for the transport of X-rays collected on the above surface up to the target.
The first step requires long computing times to be simulated, but once evaluated for each energy, it is the same for all the materials to be investigated. On the contrary, the second step is rather quick and strongly depends on the considered material.
Moreover, the two-step method gives the same results of the single step simulations.
For the above simulations, the evaluated transmissions refer to the ideal case of a 100% conversion efficiency screen. These values have to be rescaled for a real case by considering the effective efficiency of the used screen.
In order to choose the best energy values for material recognition purposes, we tried to compose these results thus to obtain useful information. The most significant information we obtained come from the composition of transmission values obtained by considering bremsstrahlung beams produced by 1 and 5.5 MeV electrons.
In Fig. 2 the X-ray transmissions evaluated for 1 and 5.5 MeV end-point bremsstrahlung beams have been composed for Al, Cu and Pb targets and for 2, 4, 6 and 8 cm target thicknesses.

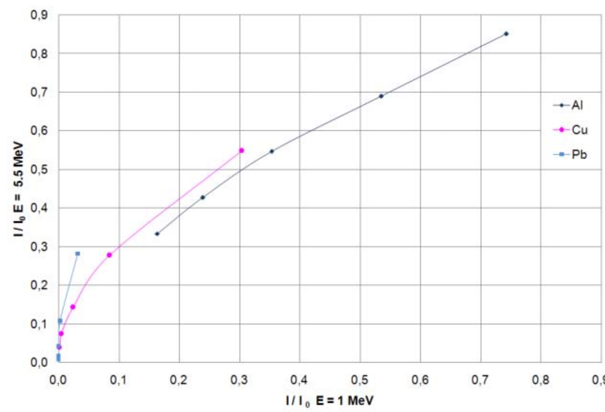

Figure 2: 1 MeV versus 5.5 MeV transmission values.

It seems that by composing transmission values corresponding to the above energies for the investigated thicknesses, it is possible to distinguish different materials.
Nevertheless, an uncertainty still exists due to the short distance among the plotted curves.
Probably, this uncertainty can be overcome in a future step, by attempting to balance in a different way the contribution of the processes determining X-ray transmission; for example by using attenuators acting on the low energy components of the incident spectrum, it is probably possible to enhance the Pair Production contribution and reduce the Photoelectric and Compton Scattering ones. In this way, it would be possible to balance the three effects and modulate the X-ray transmission thus to improve the results showed in Fig. 2.
In Fig. 3 a comparison among non-attenuated and attenuated spectra is shown for different Pb attenuator thicknesses; it is easy to see how a bremsstrahlung spectrum can be strongly modified by the attenuator. In particular, the peak of the energetic distribution moves towards higher energy components as the thickness of the attenuator increases. As a result, the shape of the entire spectrum changes.
At this stage we cannot exclude that these changes will cause a larger distance among curves reducing the uncertainty on material recognition.
Simulations are still in progress to confirm this hypothesis.
Another chance to reduce the uncertainty could be the use of different screens converting X-rays in visible light. The

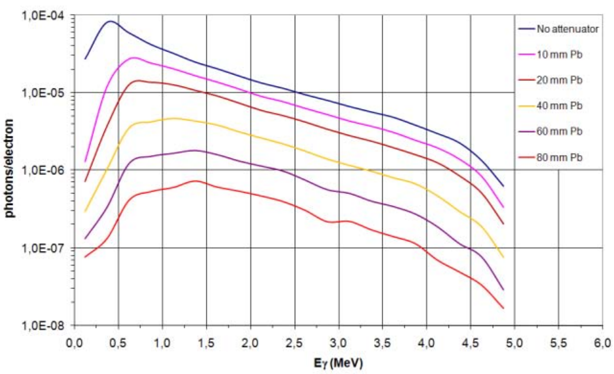

Figure 3: Attenuation of a 5 MeV end-point bremsstrahlung spectrum by a Pb attenuator.

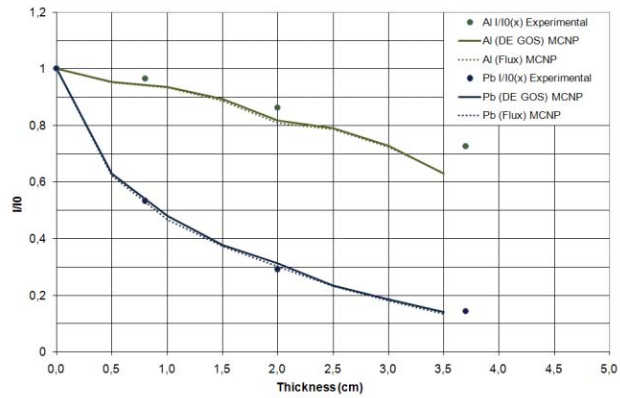

Figure 4: Comparison between experimental and theoretical transmission data.

basic idea consists in the use of two screens which efficiencies differ one each other thus to make a reasonable different selection on the energetic components of the transmitted bremsstrahlung spectra.
Also in this case there is still a lot of work to do.

SIMULATION VALIDITY

What discussed up to now refers to theoretical results which strongly depend on the way the experimental setup is reproduced with MCNP4C2.
To be more confident in simulation results, some radiographic tests have been performed and results have been compared with the theoretical ones.
A sample consisting of Pb and Al ladders, showing steps which thicknesses are 0.8, 2.0 and 3.7 cm, has been investigated.
The experimental setup is the one discussed in this paper and the estimated electron beam energy is close to 5.5 MeV. The digital radiographic images have been properly processed thus to provide the experimental transmission data.
The entire setup has been simulated with MCNP4C2 and two quantities have been evaluated: the photon flux exiting from the steps of the ladders and the energy deposited in the GOS screen. For the last evaluation, the GOS screen has been shaped defining geometric cells reproducing the projection of each step on the GOS and the energy deposition inside them has been evaluated.
In Fig. 4 the comparison between experimental and theoretical data is shown. In particular, the experimental data have been compared with the theoretical transmission data estimated both on photon flux evaluations and on data taking account of the deposited energy in the GOS screen.
As it results from the comparison, a good agreement exists between experimental and theoretical data, although little discrepancies appear for larger Al thicknesses. However, the validity of simulations seems to be confirmed.
A good agreement also exists between transmission data obtained from photon flux and energy deposition evaluations. Note that the photon flux is calculated at the exit of each step of ladders thus not taking into account GOS screen effects. On the contrary, the energy deposition is evaluated in the GOS screen thus taking into account its efficiency. The agreement we observed between these two quantities can be understood looking at the energy spectra of the used bremsstrahlung beam. The high quantity of X-rays in the 100-500 keV energy range, together with the efficiency of such a scintillator screen, causes the coincidence among these results.

CONCLUSIONS

A great simulation work has been done to well characterize the capabilities of the 5 MeV electron linac as a tool to study material recognition at high energy. From the first results it seems that a good separation can be obtained, at least between heavy and light materials. The influence of the bremsstrahlung spectra is evident, and it has to be accurately studied, and eventually modified be means of attenuators. The comparison between theoretical and experimental results seems to be good, but further studies have to be performed. It seems that very promising results could be obtained with our system.

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