GOING TOWARDS THE DUAL ENERGY X-RAY RADIOGRAPHIC SYSTEM FOR MATERIAL RECOGNITION PURPOSES

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Abstract

Non Destructive Testing (NDT) has become the most used technique to inspect objects in order to find manufacturing defects (quality control), investigate contents (custom control), detect damages (structural control).
However, the mono-energetic NDT can only discover a density variation in the analyzed sample, but in most cases no hypothesis can be done on its composition; a complete inspection of an object would require the recognition of the materials composing the analyzed sample, and this can be achieved by means of the dual energy x-ray radiography.
In this context, the INFN - Gruppo Collegato di Messina is planning to implement the radio-tomographic system of the Dipartimento di Fisica, Università di Messina, based on a 5 MeV electron linac, to the aim to provide dual energy x-ray beams for material recognition purposes.
Preliminary caculations have been performed to evaluate the different electron energies obtainable acting on the linac parameters. Moreover, according to a theoretical study on the x-ray transmission for two chosen x-ray energy spectra, the material recognition should be possible by means of the developed radio-tomographic device.

INTRODUCTION

At the Dipartimento di Fisica, Università di Messina, an x-ray radio-tomographic system has been set up by using a 5 MeV electron linac [1] as driving device. The radio-tomographic system has been designed by means of the MCNP4C2 (Monte Carlo N Particle, version 4C2) code [2] thus optimizing all parameters influencing the x-ray production and the beam geometry. Details of the design have been elsewhere discussed [3, 4].
Although the good radiographic results and the chance to inspect inside a sample avoiding destructive actions, the developed system does not allow unambiguous identification of the inspected sample composition.
In Fig.1 the radiography of four ladders consisting of four different materials is shown. Each ladder provides 3 steps which thicknesses change in a logarithmic way. From the left to the right side of Fig.1, aluminum, brass, steel and lead ladders are shown. The thickness is maintained constant going from the left to the right side, and increases going from the top to the bottom of the image (20, 37 and 60 mm).

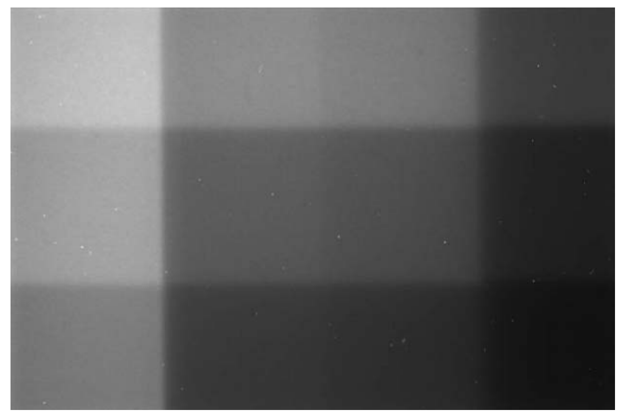

Figure 1: Radiographic image of four ladders consisting of four different materials.

Fig.2 shows the measured mean grey level value (which can be regarded as the x-ray transmission) as a function of the thickness, for each material. The same figure shows the fit of the experimental data, performed by using logarithmic curves.
If no hypothesis can be made on the thickness and the composition of the inspected sample (e.g. the sample is contained in a box), more than one material can be associated to the same mean grey level value.

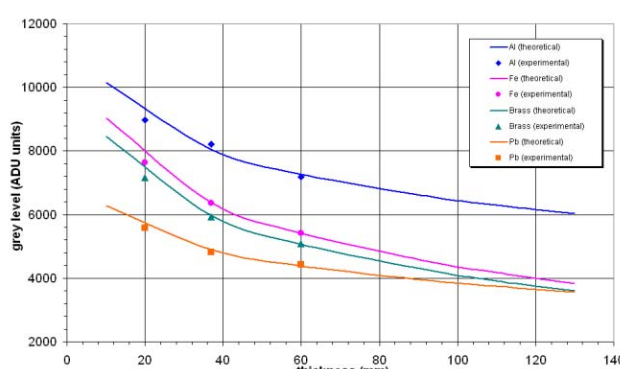

Figure 2: Experimental transmission evaluated from the radiographic image shown in Fig.1.

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In particular, for very little thicknesses, the difference between Fe and Al transmission is very low, thus not allowing the discrimination between heavy and light materials eventually present in the inspected sample.
In order to obtain unambiguous information on the composition of the inspected sample, x-ray beams with different energies, providing complementary radiographic images, have to be used.
For this reason, the INFN - Gruppo Collegato di Messina is looking towards the production of x-ray beams with different end-point energies by acting on the electron linac parameters.

CHANGING THE X-RAY BEAM ENERGY

An electron beam impinging on a suitable target, produces bremsstrahlung x-rays which energy is characterized by a continuous spectrum. The end-point of the spectrum is equal to the electron energy, and the shape is strongly dependent both on the chosen e-γ converter and the electron beam energy.
This basic idea has been used to design the x-ray source based on the 5 MeV electron linac hosted at the Dipartimento di Fisica, Università di Messina.
Main features of the 5 MeV electron linac are summarized in Table 1. The RF power generator is a tunable S-band

Nominal Energy (MeV)	5.0
Structure type	SWOAC
Nominal Peak Current (mA)	200
Operating mode	$\pi/2$
Repetition Rate (Hz)	1-300
N. Accelerating Cavities	9
Pulse duration (μsec)	3
Magnetic Lenses	NO
Peak Power (MW)	1
Length (cm)	40
Average Power (kW)	1
RF Frequency (GHz)	2.997
Beam aperture size (mm)	12

Table 1: Main features of the S-band Electron Linac held in Messina.

magnetron. In the hypothesis to work at a fixed electron beam current, a variation of both the anode voltage and the magnetic field of the magnetron causes a change of the RF output power. As a consequence, a variation of the electron beam energy is achieved.
In particular, the wide range within which the electron current can be varied (1-200 mA), allows to provide a theoretical ΔE of about 2.3 MeV, at a constant magnetron power.
Nevertheless, also the electron beam current can be varied thus allowing to have two free parameters to modulate the electron beam energy.
In the case that both magnetron output power and electron beam current are varied, and supposing to neglect power losses (ideal case), the theoretical electron beam energies can be evaluated for different $P_{out}(magnetron\ output\ power)$ – $I_e(electron\ beam\ current)$ combinations.
Fig.3 shows the calculated electron beam energy as a function of both electron beam current and magnetron output power. Each line in the plot corresponds to a fixed magnetron power. Moving along the same line, the variable parameter is the electron current. It can be seen that the way the electron beam energy varies as a function of the electron beam current is characterized by a linear curve.
Moving vertically along the plot, i.e. at fixed electron current, the electron energy can be varied by modifying the output magnetron power (i.e. switching from a line to another line in the plot). Also in this case a linear trend is observed.
Nevertheless, we are here considering the ideal case where power losses are neglected. Once the real case has to be analyzed, the linear trends could not be linear any more.

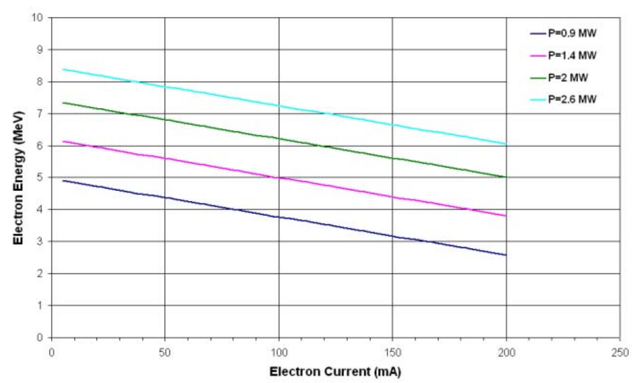

Figure 3: Electron energy plotted as a function of both magnetron power and electron current.

By considering all the possible combinations, theoretical energy values vary from 2.6 MeV, at the minimum magnetron power and maximum electron current, to 8.4 MeV, at the maximum magnetron power and minimum electron current. The theoretical achievable ΔE is about 5.8 MeV.
The range is wide, and an experimental validation of the theoretical calculations is at begin.
Another aspect to take into account is that the accelerating structure of the 5 MeV electron linac has been designed thus to provide the electron beam focusing, as described in [1]. According to the chosen combination $P_{out} - I_e$, the RF frequency has to be adjusted thus to optimize the electron beam focusing. This could be achieved by means of an automatic device, designed *ad hoc* for the used electron linac and activated by a remote control.
Once refined the methodology to change the electron beam energy, x-ray beams showing very different energy spectra can be produced. Nevertheless, the choice of

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the x-ray beam energy is strictly related to the sample to be inspected, and a study of the x-ray attenuation inside materials has to be performed in order to make a proper choice.

THE THEORETICAL APPROACH

As discussed in [5], it would be possible to obtain complementary information by means of the acquisition of two images of the same object at two different x-ray beam energies, E_1 and E_2. Notice that, being available a bremsstrahlung x-ray beam, we will refer to the beam energy as to the end-point of the x-ray energy spectrum.
When a x-ray beam interacts with matter, its attenuation depends on its initial energy and on the atomic number of the element with which the beam is interacting. As a consequence, the x-ray beam with E_1 energy will be attenuated in a different way with respect to the x-ray beam at E_2 energy, when traversing the same sample. The outgoing x-ray beams interact with the scintillating screen which converts the signal into visible light. Two different radiographic images are then generated.
By analyzing these images, it is possible to distinguish, the sample being equal, two different grey level (i.e. transmission) values, each corresponding to an energy value.
By composing the results, and plotting the transmission corresponding to the energy E_1 *vs* the transmission corresponding to the energy E_2, the material composition can be univocally determined.
As discussed in [5], it would be at least possible to discriminate between light and heavy materials.
As an example of the application of the discussed theoretical approach, and referring to the electron energy values we can obtain by properly choosing a $P_{out} - I_e$ combination, the x-ray transmission has been calculated for 1 and 5 MeV x-ray energies. The composition of the two calculated transmissions is shown in Fig.4 for aluminum, iron, lead and concrete.

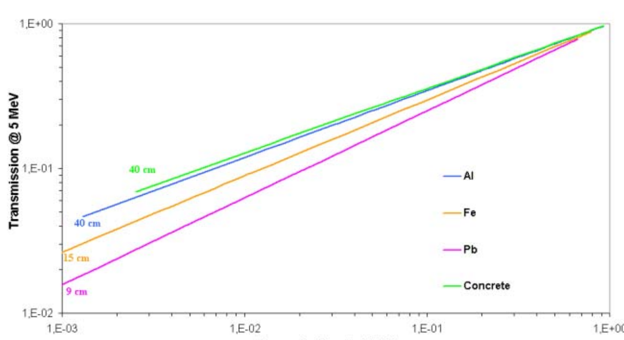

Figure 4: X-ray transmission calculated for 1 MeV and 5 MeV x-ray energies.

Each line in the plot corresponds to a material, and each point on a line identifies a thickness.
Let us consider a sample and suppose to acquire two images of it, one at 1 MeV and the other one at 5 MeV. By analyzing the two images, we register two transmission values. Let us suppose that we obtain $T_{E1} = 1e - 02$ and $T_{E2} = 5e - 02$ values, corresponding to the images acquired at E_1 and E_2 energies, respectively.
These two values univocally identify a line in the plot (the one corresponding to lead) thus providing information on the material composing the sample. Moreover, being the two transmission values also related to the thickness of the identified material, information on the dimension of the sample can be retrieved.
However, looking at the lines corresponding to aluminum and concrete, their very close position in the plot could let to think that, not having any information about the thickness, an ambiguous result could be still obtained. Nevertheless, if we suppose to consider a sample 40 cm thick, two very different (T_{E1}, T_{E2}) sets will be obtained. This is shown in Fig.4, where the two lines corresponding to aluminum and concrete have been terminated for 40 cm thickness and the points in the plot are easily distinguishable.
In conclusion, the ambiguity found analyzing results shown in Fig.2, obtained working at a single energy, seems to be overcome; the combination of the two transmission values univocally identifies the inspected material. As a consequence, it is theoretically possible to distinguish among different materials without introducing any *a priori* hypothesis on the sample.

CONCLUSION

The INFN - Gruppo Collegato di Messina is looking towards the chance to use the assembled radio-tomographic device also for material recognition purposes.
Promising theoretical results, indicating an unambiguous identification of inspected materials, have been obtained.
A lot of work has still to be done to better refine the methodology, to find the proper choice of irradiation parameters according to the sample to inspect, and to experimentally validate the theoretical calculations.

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