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X-ray characterization of a table-top synchrotron light source

M. Gambaccini(*), A. Taibi, P. Cardarelli, G. Di Domenico,
M. Marziani and E. Mastella

Dipartimento di Fisica, Università di Ferrara and INFN, Sezione di Ferrara
via Saragat 1, 44122 Ferrara, Italy

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Summary. — An accurate characterization of hard X-rays emitted from thin targets, irradiated by electron beams circulating in the MIRRORCLE storage ring was performed. MIRRORCLE is a table-top synchrotron light source being investigated within an EC funded project named LABSYNC. Simulation of X-ray imaging performance of the novel source showed that physical image quality is similar to a conventional X-ray source for mammography when the X-ray emission is viewed from an output port antiparallel to the direction of the incident electron beam. Furthermore, to evaluate the potential of the MIRRORCLE system for medical imaging applications, a set of measurements were performed at the Photon Production Laboratory (Japan). By means of calibrated thermoluminescent dosimeters (TLD) the average electron beam current circulating in the storage ring was also calculated. It was demonstrated that the available current is not sufficient at this stage for clinical applications. Finally, X-ray images of known details were obtained for different wire targets. From these measurements an evaluation of the electron beam size was performed. Results suggested that the cross-section of the electron beam circulating within the storage ring is about 6 mm.

PACS 07.85.Fv – X- and γ-ray sources, mirrors, gratings, and detectors.
PACS 87.59.-e – X-ray imaging.

1. – Introduction

An accurate characterization of hard X-rays emitted from thin targets, irradiated by electron beams circulating in the MIRRORCLE storage ring [1, 2] was performed within the EC funded project Labsync [3]. Description of the project and details of the MIRRORCLE X-ray source have been reported in the Proceedings of the Channeling 2008 Conference [4].

(*) E-mail: gambaccini@fe.infn.it

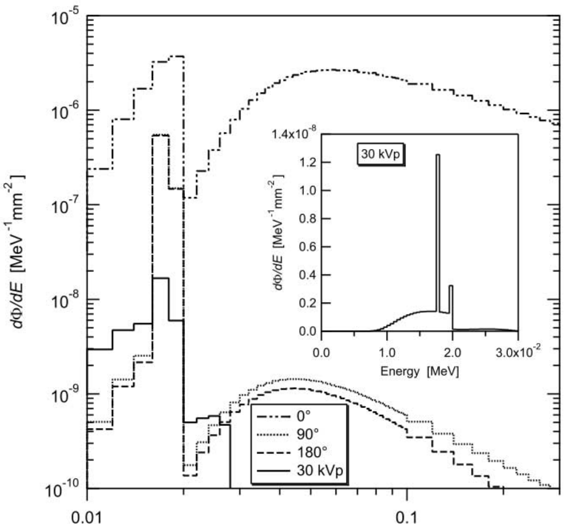

Fig. 1. – Comparison of MIRRORCLE X-ray spectra viewed at different angles. A conventional X-ray spectrum for mammography application is also plotted.

The transport of 6 and 20 MeV electrons in thin molybdenum, rhodium and tungsten wire targets was first studied by means of Monte Carlo simulations using the MCNPX code [5] (Monte Carlo N-Particle eXtended code, version 2.7A). It was shown that the emitted X-ray beams can be far more intense than those generated by conventional X-ray tubes for radiography applications [6].

To evaluate the potential of the MIRRORCLE source for medical imaging applications, a set of measurements were then performed at the Photon Production Laboratory (Japan). Radiographic images of known details were obtained for different X-ray targets. From these measurements an evaluation of the electron beam size was performed. Moreover, by means of calibrated thermoluminescent dosimeters (TLD) the average electron beam current circulating in the storage ring was also calculated. The X-ray imaging experiment also revealed an interesting effect of edge enhancement due to the wide X-ray spectrum used to obtain the radiographs [7].

Finally, the focal spot size of the 6 MeV machine was also measured. X-ray images of test objects were obtained by making use of a digital X-ray detector, and the focal spot size was evaluated from the edge profiles of a 1 mm thick metal washer exposed to the X-ray beam produced by a rhodium target ($d = 120\,\mu$m).

2. – Characterization of the MIRRORCLE source

2·1. *Simulation of X-ray imaging performance.* – Results of the MCNPX simulation also showed that an appreciable improvement in the monochromaticity of the beams can be obtained by viewing the X-ray emission from an output port antiparallel to the direction of the incident electron beam. Indeed, fig. 1 shows the comparison between MIRRORCLE spectra viewed at different angles with respect to the electron-beam direction. The comparison also includes a spectrum generated by a conventional X-ray tube with a Mo-anode.

TABLE I. – *Simulation of X-ray imaging performance for various X-ray sources.*

X-ray spectrum	Filtration	Direction	Contrast	Dose (mGy)	SNR	SNR^2/Dose
6 MeV, Mo 100 μm	Mo 30 μm	(0°)	0.15%	6.09E-01	2.06	6.93E+00
6 MeV, Mo 100 μm	Mo 30 μm	(90°)	1.76%	3.51E-01	8.05	1.84E+02
6 MeV, Mo 100 μm	Mo 30 μm	(180°)	1.89%	3.50E-01	8.26	1.95E+02
30 kVp, Mo anode	Mo 30 μm	-	2.08%	3.35E-01	8.18	2.00E+02
32 kVp, Rh anode	Mo 25 μm	-	1.55%	3.38E-01	8.42	2.10E+02

X-ray imaging performance of such spectra was compared in terms of physical image quality by MC simulation. The spectra used in these simulations were obtained by interaction of a 6 MeV electron beam impinging on a Mo wire ($d = 100\,\mu$m); different X-ray spectra are obtained if we change the direction of the radiation emitted with respect to the electron beam propagation direction:

– parallel (0°);

– perpendicular (90°);

– antiparallel (180°).

Furthermore, simulations were also carried out with two conventional mammography spectra, namely Mo 30 kVp and Rh 32 kVp (see table I for details about filtration). The aim of simulations was to obtain the radiograph of a test object containing a detail, as recorded by a digital detector. The phantom used was a PMMA slab having a size of $2.5 \times 2.5 \times 4.5\,\text{cm}^3$ and the detail was an Al disk 20 μm thick (diameter of 1.0 cm) placed upon it. We simulated a RadEye2 C-MOS digital X-ray detector (Rad-Icon Imaging Corp., USA) which is made up of a 1 mm thick graphite cover and a scintillator layer coupled to the C-MOS. The pixel array is 1024 × 1024 and the size of each pixel is $48 \times 48\,\mu\text{m}^2$, thus resulting in a total active area equal to $5 \times 5\,\text{cm}^2$. To produce the radiographic image we calculated the energy absorbed per pixel in the scintillator crystal layer, made of $31.7\,\text{mg/cm}^2$ of Gd_2O_2S. The radiation was assumed to be parallel and uniform over the whole surface of the PMMA phantom. For each image 5×10^9 photons were simulated. In order to calculate both radiographic contrast and signal-to-noise ratio (SNR), images obtained only with primary radiation were used (no X-ray scattering) and the Regions of Interest (ROIs) shown in fig. 2 were considered to calculate pertinent physical parameters.

As a figure of merit the value of $\text{SNR}^2/Dose$ was used, where *Dose* is the dose absorbed in the PMMA phantom (mGy). By comparing the data of the table it is apparent that the physical image quality is similar to a conventional X-ray source for mammography when the X-ray emission is viewed from an output port antiparallel to the direction of the incident electron beam.

2·2. *Measurement of electron beam current.* – In the MIRRORCLE-6X system X-rays are generated when a thin target is inserted in the circular orbit of the 6 MeV relativistic electron beam. It is possible to insert targets of different size and shape to produce a hard X-ray beam. However, not all the electrons that circulate in the storage ring hit the

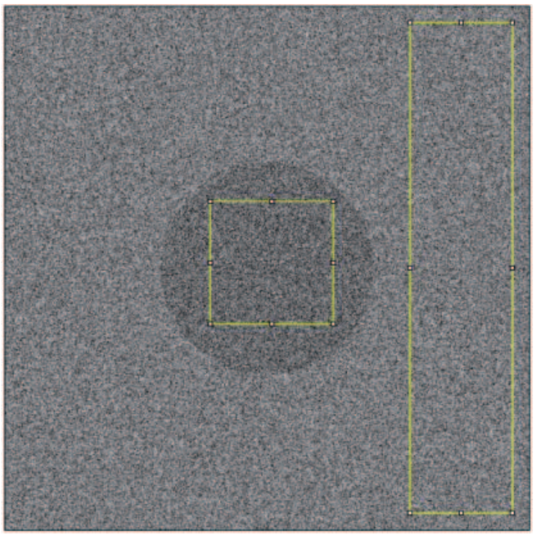

Fig. 2. – Simulation of the X-ray image recorded by a digital detector. The ROIs used to calculate pertinent physical parameters are also shown.

target. One of the aims of this work was to estimate the electron current that actually hits a tungsten wire of diameter equal to $d = 125\,\mu$m. Since it was not possible to directly measure the impact current of the MIRRORCLE, an evaluation of this current was performed by correction of dosimetric measurements with simulated data.

The method used to estimate the number of electrons that hit thin wire targets is based on the absorbed dose of several TLDs. The TLDs have been irradiated in different experimental conditions at the Ritsumeikan University (Japan) to measure the output kerma rate. The dosimeters, lithium fluoride (LiF) in our case, have a thickness of 1 mm and a square surface equal to $9\,\text{mm}^2$ and were exposed to an X-ray beam placed at a distance of 265 cm (see fig. 3).

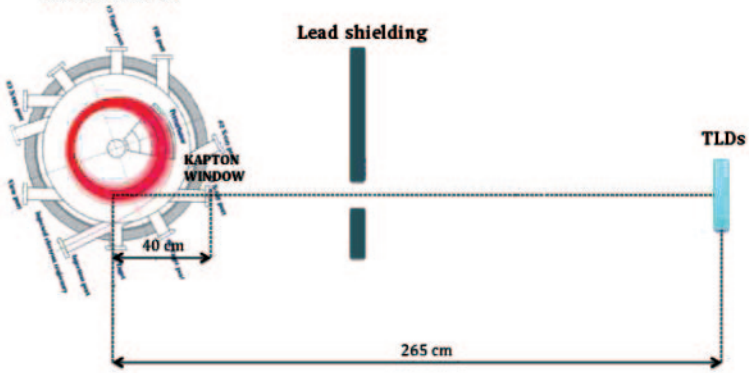

Fig. 3. – Experimental set-up for the measurement of the impact current in the MIRRORCLE 6-X system (not to scale).

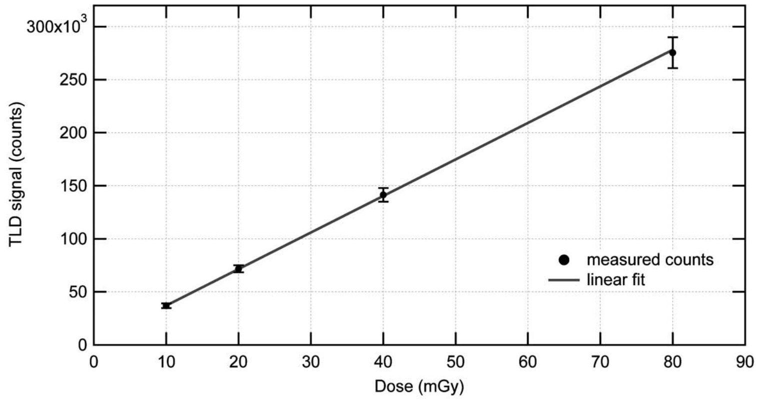

Fig. 4. – Calibration of TLDs with experimental data obtained in Belgium.

First, we compared the TLDs' readings in Japan with the TLDs' readings of the same set of dosimeters exposed at the Department of Experimental Radiotherapy of the Katholieke Universiteit of Leuven, Belgium. These TLDs were irradiated at different nominal air doses measured by an ionization chamber in the range 10 to 80 mGy at a distance of 5 m from an accelerator running at 6 MVp. All readings were done with the TLD reader (Toledo 654 TLD Reader, Vinten Instruments, U.K.) available at the Department of Physics of our University. The air kerma of the TLDs exposed in Japan was obtained by the linear interpolation of the TLDs output calibrated in Belgium (see fig. 4). From this interpolated value it is possible to calculate the impact current, knowing the air kerma per incident electron and the exposure time. With the results of this calculation we obtained an electron current, that hits the W wire, of $0.8 \pm 0.1\,\mu$A. Since conventional X-ray tubes can be loaded with electron currents of about 100 mA we demonstrated that the available current in the MIRRORCLE prototype is not sufficient at this stage for clinical applications.

2˙3. *Size of the focal spot.* – To measure the size of the focal spot, the radiograph of a 1 mm thick metal washer was used. We studied the edge profiles of this test object when irradiated by an X-ray beam produced with a thin Rh wire target ($d = 120\,\mu$m). The edge profiles of this sample were analyzed in two situations, with the washer in contact with the digital X-ray detector and at a certain distance from the detector, therefore magnified by a factor $M = 1.28$.

Using the magnified image of a test object having a sharp edge, one can estimate the size of the focal spot by measuring the width of the penumbra in the radiographic image. By simple geometrical considerations it is possible to show that the width of a focal spot f is

$$f = p/(M - 1), \quad (1)$$

where p is the penumbra width and M is the magnification factor.

The distribution of the focal spot generated by this specific target has different trends in the two directions, the one parallel to the electron beam, defined as y, and the other perpendicular to the electron beam, defined as x. In the first case, because of the thin diameter of the wire, we observe the typical behaviour of a point source, *i.e.* we do not

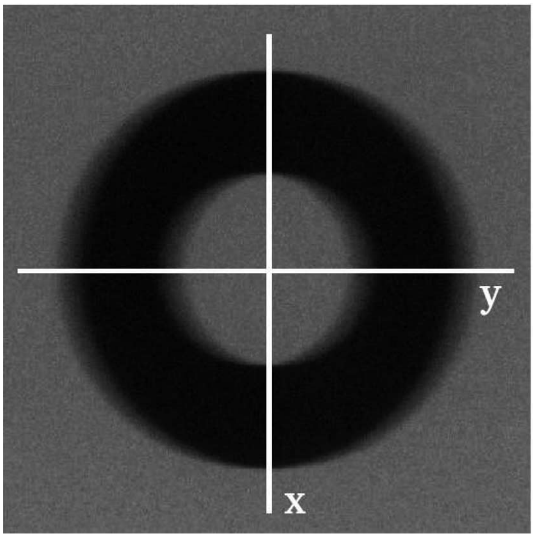

Fig. 5. – Magnified radiographic image of a metal washer.

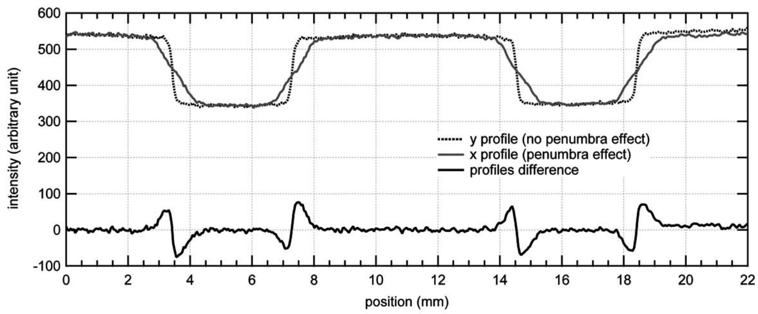

Fig. 6. – Transmission profiles of the metal washer along the two directions and their subtraction.

observe a penumbral blur in the magnified image. On the contrary, penumbral effects are evident in the other direction, due to the finite dimension of the Rh wire along x, as shown in fig. 5.

In order to estimate the penumbra width along the horizontal direction, the difference of the two transmission profiles x and y was performed. The subtraction is shown in fig. 6 as a continuos black line. This plot is approximately equal to zero with exception of the region corresponding to the penumbra. Thus, the width of each non-zero region is a measure of the penumbra width p. The average of four measurements is 1.6 ± 0.1 mm. By using eq. (1) this results in f equal to 5.8 ± 0.2 mm.

This last result is very useful for the estimation of the cross-section of the electron beam circulating within the storage ring.

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REFERENCES

[1] Yamada H., Hirai T., Morita M., Hanashima T., Sasaki M., Hasegawa D., Hayashi T., Yamada T. and Saisho H., in *Proc. 8th Int. Conf. X-ray* (Microscopy IPAP Conf. Series 7) pp. 130-132.

[2] Yamada H., *Nucl. Instrum. Methods B*, **199** (2003) 509.

[3] http://www.kuleuven.be/labsync/.

[4] Di Domenico G., Franconieri A., Gambaccini M., Marziani M., Taibi A. and Tartari A., in *Channeling 2008, Proceedings of the 51st Workshop of the INFN Eloisatron Project*, edited by Dabagov S. B. and Palumbo L. (World Scientific, Singapore) 2010.

[5] Pelowitz D. B., Hendricks J. S., Durkee J. W., James M. R., Fensin M. L., McKinney G. W., Mashnik S. G. and Waters L. S., Los Alamos National Laboratory report No. LA-CP-07-1473 (2008) https://mcnpx.lanl.gov.

[6] Marziani M., Taibi A., Di Domenico G. and Gambaccini M., *Med. Phys.*, **36** (2009) 4683.

[7] Taibi A., Cardarelli P., Di Domenico G., Marziani M., Gambaccini M., Hanashima T. and Yamada H., *Appl. Phys. Lett.*, **96** (2010) 144102.