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Departamento de Ingeniería Química y Nuclear.

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Dear Sir:

I am pleased to address you the manuscript entitled:

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to be published in the special issue of the A Applied Radiation and Isotopes. The manuscript has not been submitted to another journal for possible publication. It has been presented at the 6th CHERNE workshop held in Coimbra (Portugal)

Your sincerely,

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Manuscript

Parametric study of the X-ray primary spectra obtained with the MTSVD unfolding method

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ABSTRACT

The Modified Truncated Singular Value Decomposition (MTSVD) unfolding method is applied to obtain primary spectra for X-ray tubes in radiodiagnostic. Three parameters – voltage, anode angle and filter thickness- of the tube are tested. Unfolded spectra are compared with theoretical extracted from IPEM-78 catalogue. A 2σ error criterion is applied to assess the minimum variations in tested parameters that permits distinguishing between close spectra.

1- INTRODUCTION

X-ray tubes used in radiodiagnostic range (10 -150 keV) require a complex Quality Control (QC) protocol. However, these QC procedures normally do not include any routine characterization of the primary photon beam. Normally, primary spectrum determination is skipped by measuring other QC parameters easier to be obtained in practice (high voltages, half value layer, homogeneity factor, ripple factor, etc).

The use of direct spectrometry for determining primary X-ray spectrum is practically forbidden as detectors cease to work properly at high count rates. To avoid the pile-up effect in the detector produced by a high fluence rate, a Compton spectrometry technique is proposed. In previous works (Gallardo et al., 2004) (Gallardo et al., 2006) authors described a Monte Carlo (MC) model that uses the MCNP5 code (X-5 Monte Carlo Team, 2005) to obtain Pulse Height Distribution (PHD) by simulating the Compton spectrometry process.

The relation between the PHD and primary spectrum is defined by a Response function, expressed as a matrix. This Response matrix is ill conditioned and an unfolding method –such as MTSVD- should be applied to obtain the inverse matrix and hence the primary spectrum.

It is necessary to qualify the accuracy of the unfolding method applied, to know whether the primary beam is properly reproduced.

With this goal in mind, small variations in the working conditions are introduced to obtain different PHDs that after being unfolded are compared with reference spectra (IPEM 78 Report Catalogue).

2. THE MONTE CARLO MODEL

The MC model developed includes a point source simulating the X-ray focus, the Compton spectrometer (Matscheko, 1998) and a Germanium detector (Canberra, 2009). A layout of the model can be seen in figure 1.

The Compton spectrometer consists of a shielding chamber, a scattering chamber containing the scattering material (PMMA) and a spectrometer tube with lead collimators.

The Compton scattering process produces an important decrease on the number of photons entering in the spectrometer tube. Therefore, statistics of the simulation is very poor. To improve statistics the geometry is splitted in two parts, as was presented in Gallardo et al., (2004). The final result, obtained with an F8 tally, is the PHD in the detector.

Electron transport has been activated in the model. However, a 10 keV energy cut-off has been applied to limit the total computer time.

3. THE RESPONSE FUNCTION

The relation between PHD and the primary spectrum can be expressed by equation (1):

$$R\vec{s} = \vec{m} \qquad (1)$$

where $\vec{s} = (s_1, \ldots, s_N)^T$ is the unknown primary spectrum, $\vec{m} = (m_1, \ldots, m_M)^T$ is the PHD recorded in the detector system, and **R** is the Response matrix. The Response matrix, **R**, can be obtained by calculating with MCNP5 the PHDs produced by different monoenergetic primary spectra.

Once **R** is known, the equation (1) theoretically permits to obtain the primary spectrum. But as the determination of this matrix is affected by some errors, an approximation $\tilde{\vec{s}}$ to $\vec{s}$ is chosen in such a way that minimizes the 2-norm of the residual vector, as expressed by equation (2).

$$\left\| R\tilde{\vec{s}} - \vec{m} \right\|_2 \qquad (2)$$

Since **R** is a real MxN matrix, it admits a Singular Value Decomposition (SVD). But **R** is rank deficient, so there are many solutions for the Least Squares problem. An optimal solution can be obtained generating a new Response matrix and removing the parts of the solution corresponding to the smallest singular values (Golub and Van Loan, 1996).

Then the MTSVD method can be used to obtain a new matrix, $\mathbf{R_k}$, where k is the number of singular values of **R** (or rank of **R**) that are considered (Forsythe et al., 1977).

4. RESULTS AND DISCUSSION

Three parameters of an X-ray tube have been tested: high voltage, anode angle, and filter thickness. The obtained PHDs for 68, 69, 70, 71 and 72 kVp are represented in figure 2. It can be seen that small variations in voltage produce small changes in PHDs that are more evident at higher energies. The same effect has been observed for higher voltages (80 and 90 kVp).

PHDs obtained for different anode angles (8°, 9°, 10°, 11° and 12°) and for different filter thickness (2.5, 3.5, 4.5 and 5.5 mm of aluminium) are represented respectively in figures 3 and 4. Variations in anode angle have less influence on obtained PHDs, while a change in the filter thickness has more importance mostly at low energies.

Once PHD and Response matrix are obtained, the MTSVD method is applied to unfold the PHD obtaining the primary spectrum.

The quality of the result of the MTSVD method strongly depends on the regularization parameter. This parameter can be selected plotting the L-curve, which consists in representing the 2-norm of the solution vector versus the 2-norm of the residual vector. The L-curve obtained is shown in figure 5. The optimal value for k is 115.

Primary spectra obtained with the unfolding method, that is, the unfolded spectra, have been compared with theoretical spectra extracted from the IPEM-78 catalogue. This comparison is shown in figures 6, 7 and 8 for variations in voltage, anode angle and filter thickness respectively. An error analysis has been performed by calculating the relative error.

Variations in voltage mainly affect spectra at high energy, hence the unfolded spectra taking into account 2σ errors bars must not overlap at high energy range. As it can be seen in figure 9 this is possible for a variation of 2 kVp or higher.

The influence of variations in anode angle is less significant and observed only at low energy. With the same criterion unfolded spectra with 2σ error bars are represented in figure 10, where it can be seen that overlapping is not produced for variations of 3° or more in anode angle.

Finally, variations in filter thickness mostly affect spectra at low energies. Therefore, the overlapping of spectra must be avoided at this energy range. From the representation in figure 11, it can be stated that a minimum change of 2 mm in the thickness is required.

5. CONCLUSIONS

The MTSVD method is adequate to unfold PHDs to obtain primary spectra for X-ray tubes in radiodiagnostic applications.

Variation in three parameters of the X-ray tube –voltage, anode angle and filter thickness- has been tested.

A comparison of unfolded spectra with theoretical ones extracted from IPEM-78 catalogue has been performed using a 2σ criterion.

Maximum variations of 2 kVp for voltage, 3° for anode angle and 2 mm Al for filter thickness are required to avoid an overlapping of spectra in the energy range mostly affected.

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FIGURE CAPTIONS

Fig. 1. Layout of Compton spectrometer.

Fig. 2. PHD obtained for 68, 69, 70, 71 and 72 kVp.

Fig. 3. PHD obtained for 90 kVp varying the anode angle: 8º, 9º, 10º, 11º and 12º.

Fig. 4. PHD obtained for 100 kVp varying the filter thickness 2.5, 3.5, 4.5 and 5.5 mm of Al.

Fig. 5. L-curve MTSVD method.

Fig. 6. Comparison between the IPEM 78 catalogue and the unfolded spectra obtained for 68 and 72 keV.

Fig. 7. Comparison between the IPEM 78 catalogue and the unfolded spectra obtained for 90 keV 8º and 12º.

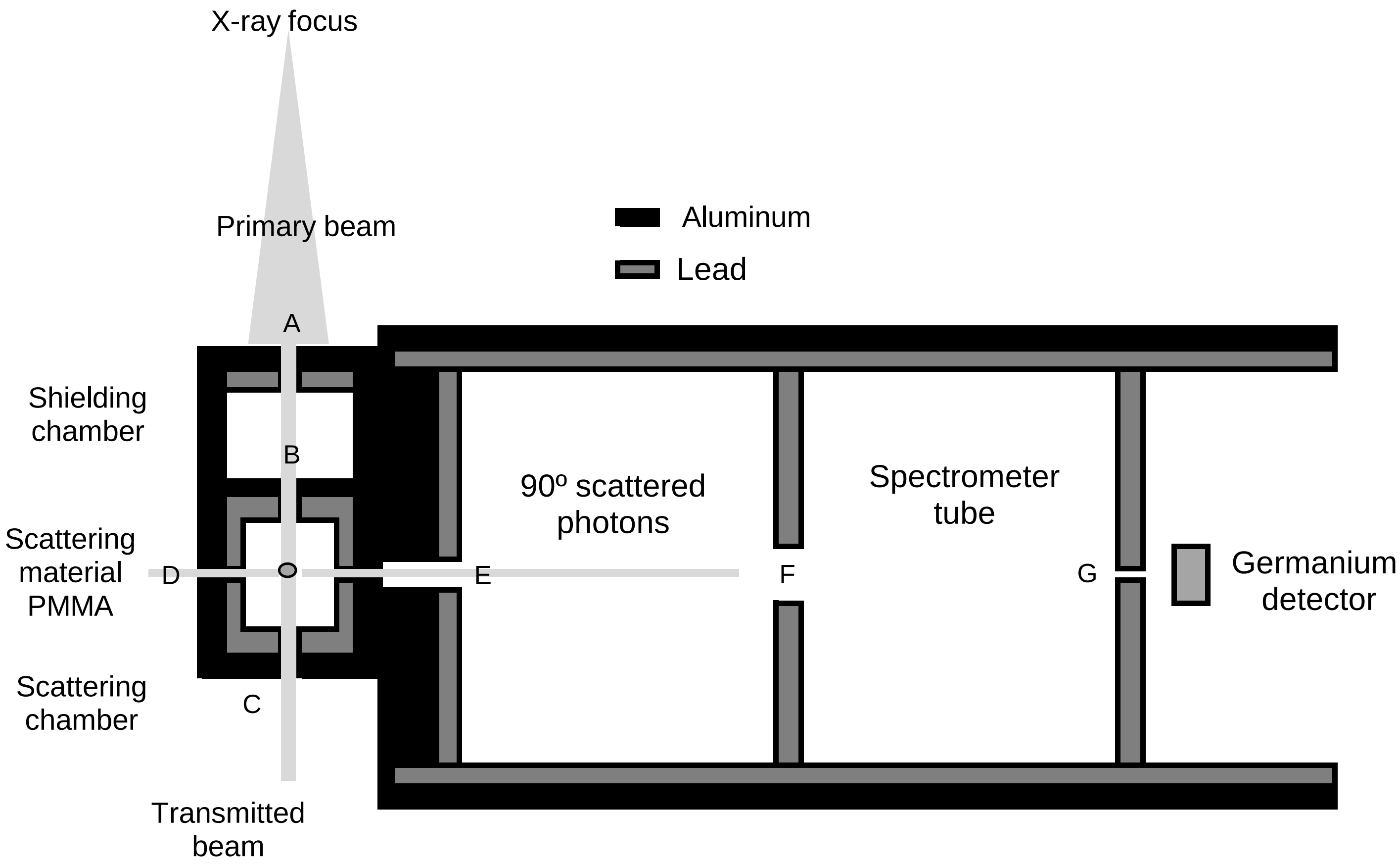
Fig. 8. Comparison between the IPEM 78 catalogue and the unfolded spectrum obtained for 100 keV 2.5 and 5.5 mm of Al.

Fig 9. Comparison between unfolded spectra for 70 and 72 kVp with their errors.

Fig 10. Comparison between unfolded spectra for 8° and 11° with their errors.

Fig 11. Comparison between unfolded spectra for 2.5 and 4.5 mm of Al with their errors.

Figure 1



X-ray focus
Primary beam
Aluminum
Lead
A
Shielding chamber
B
90º scattered photons
Spectrometer tube
Scattering material PMMA
D
E
F
G
Germanium detector
Scattering chamber
C
Transmitted beam

Figure 2

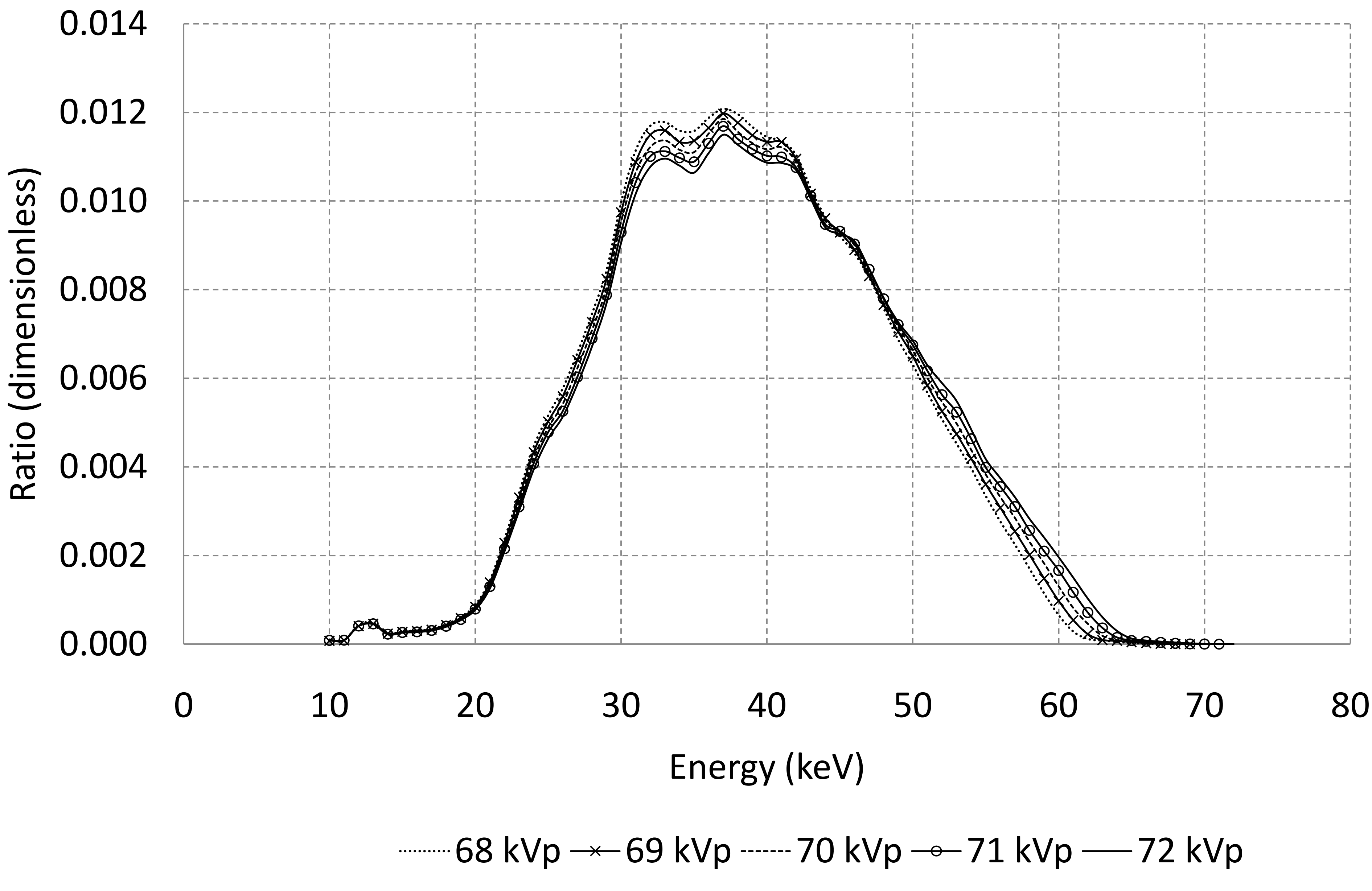
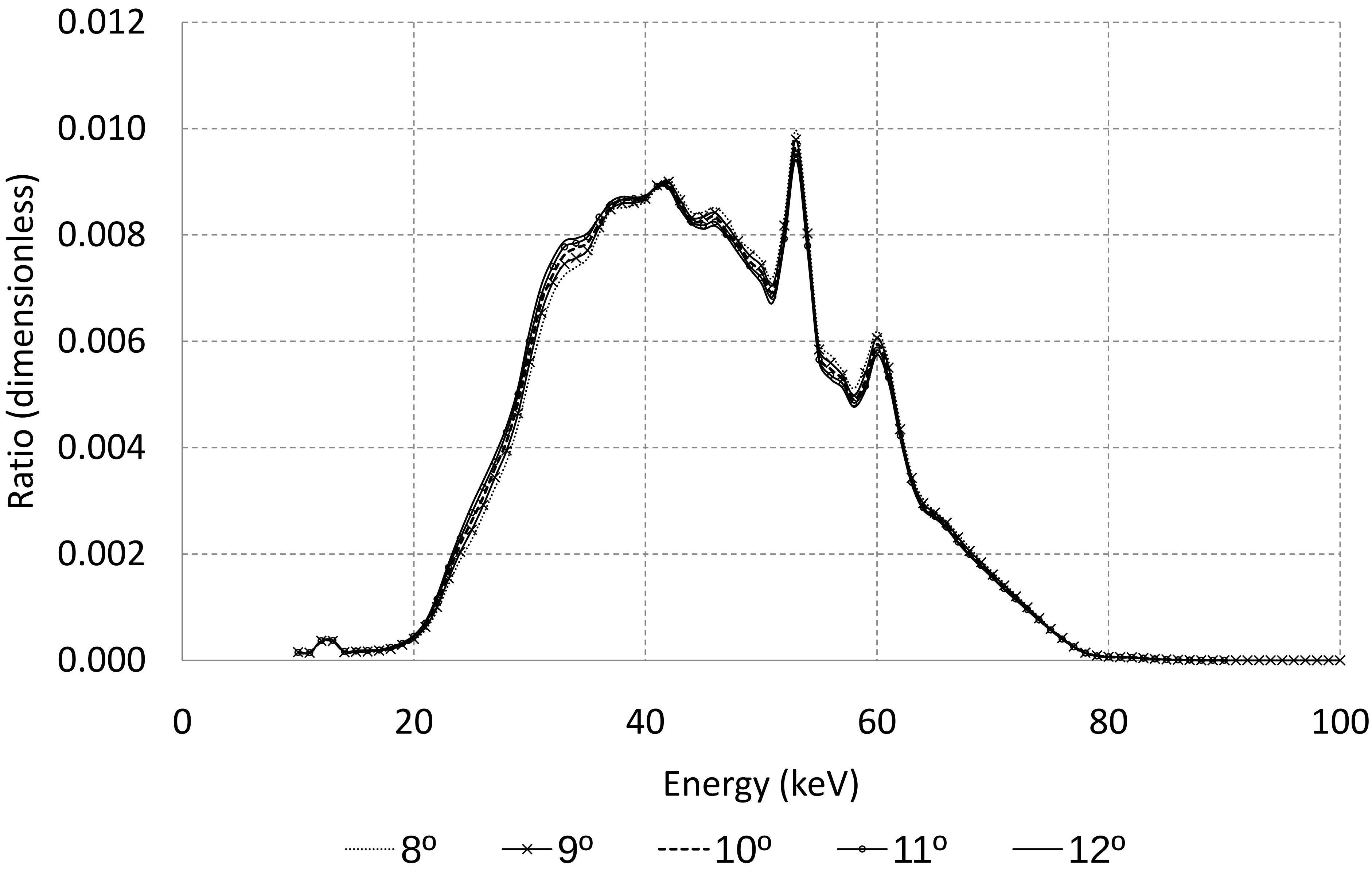
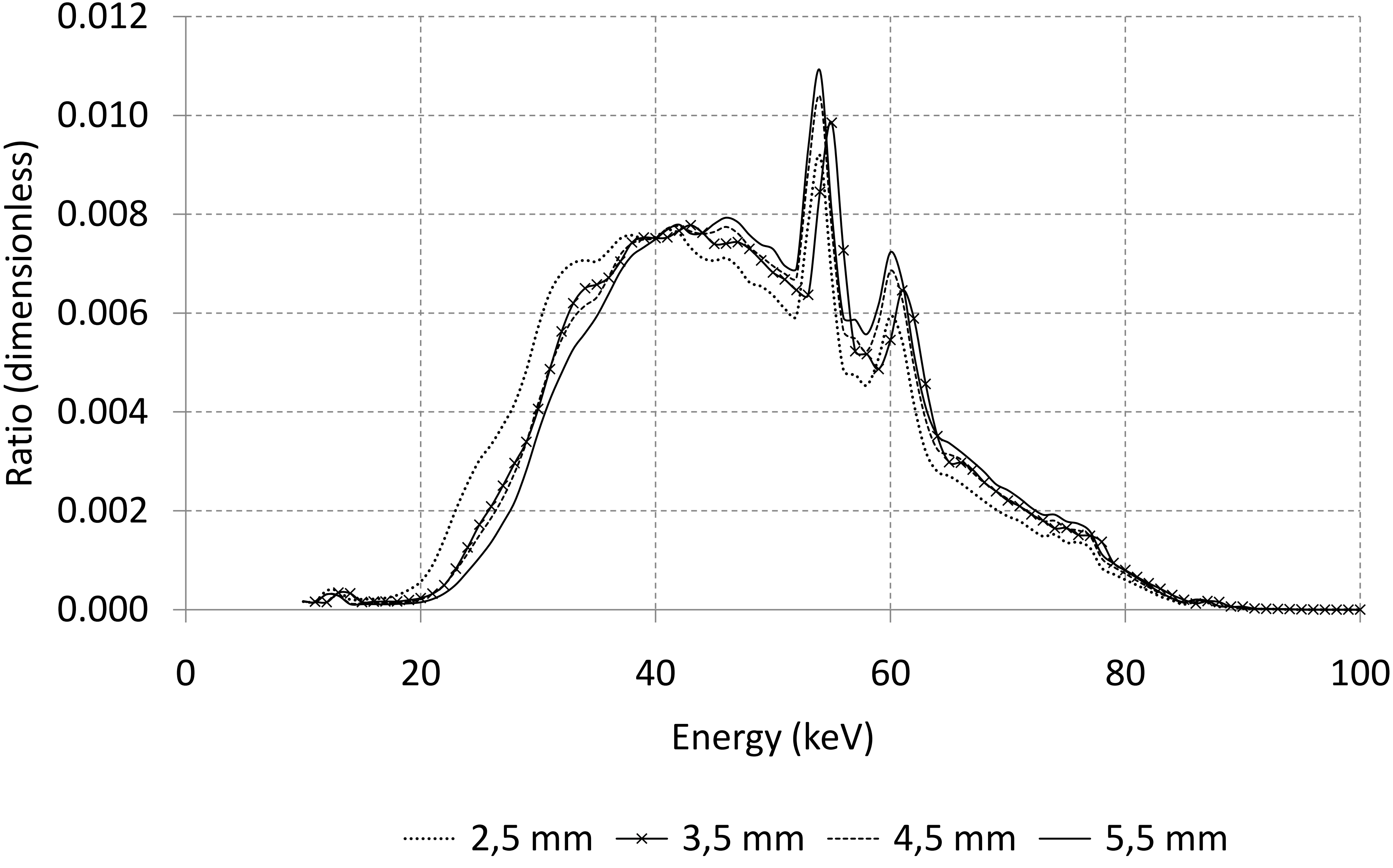

0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Ratio (dimensionless)
0
10
20
30
40
50
60
70
80
Energy (keV)
68 kVp
69 kVp
70 kVp
71 kVp
72 kVp

Figure 3



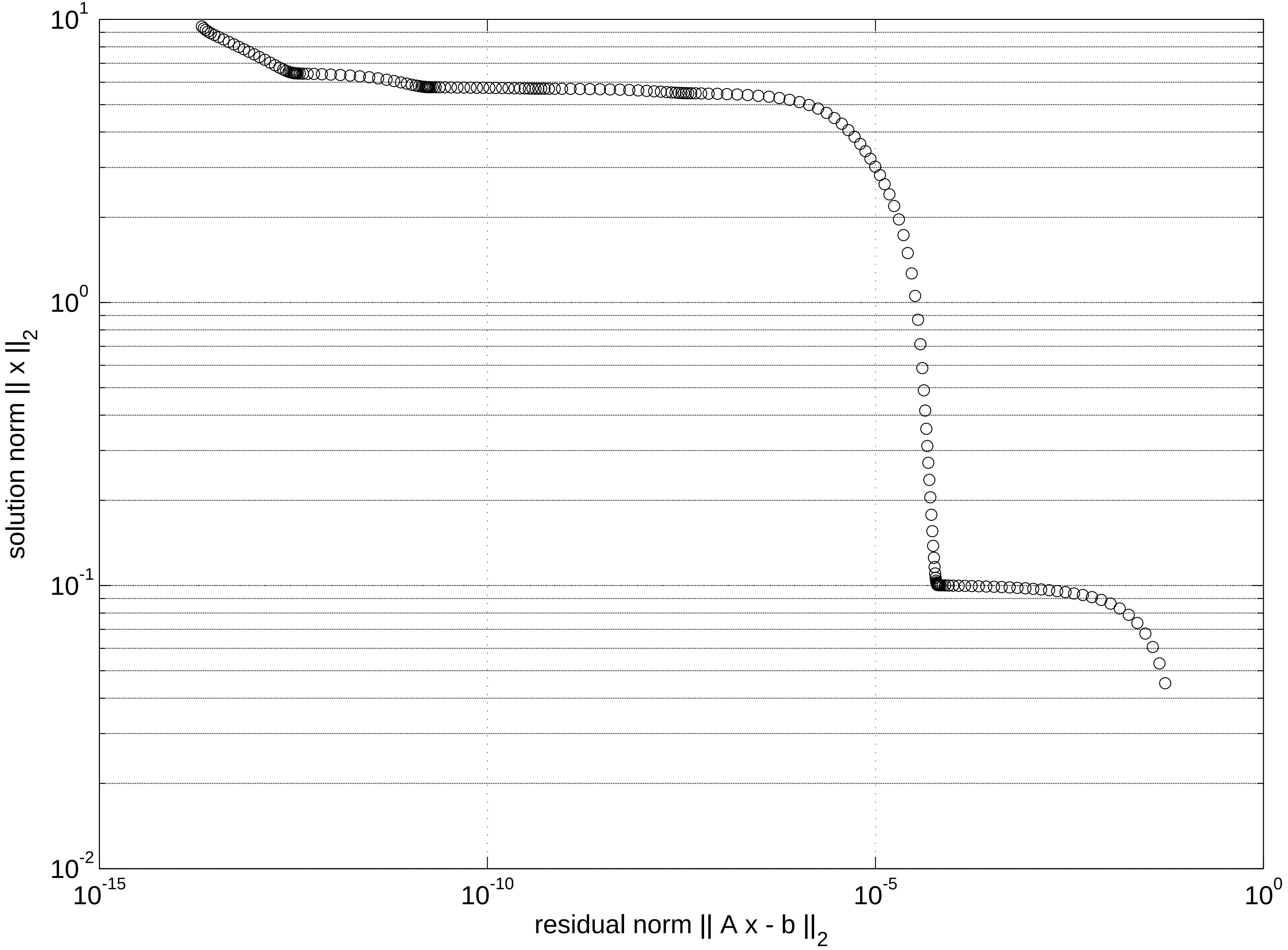
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Ratio (dimensionless)
0
20
40
60
80
100
Energy (keV)
8º
9º
10º
11º
12º

Figure 4



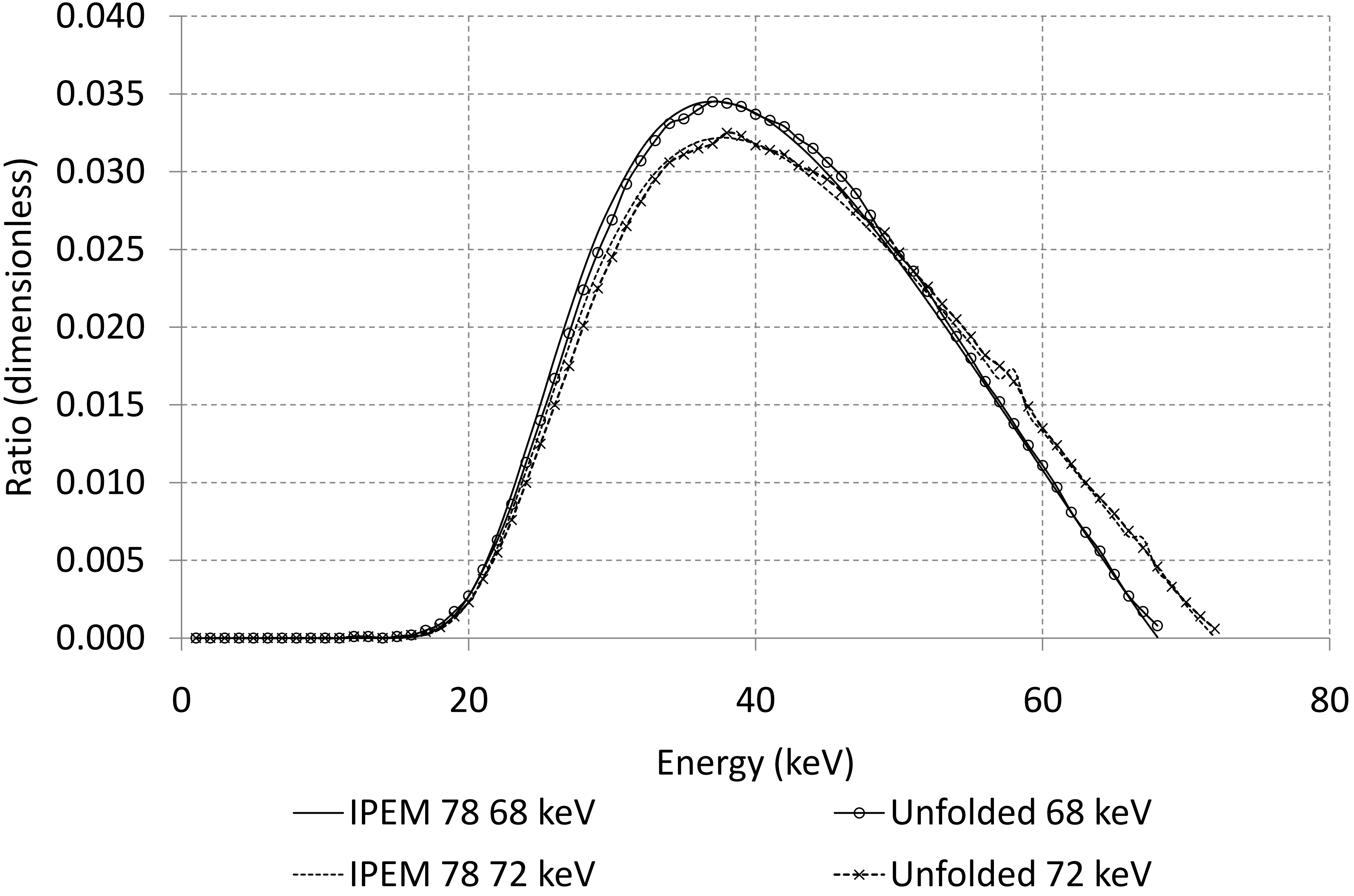
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Ratio (dimensionless)
0
20
40
60
80
100
Energy (keV)
2,5 mm
3,5 mm
4,5 mm
5,5 mm

Figure 5



10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-15}
10^{-10}
10^{-5}
10^{0}
solution norm || x ||$_2$
residual norm || A x - b ||$_2$

Figure 6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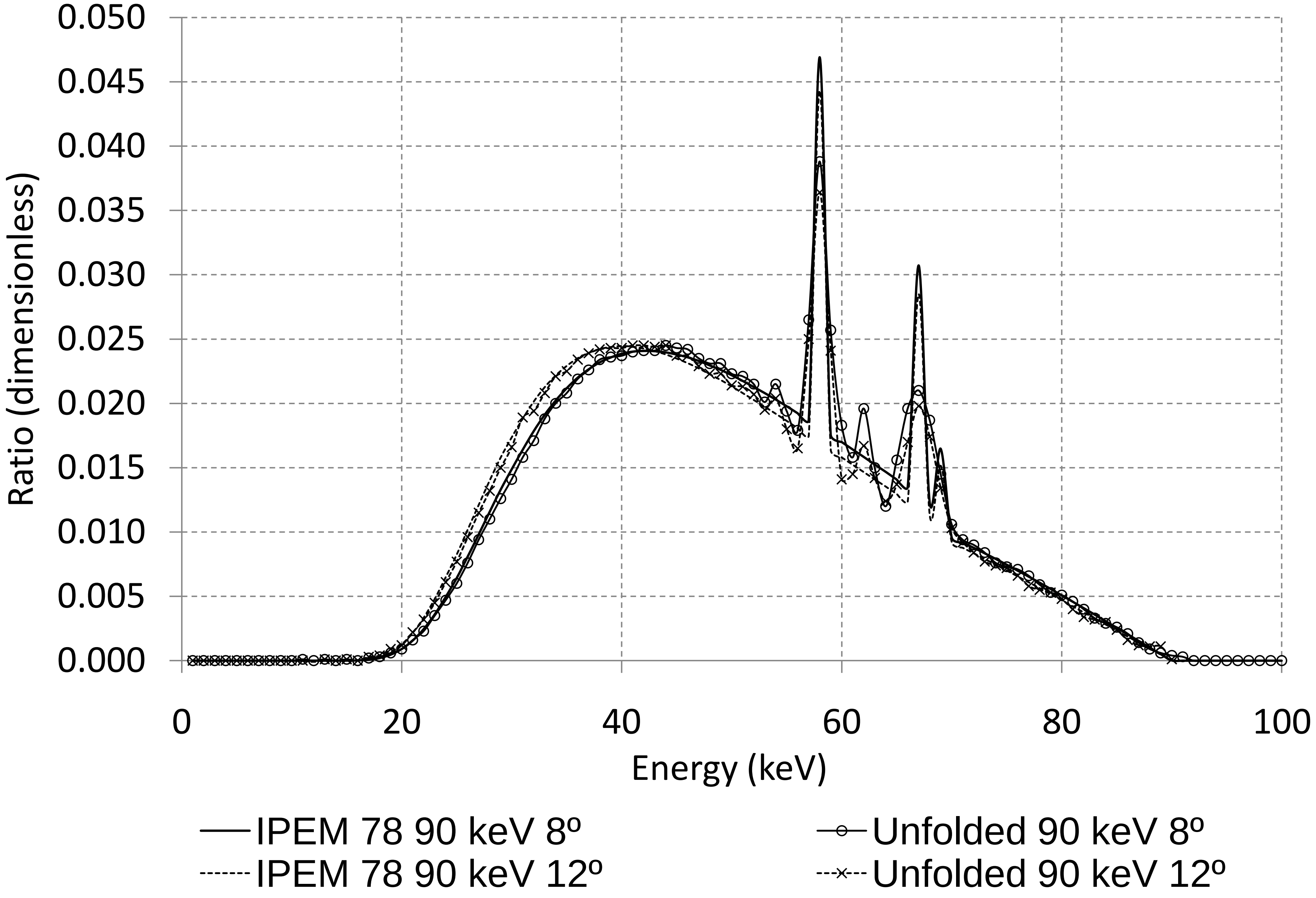
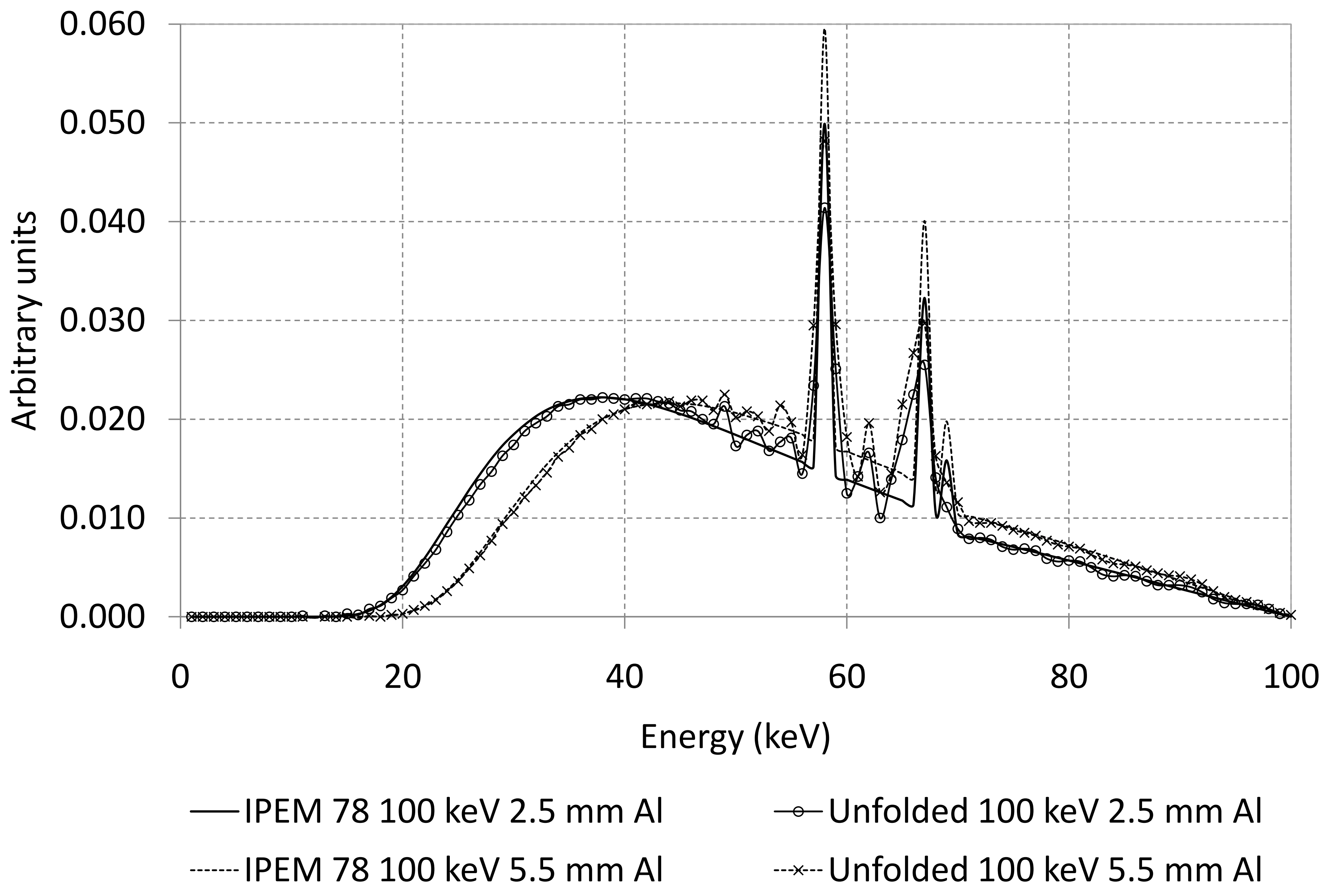
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
Ratio (dimensionless)
0
20
40
60
80
Energy (keV)
IPEM 78 68 keV
Unfolded 68 keV
IPEM 78 72 keV
Unfolded 72 keV

Figure 7



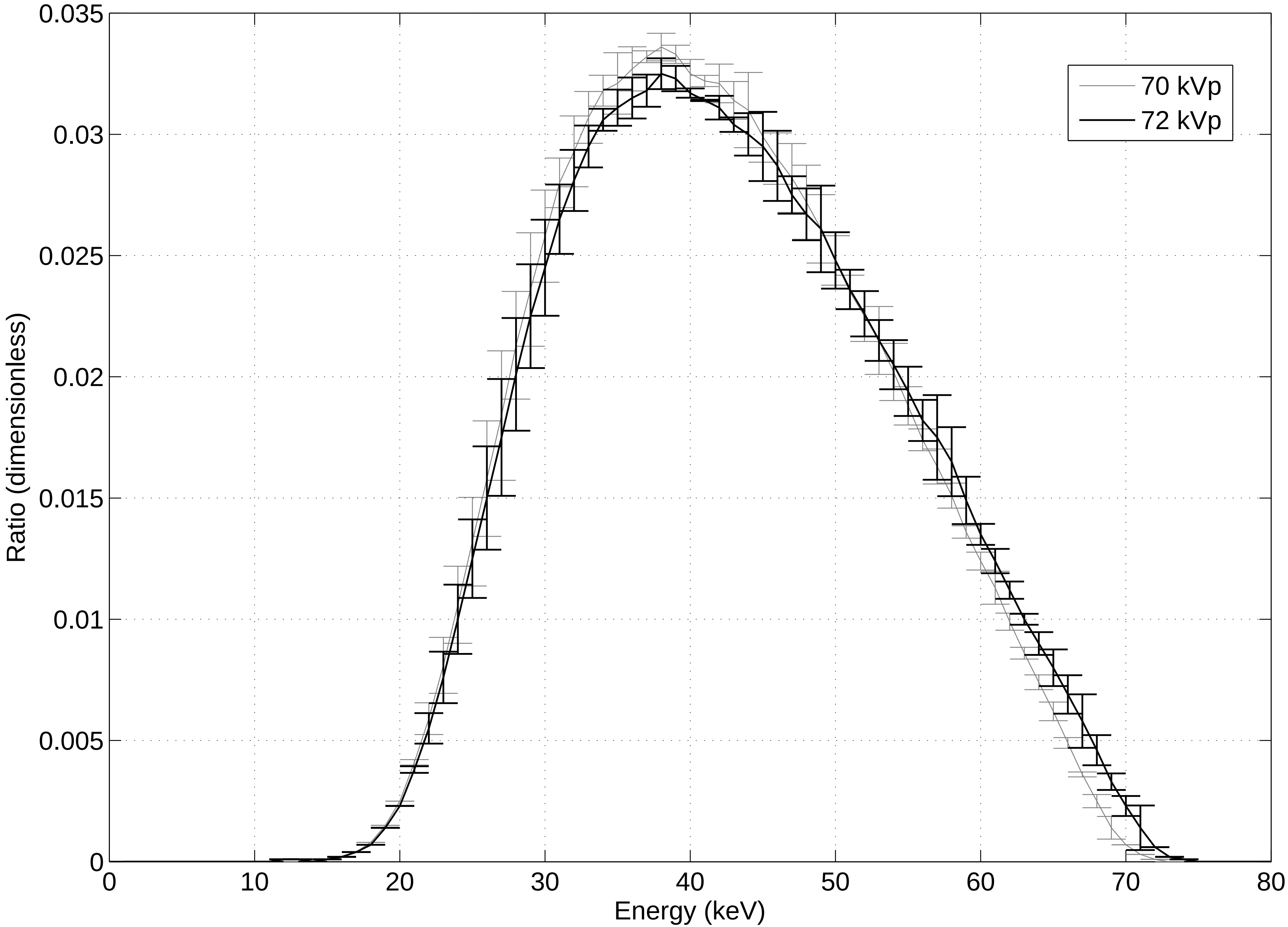
0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
Ratio (dimensionless)
0
20
40
60
80
100
Energy (keV)
IPEM 78 90 keV 8º
Unfolded 90 keV 8º
IPEM 78 90 keV 12º
Unfolded 90 keV 12º

Figure 8



0.060
0.050
0.040
0.030
0.020
0.010
0.000
Arbitrary units
0
20
40
60
80
100
Energy (keV)
IPEM 78 100 keV 2.5 mm Al
Unfolded 100 keV 2.5 mm Al
IPEM 78 100 keV 5.5 mm Al
Unfolded 100 keV 5.5 mm Al

Figure 9



0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Ratio (dimensionless)
0
10
20
30
40
50
60
70
80
Energy (keV)
70 kVp
72 kVp

Figure 10

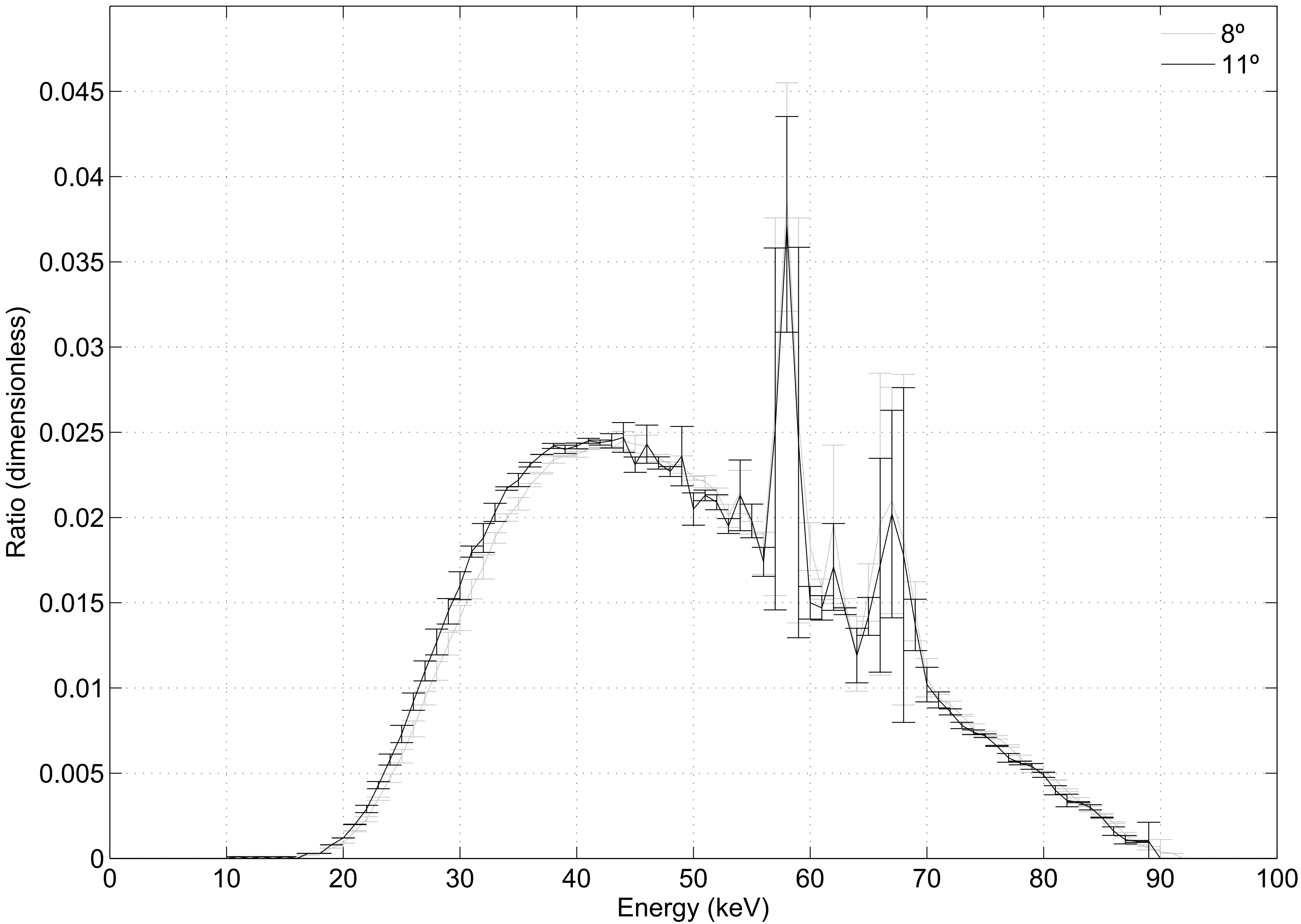
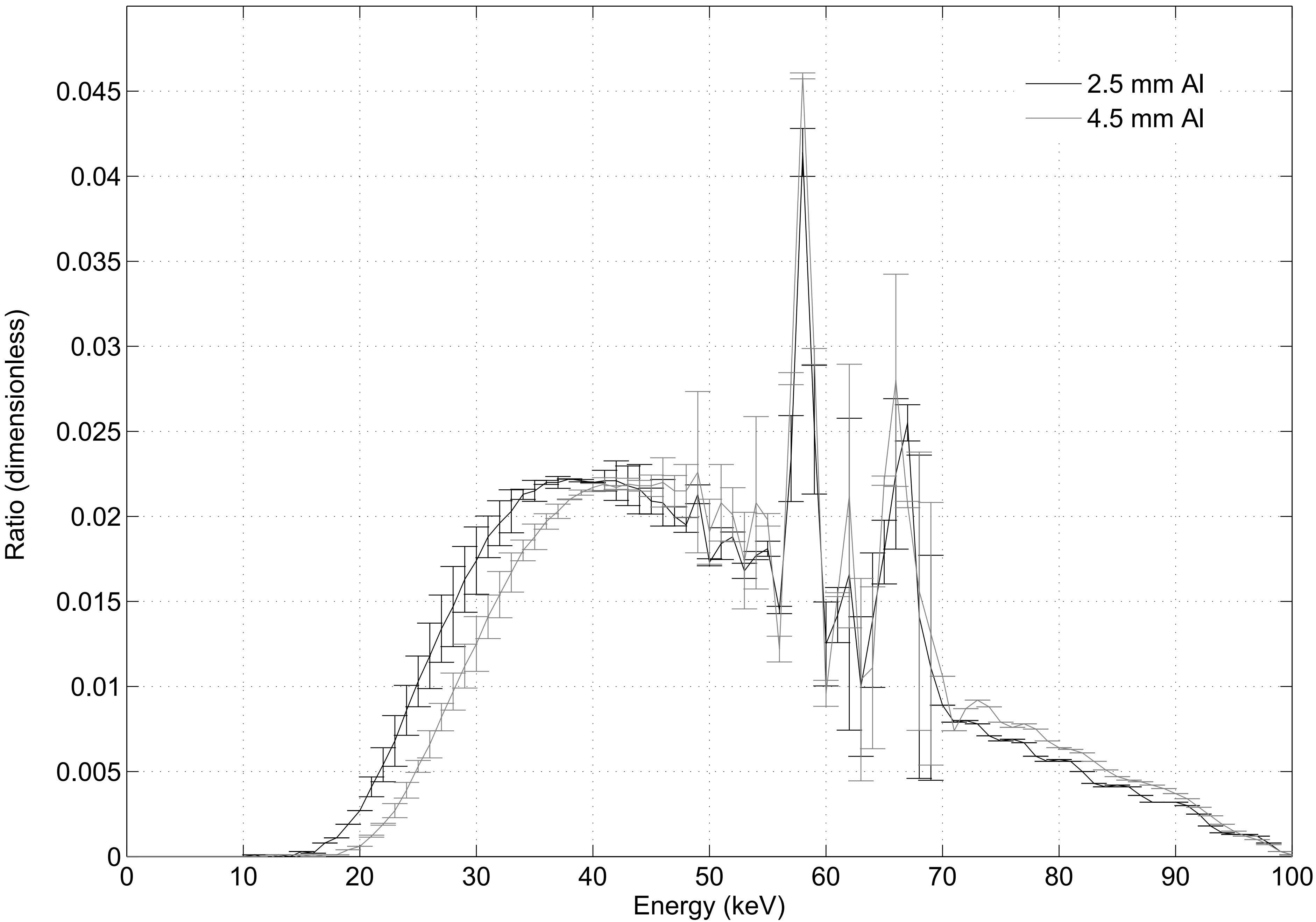

8º
11º
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Ratio (dimensionless)
0
10
20
30
40
50
60
70
80
90
100
Energy (keV)

Figure 11



2.5 mm Al
4.5 mm Al
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Ratio (dimensionless)
0
10
20
30
40
50
60
70
80
90
100
Energy (keV)