A COMPACT 5 MeV, S-BAND, ELECTRON LINAC BASED X-RAY TOMOGRAPHY SYSTEM.

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Abstract

The availability of commercial x-ray tubes made of radiography and tomography two of the most used non-destructive testing techniques both in industrial and cultural heritage fields. Nevertheless, the inspection of heavy materials or thick objects requires x-ray energies larger than the maximum energy provided by commercial x-ray tubes (600 kV).
For this reason, and owing to the long experience of the INFN-Gruppo Collegato di Messina in designing and assembling low energy electron linacs, at the Dipartimento di Fisica, Università di Messina, a 5 MeV electron linac based x-ray tomographic system has been developed.
The x-ray source, properly designed by means of the MCNP-4C2 code, provides a 16 cm diameter x-ray spot at the sample position, and a beam opening angle of about 3.6 degree. The image acquisition system consists of a CCD camera and a scintillator screen.
Preliminary radiographies and tomographies showing the high quality performances of the tomographic system have been acquired. Finally, the compactness of the linac is one of the advantages of this system, that could be used for *in situ* inspections when huge structures have to be tested.

EXPERIMENTAL SETUP

The tomographic system is based on the 5 MeV electron linac designed and assembled by the INFN - Gruppo Collegato di Messina, at the Dipartimento di Fisica, Università di Messina [1]. The accelerating structure is very compact, thus being a promising starting point for the design of a mobile tomographic system for *in situ* inspections.
In Fig.1 the design of a compact linac prototype with the same accelerating structure of the existing linac is shown. Moreover, both electron current and repetition rate can vary within wide ranges, allowing the user to set a variety of different irradiation conditions, thus satisfying the most different experimental requirements.
The Bremsstrahlung source [2], entirely designed by means of the MCNP-4C2 (Monte Carlo N Particle, version 4C2) code [3], has been assembled using a W converter, 1 mm thick, coupled to a 9 mm thick Cu layer, filtering the produced x-ray beam both from primary electrons and low energy x-rays. It has been then coupled to a collimation system, providing an x-ray spot of about 16 cm diameter at the sample position, and a beam aperture of about 3.8 degrees.
The image acquisition system consists of a CCD camera and a scintillator screen.
Main parameters of the CCD camera (Alta Apogee E1) are: 768x512 pixel resolution; 9x9 μm^2 square pixels; low dark current ($< 10pA/cm^2@25^oC$); cooling range of 40^oC below the room temperature. In order to preserve the CCD camera from radiation damage, it has been set at 90 degrees with respect to the beam direction and 100 cm far from the mirror reflecting the image from the scintillator screen to the camera. An alluminated mirror has been used thus reducing image distortion.
A lead glass, 2.5 cm thick, has been inserted between alluminated mirror and CCD camera, to the aim to avoid that spurious x-rays reach the CCD. Lead glass reduces *mottle* in acquired images; in Fig.2 area profiles 1D projections of images acquired with and without lead glass are shown.
Peaks indicate *mottle* corresponding to pixels registering spurious x-rays. Lead glass reduces mottle intensity, allowing the acquisition of images showing low noise level, and the sample reconstruction without artifacts.
As x-rays-to-light conversion device, a GOS or glass scintillator screen has been used, depending on required resolu-

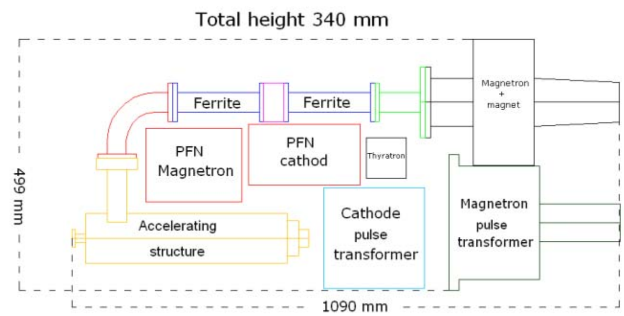

Figure 1: Design of a compact 5 MeV, S-band, 1 kW, electron linac for *in situ* applications.

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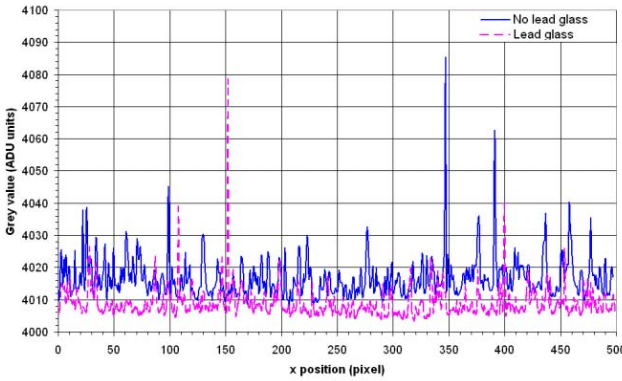

Figure 2: Area profile 1D projections showing the influence of lead glass on mottles reduction.

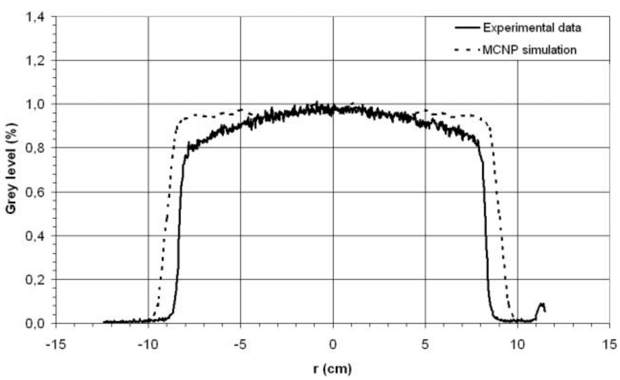

Figure 3: Comparison between the experimental x-ray spot profile and the MCNP simulation.

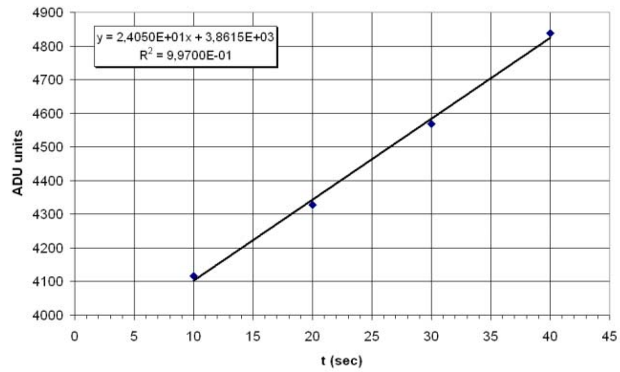

Figure 4: Grey level in ADU units *versus* exposure time showing the linearity of the imaging system.

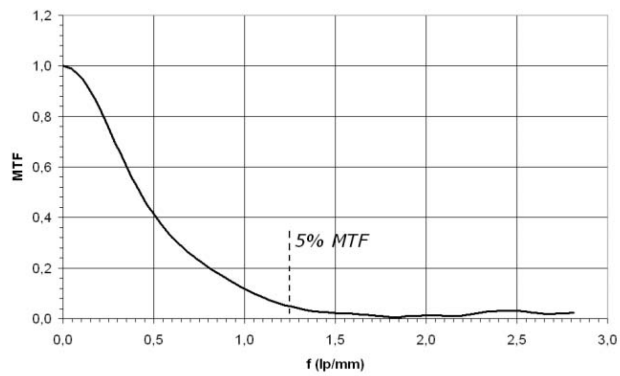

Figure 5: Pre-sampled MTF evaluated with a detection pixel size of $0.175\ mm$.

tion and size of the sample to inspect. The GOS scintillator screen (Inspex HE type, by Applied Scintillation Technologies) is 300x400 mm wide, 1.1 mm thick, and has been coupled to a brass backing, 1.3 mm thick, thus to intensify the light image.
Glass screen is 70x100 mm wide, 20 mm thick, and has been coupled to a micrometric aluminum layer to intensify the produced light. A comparison between the two screen performances has been performed. As a result, the glass screen has provided higher response in light than the one provided by the GOS. Moreover, it shows higher spatial resolution and lower light dispersion if compared with the GOS screen.

SYSTEM CHARACTERIZATION

An acquisition of the x-ray spot has been performed by coupling the CCD to the GOS scintillator screen, thus to view the whole x-ray spot. In Fig.3 the experimental x-ray spot profile is shown, together with the MCNP simulation results.
X-ray spot profile gives information both on the photon flux uniformity overall the spot extension, resulting to be quite good, and on the beam collimation. The detection pixel size has been set at 0.312 mm. This value has been then modified in performing tomographies, according to the dimensions of the sample to inspect.
Linearity of the imaging system has been confirmed by analyzing the grey level value in projections as a function of the exposure time, both for GOS and glass scintillator screens. In Fig.4 the grey level (in ADU units) *versus* the exposure time is plotted for the glass screen. In this study only the exposure time has been varied, while the irradiation parameters have been kept constant.
A measurement of the spatial resolution has been performed by using both the available scintillator screens. Modulation Transfer Function (MTF) has been measured by means of the edge method. The edge device has been chosen as a lead brick which thickness and width were $50\ mm$ and $50x30\ mm^2$, respectively. Lead brick size has been properly chosen according to the x-ray energy thus to produce an image with a sharp dark-to-light ratio.
The edge device has been positioned along the central axis of the x-ray beam and at the sample position, at $250\ cm$ from the beam source.
The Edge Spread Function (ESF) has been then evaluated together with its derivative, thus obtaining the Line Spread Function (LSF) of the edge device. Monodimensional MTF has been computed as the Fourier Transform of LSF. Fig.5 shows the pre-sampled MTF evaluated for the glass scintillator. The detection pixel size is of $0.175\ mm$ and, for a $1.25\ lp/mm$ frequency value, MTF drops to 5% its maximum value.

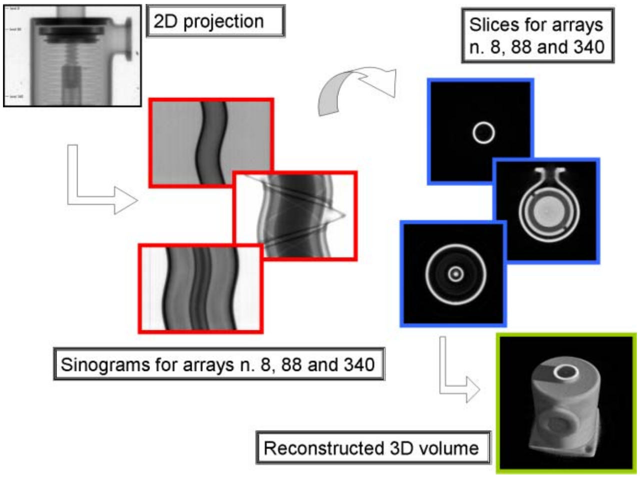

Figure 6: A schematic representation of the 3D image reconstruction procedure.

Figure 7: The 3D visualization of the reconstructed sample.

PRELIMINARY TOMOGRAPHY

Many preliminary radiographies [2, 4] have been acquired to evaluate spatial resolution for different screens, limits in inspecting heavy materials, influence of the coarseness of available screens on the image quality, optimal exposure level for high contrast and quality images.
Analysis of these images allowed us to choose the best experimental conditions to perform a steel vacuum valve tomography. The electron current and repetition rate have been set at $80\ mA$ and $3\ Hz$ respectively. Due to its best performances in spatial resolution if compared to the GOS screen, glass scintillator has been chosen as x-to-light scintillator screen. This choice is also related to the valve dimensions and the need of a small detection pixel size.
The sample has been positioned on a micrometric rotation stage along the central beam axis. A set of 360 2D projections have been acquired, by changing the sample position of 1 degree at each 2D projection acquisition.
After a dark current subtraction and image calibration, images have been processed by means of the Octopus reconstruction software [5], which takes also into account beam hardening correction.
A schematic procedure to reconstruct the sample is shown in Fig.6. The *n* 2D projections are processed by the reconstruction software. According to the sample size and CCD viewing field, images are resized thus to allow the software to make a faster reconstruction. A normalization and a subtraction of noise is performed overall the images set. For each pixel array, sinograms are evaluated, thus allowing the determination of the corresponding slice. An analysis of the reconstructed slices allow the user to find defects inside the sample and locate them with high precision. The slices overlap generates the 3D sample image.
Due to the shape of the sample basis, the valve moved during the image acquisition thus requiring a tilt correction of about 0.5 degree during the reconstruction process. A 357 pixel wide window has been considered for reconstruction.

Fig.7 shows the reconstruction result. All the valve inner details are visible (screw threads, stainless steel flexible pipe) with high definition. Moreover, by the correspondence pixel-to-mm, the valve inner structure can be exactly reconstructed.

CONCLUSION

A compact tomographic system has been assembled at the Dipartimento di Fisica, Università di Messina, by the INFN - Gruppo Collegato di Messina. It is based on a 5 MeV, S-band, 1 kW, electron linac, which size can be furtherly reduced by means of the use of new generation components. Such a project makes the system suitable for *in situ* inspection of big structures. Preliminary tomographies of samples which cannot be inspected by commercial x-ray tube based radiographic systems, show the high quality performances of the developed device.
Work is in progress in order to improve spatial resolution, x-ray-to-light conversion, heavy and thick material detail inspection, exposure time.

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