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# Evaluation of energy distribution of quasi-monochromatic x-ray beams for sources with extremely high instantaneous flux using a *k*-edge subtraction technique

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ABSTRACT

The characterization of novel x-ray sources includes the measurement of the photon flux and the energy distribution of the beam produced. The aim of the BEATS2 experiment at INFN-LNF is the study of medical applications of an x-ray source based on Thomson relativistic backscattering. This source is expected to produce pulsed quasi-monochromatic x-ray beam with an instantaneous flux of $10^{20}$ ph/s in pulses 10 ps long and with an average energy of 20 keV. A direct measurement of energy distribution of this beam with traditional detectors, such as HPGe, CZT or CdTe, is very difficult because of the extremely high photon flux. For this reason we have planned to use a technique based on beam filtration using *k*-edge absorbing foils in the energy range of interest (16–22 keV). By measuring the photon flux of the photon beam filtered with appropriate thicknesses of *k*-edge absorbers, it is possible to retrieve the energy distribution of the incident x-ray beam. The energy resolution obtainable depends on the number and energy separation of *k*-edges of filter used.

A preliminary test of the technique was made using an x-ray tube with a tungsten anode at 22 kVp, filtered with 3.1 mm of Al providing an x-ray spectrum with an energy distribution similar to that expected from a Thomson source. The comparison between the results obtained directly measuring this spectrum with an HPGe detector and using the *k*-edge subtraction technique showed good agreement.


## 1. Introduction

The research for novel intense monochromatic x-ray sources is of great interest in the scientific community.

Among others quasi-monochromatic x-ray sources, those based on relativistic Thomson back-scattering (*Thomson sources*) are very promising [1,2]. BEATS2 experiment, funded by Istituto Nazionale di Fisica Nucleare (INFN) at National Laboratories of Frascati (LNF), is aimed to the study of medical application of an x-ray Thomson source. This source, which will be operational in 2013, is expected to produce pulsed quasi-monochromatic x-ray beam with an instantaneous flux of about $10^{20}$ ph/s in pulses 10 ps long and with energy ranging from 16 to 21 keV, depending on angular acceptance [3]. The knowledge of the energy distribution of an x-ray source is fundamental for the study and development of its applications. In particular, during the realization of a Thomson source the spectrum of emitted photons is an important signature of the apparatus proper working, in terms of beams energies, focusing and collision alignment.

Several techniques have been proposed in order to retrieve the photon energy distribution from dose measurements of filtered beam with different absorbing materials and thicknesses [4,5].

The technique described in this work is someway similar because filtration with x-ray absorbing materials is used; the difference lies in the fact that inverse-problem computation or reconstruction approach are not required, but the information on photon energy is obtained using the absorption discontinuity due to photoelectric *k*-edge of appropriate materials.

## 2. Theory of method

Consider energy spectrum $\varphi(E)$ of a photon beam as the distribution of the photon flux with respect to energy.

The total photon flux $\varphi$ (ph/s) will be given by integration of spectrum over the whole energy range:

$$\varphi = \int_{E_{min}}^{E_{max}} \varphi(E)\, \mathrm{d}E.$$

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As previously mentioned, it is possible to obtain an evaluation of the energy spectrum of an x-ray beam by measuring x-ray fluxes transmitted by appropriate *k*-edge absorbing foils.

In particular, consider $\varphi(E)$ to be the energy distribution that needs to be evaluated. First of all, an absorbing material having no *k*-edge in the energy interval $[E_{min} : E_{max}]$ in which $\varphi(E) \neq 0$ is required. Consider this material with attenuation coefficient $\mu_f(E)$, thickness $t_f$ and transmitted spectrum $\varphi_f(E)$ and, in addition to this, other materials with *k*-edge in the energy range of interest with attenuation coefficient $\mu_{k_i}(E)$, thickness $t_{k_i}$ and transmitted spectrum $\varphi_{k_i}(E)$.

To be effective, this technique requires the fulfillment of two conditions:

1. The thickness $t_{k_i}$ of each *k*-edge filter has to be chosen in such a way that the absorption of all the filters have to be equal to the absorption of the filter without *k*-edge, up to the corresponding *k*-edge energy $E_{k_i}$ of each filter:

$$\mu_f(E)t_f = \mu_{k_i}(E)t_{k_i} \quad \text{if } E_{min} \le E \le E_{k_i}. \tag{1}$$

2. The *k*-edge filters transmission has to be negligible for photons having energies above the *k*-edge:

$$e^{-\mu_{k_i}(E)t_{k_i}} \approx 0 \quad \text{if } E > E_{k_i}. \tag{2}$$

When conditions (1) and (2) are satisfied, it is possible to demonstrate that the subtraction of total fluxes of two filtered x-ray beams $\varphi_f$ and $\varphi_{k_1}$ will be

$$\varphi_f - \varphi_{k_1} = \int_{E_{k_1}}^{E_{max}} \varphi(E) e^{-\mu_f t_f}. \tag{3}$$

This means that the difference of total fluxes is equal to the flux of photons with energies higher than $E_{k_1}$ in the beam filtered with no *k*-edge. Lets now consider two *k*-edge filters with *k*-edge at energies $E_{k_1} < E_{k_2}$ and thicknesses $t_1$ and $t_2$, similar to the previous case, if conditions (2) and (1) are satisfied, it is straightforward to demonstrate that the subtraction of the total transmitted flux $\varphi_{k_1}$ to $\varphi_{k_2}$ is

$$\varphi_{k_2} - \varphi_{k_1} \cong \int_{E_{k_1}}^{E_{k_2}} \varphi(E) e^{-\mu_f(E) t_f} \, dE. \tag{4}$$

Eq. (4) shows that the difference between the total fluxes transmitted by two different *k*-edge absorbers is equal to the photon flux $\varphi_f(E_{k_2} : E_{k_1})$ transmitted from the filter with no *k*-edge in the range of energy between the two *k*-edge energies $E_{k_1}$ and $E_{k_2}$ (See Fig. 1). To obtain the unfiltered (and sought) $\varphi(E_{k_2} : E_{k_1})$ from $\varphi_f(E_{k_2} : E_{k_1})$, it is sufficient to take into account the attenuation of the filter with no *k*-edge:

$$\varphi(E_{k_2} : E_{k_1}) = \varphi_f(E_{k_2} : E_{k_1}) / e^{-\mu_f t_f}. \tag{5}$$

Repeating this procedure for several suitable couples of *k*-edge absorbers a complete investigation of the energy interval of interest is possible.

Finally, measuring the photon flux transmitted by properly chosen *k*-edge materials with a suitable detector, such as a silicon PIN diode [6,7], it is possible to perform an evaluation of the energy distribution with a resolution that is equal to the energy distance of *k*-edges used.

## 3. Materials and methods

### 3.1. X-ray beam for experimental test

This technique has been developed in order to evaluate the spectrum of a Thomson source at LNF that is expected to be quasi-monochromatic, with energy ranging from 16 to 21 keV as shown in the simulated spectrum in Fig. 2.

To obtain experimentally an x-ray energy distribution similar to the expected one, an x-ray tube with a tungsten (W) anode (mod. GS 340 5, CGR, Paris, France) operating at 22 kVp with an added filtration of 3.10 mm of aluminum (Al) was used in order to reduce the low energy part of spectrum. A plot of the spectrum measured with an HPGe detector is shown in Fig. 3. In order to perform flux measurement, a PIN diode was used. The current produced in a PIN diode is proportional to the rate of energy released in the photodiode active area by the radiation. The device used for this measurements was a PIN diode (HAMAMATSU Photonics, mod.S3584-09) in photo-voltaic mode, i.e. without the application of a reverse polarization. The current produced during x-ray exposure was measured by an electrometer (Keithley Instruments Inc., mod. 6517B).

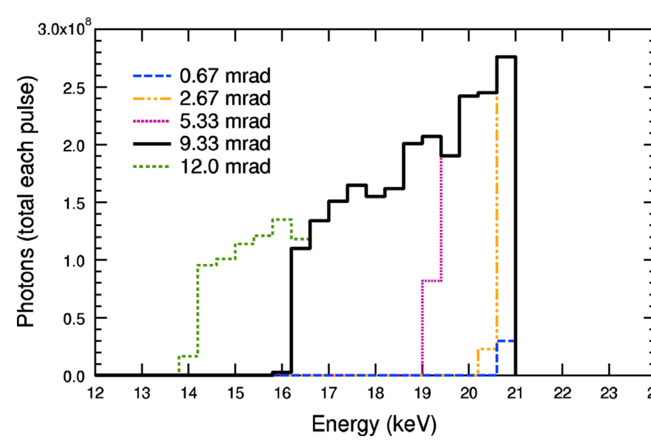


**Fig. 2.** Simulated spectrum expected for the BEATS Thomson source. The energy distribution depends on the angular acceptance, plot shown refers to an angular semi-acceptance equal to 9.33 mrad, corresponding to the experimental application setup.

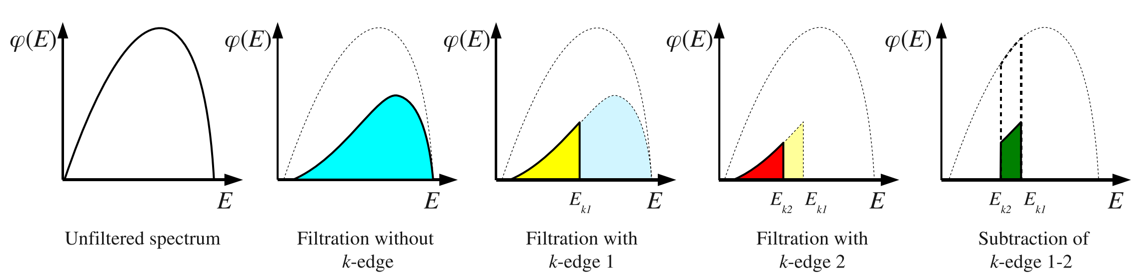


**Fig. 1.** Schematic diagram of the *k*-edge subtraction technique.