Northampton General Hospital NHS
NHS Trust

Energy spectra and transmission characteristics of scattered radiation from CT: a Monte Carlo study

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Why?

- Current transmission data for CT scatter were derived from Monte Carlo calculations (EGS4) using primary CT beams as the x-ray source[1]

- NCRP report 147 and BIR's "Radiation shielding in diagnostic radiology" use a refit of this data

- What is the transmission of true CT scatter through lead?

1. Simpkin DJ, "Transmission of scatter radiation from computed tomography (CT) scanners determined by a Monte Carlo calculation", Health Physics, 58 (3), p 363-367, 1990.

Health Physics Vol. 58, No. 3 (March), pp. 363–367, 1990
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● *Note*

As in Report No. 49 of the National Council on Radiation Protection and Measurements (NCRP 1976, hereafter referred to as NCRP No. 49), it will be assumed that the scatter spectrum from a CT scanner is of the same penetrating ability as the central ray of the primary beam.

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(CT) scanner, the
surprisingly little
provide a scatter survey from which weekly radiation doses to the unshielded scanner environs may be estimated, the physicist is not provided with an accurate estimate of the transmission of this scatter x-ray beam through the barrier materials commonly available. Thus the thicknesses required to bring a weekly dose down to an acceptable level cannot be accurately determined. If one assumes that the scatter radiation is attenuated by the barrier with a constant half-value layer (HVL) equal to that of the primary beam at very high attenuation, one will be overshielding by a possibly wasteful amount.

The purpose of this report is to present a more accurate estimate of the transmission of CT radiation spectra through Pb, concrete, gypsum wallboard, steel and plate glass as determined by a Monte Carlo calculation. As in Report No. 49 of the National Council on Radiation Protection and Measurements (NCRP 1976, hereafter referred to as NCRP No. 49), it will be assumed that the scatter spectrum from a CT scanner is of the same penetrating ability as the central ray of the primary beam. Published constant potential x-ray spectra were hardened to mimic the primary CT beam spectrum and then transmitted through various barrier thicknesses by the EGS4 Monte Carlo code to provide conservative estimates of the broad-beam scatter transmission. Note that this technique considers only the scatter radiation from the scanner. A certain, presumably small but very penetrating, amount of leakage and transmitted primary beam intensity may emanate from the CT scanner at specific locations. This problem has yet to be addressed.

THE MONTE CARLO SIMULATION

The x-ray energies to be transported through the shielding barrier by the Monte Carlo calculation were de-

Al first HVL seen for the central ray of the fan beam in clinically installed CT scanners. This was achieved by multiplying the spectra by the factor $\exp[-\mu(h\nu) \times X]$, where $\mu(h\nu)$ is the total linear attenuation coefficient for Al at energy $h\nu$ and X is 4.0 mm and 3.0 mm for the 120- and 140-kVp beams, respectively. This yields beams whose first half-value layers are calculated to be 6.9 mm Al at 120 kVp and 7.3 mm Al at 140 kVp. The spectra presented by Fewell et al. were published with a resolution of 2 keV. For these shielding calculations it is assumed that only even energy photons are present in the incident photon beam. This coarseness should be averaged out by a sufficiently broad spectrum and a large number of incident photons.

The EGS4 Monte Carlo code system (Nelson et al. 1985) was used to simulate the transport of an infinitely broad parallel beam of photons through slabs of shielding materials. The scoring geometry, energy cutoffs, and lack of bremsstrahlung modeling have been discussed previously (Simpkin 1989). The reader is referred to that paper for validation of the EGS4 code for the transport of broad diagnostic x-ray beams through slabs of barrier materials. The problem of CT scanner shielding was addressed by starting five groups of photons chosen randomly from the hardened 120- and 140-kVp spectra and transporting them with EGS4 through the shielding materials listed in Table 2 of Simpkin (1989). As few as 2000 photons per group yielded reasonable results for gypsum, while up to 50,000 photons were required for Pb. The uncertainty in the Monte Carlo results are reported as the standard deviation of the transmission determined by the five batches.

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* General Electric Corporation, Milwaukee, WI 53201.

How? Primary CT beams

- Primary CT spectra using IPEM report 78

  6.8 mm Al filtration, 10° anode, 0 % ripple

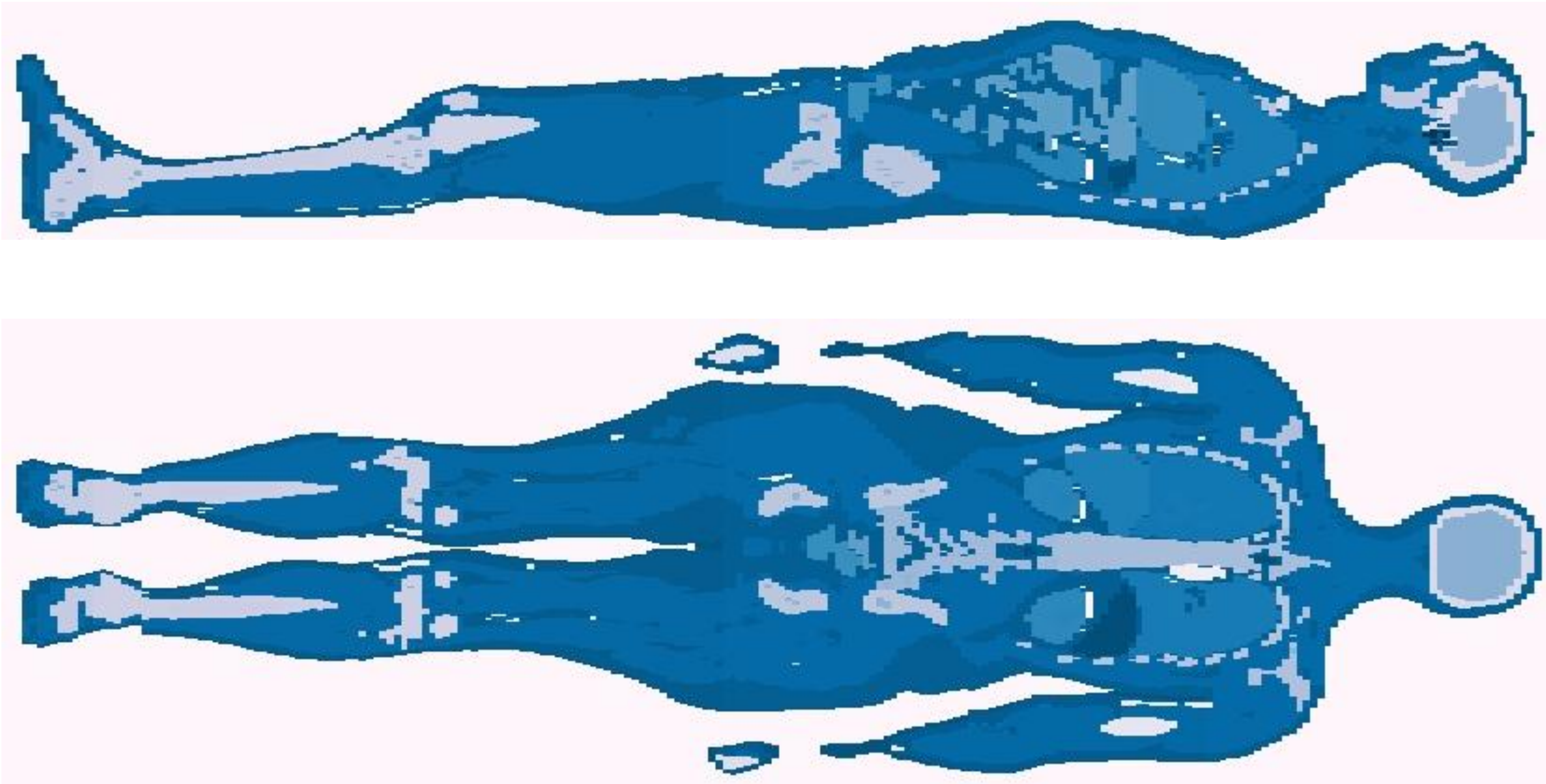
  9.8 mm Al filtration, 7° anode, 0 % ripple

  Chosen to reflect clinical diagnostic CT systems

  Beam energies of 120 and 140 kVp

  The most commonly used kVp values

How? Mathematical phantom



ICRP 110 male phantom, 73 kg, 1.76 m tall
ESGnrc phantom file created from the report data using custom-written IDL routine

How? Phantom materials

- ICRP report 110 provides elemental composition and density of the phantom media
- EGSnrc interaction cross-sections generated from these using pegs4 tool

XCOM cross-section data

AP = 0.001, lower cut-off energy for photons (MeV)

UP = 0.150, upper energy limit for photons (MeV)

AE = 0.521, lower cut-off energy for e^- (MeV)

UE = 100.0, upper energy limit for e^- (MeV)

How? Transport parameters

```
:start MC transport parameter:
   Global ECUT = 0
   Global PCUT = 0
   Global SMAX = 1e10
   ESTEPE = 0.25
   XIMAX = 0.5
   Boundary crossing algorithm = EXACT
   Skin depth for BCA = 0
   Electron-step algorithm = PRESTA-II
   Spin effects = On
   Brems angular sampling = KM
   Brems cross sections = NIST
   Photon cross sections = xcom
   Bound Compton scattering = On
   Rayleigh scattering = On
   Atomic relaxations = On
   Electron impact ionization = On
:stop MC transport parameter:
```

How? Simulation geometry

EGSnrc, Epp user code[1]

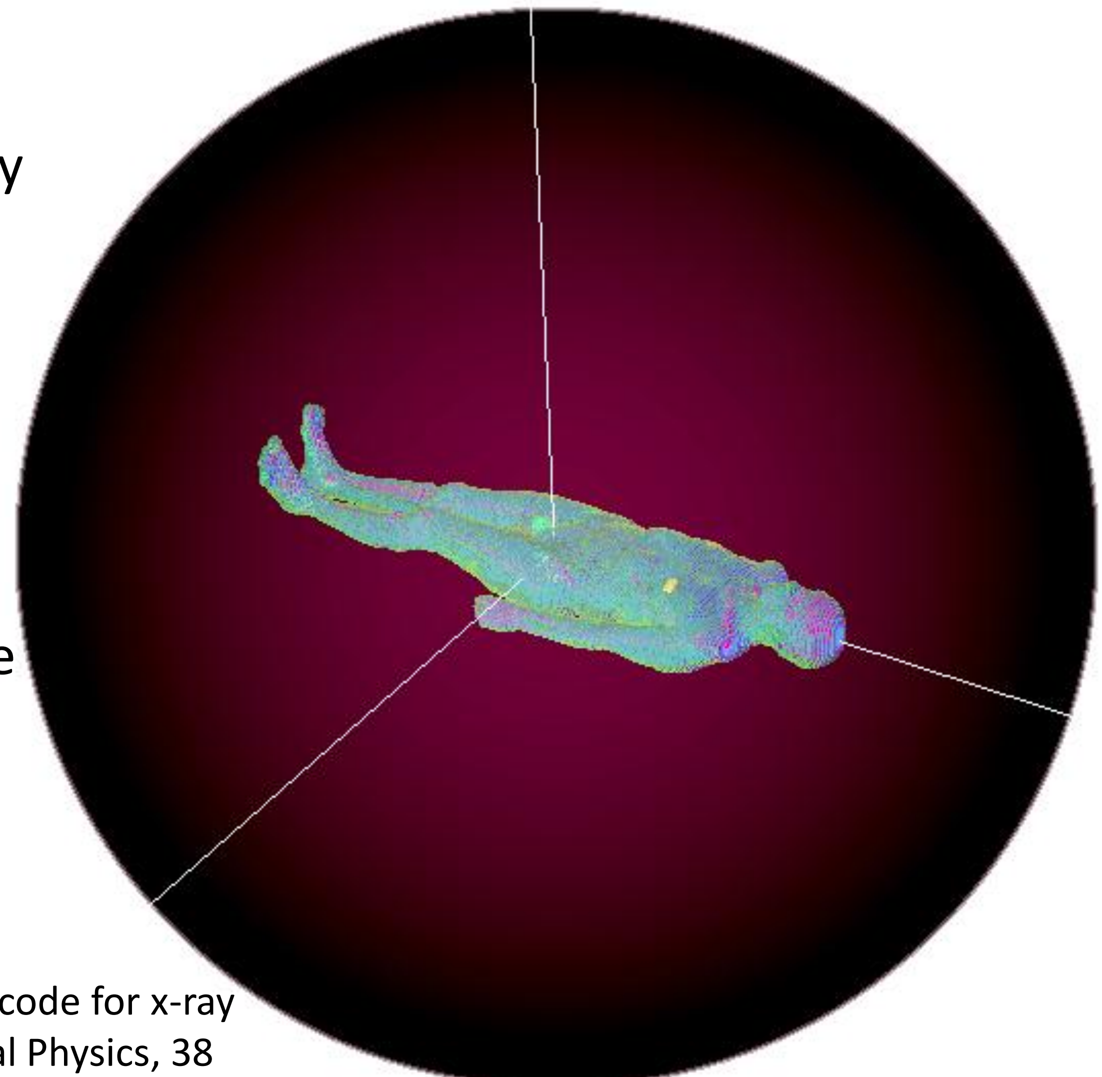
1.5 m radius spherical geometry

ICRP 110 phantom at centre

50 x 16 cm x-ray field, focus 60 cm from isocentre

4 contiguous locations along phantom (apices of lungs to the ischium of pelvis)

8 angles at each location, 0° to 315° in 45° steps



1. Lippuner J et al, “Epp: A c++ EGSnrc user code for x-ray imaging and scattering simulations”, Medical Physics, 38 (3), p 1705-1708, 2011.

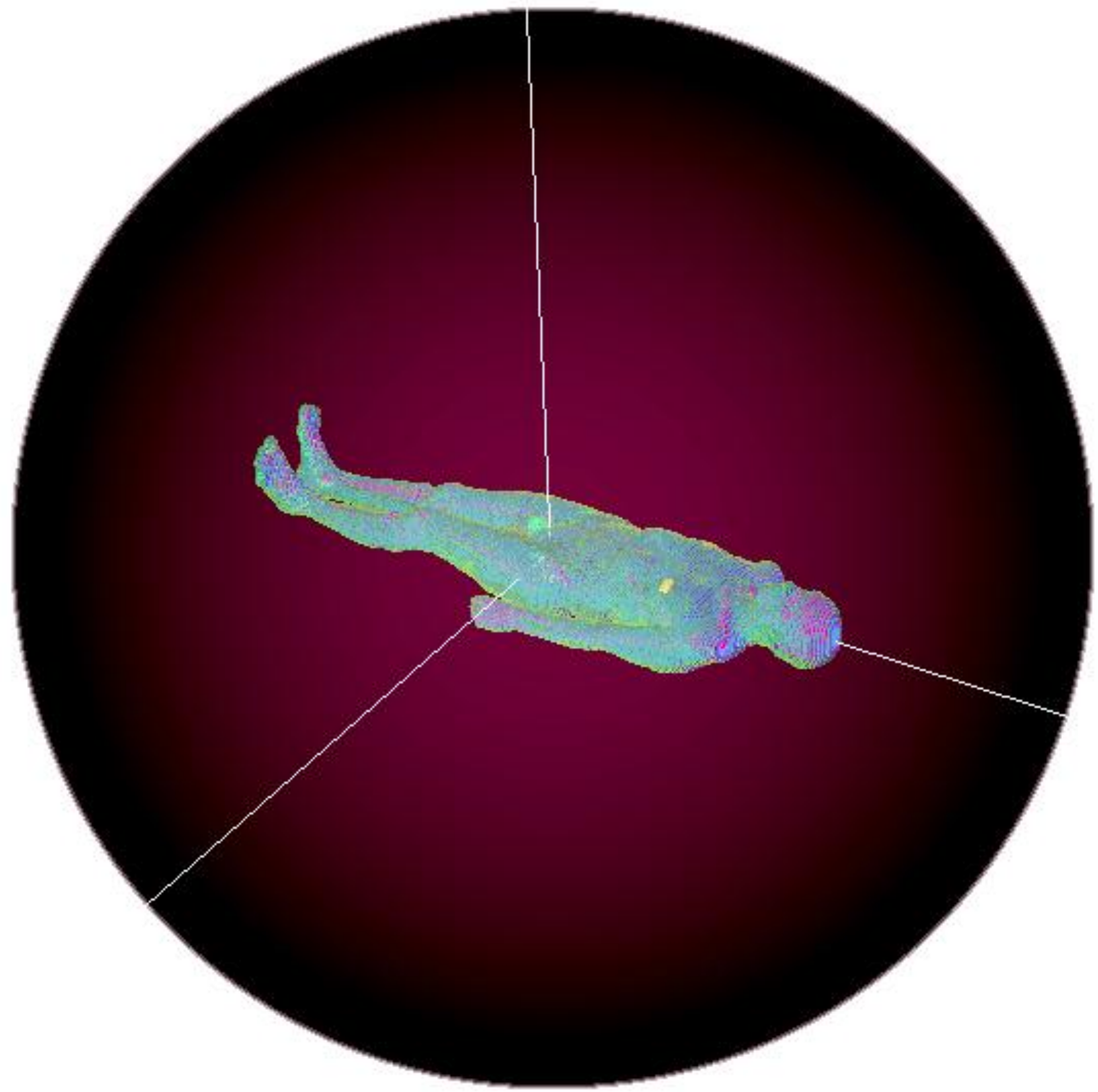
How? Simulation geometry

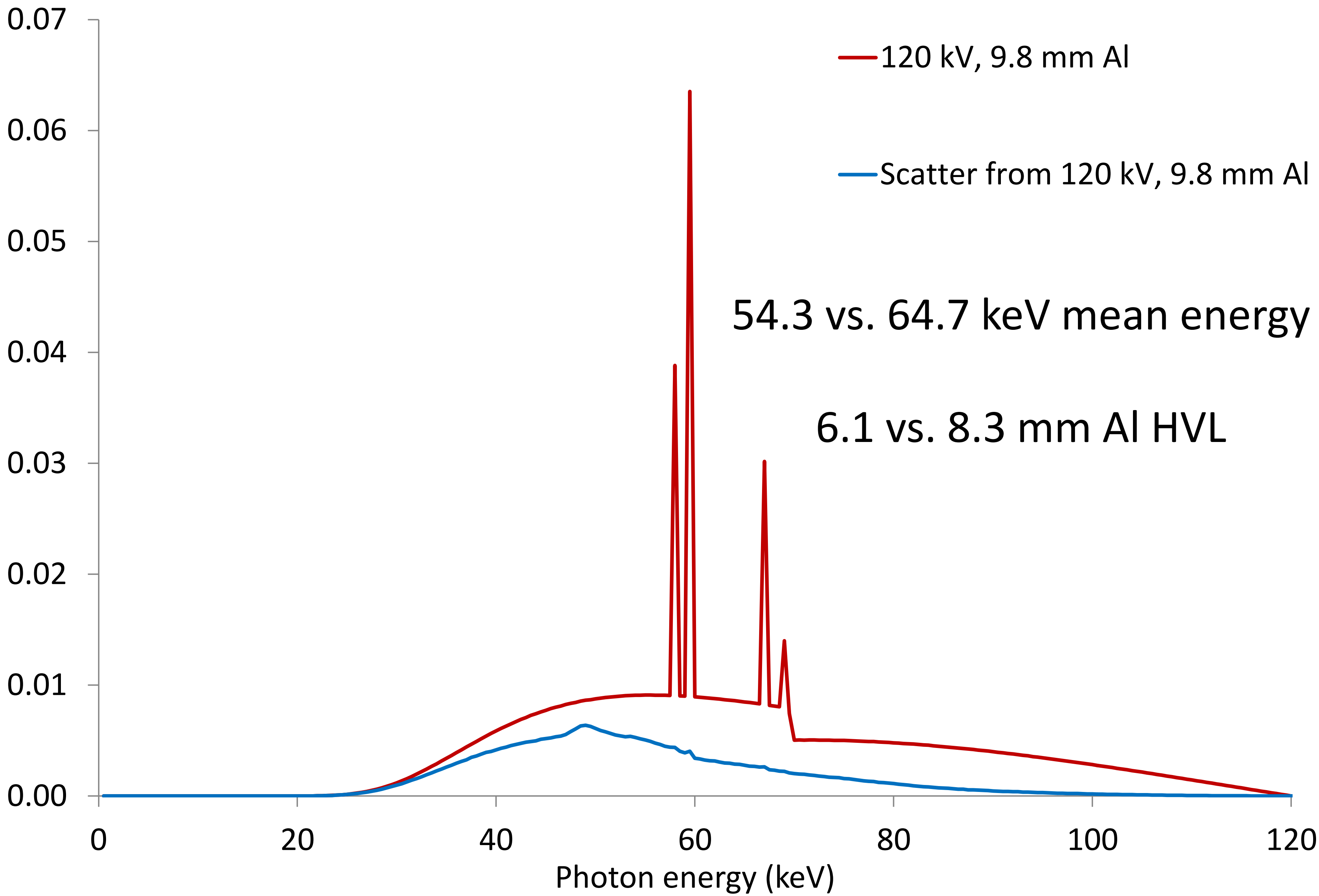
10,000,000 primary photons simulated

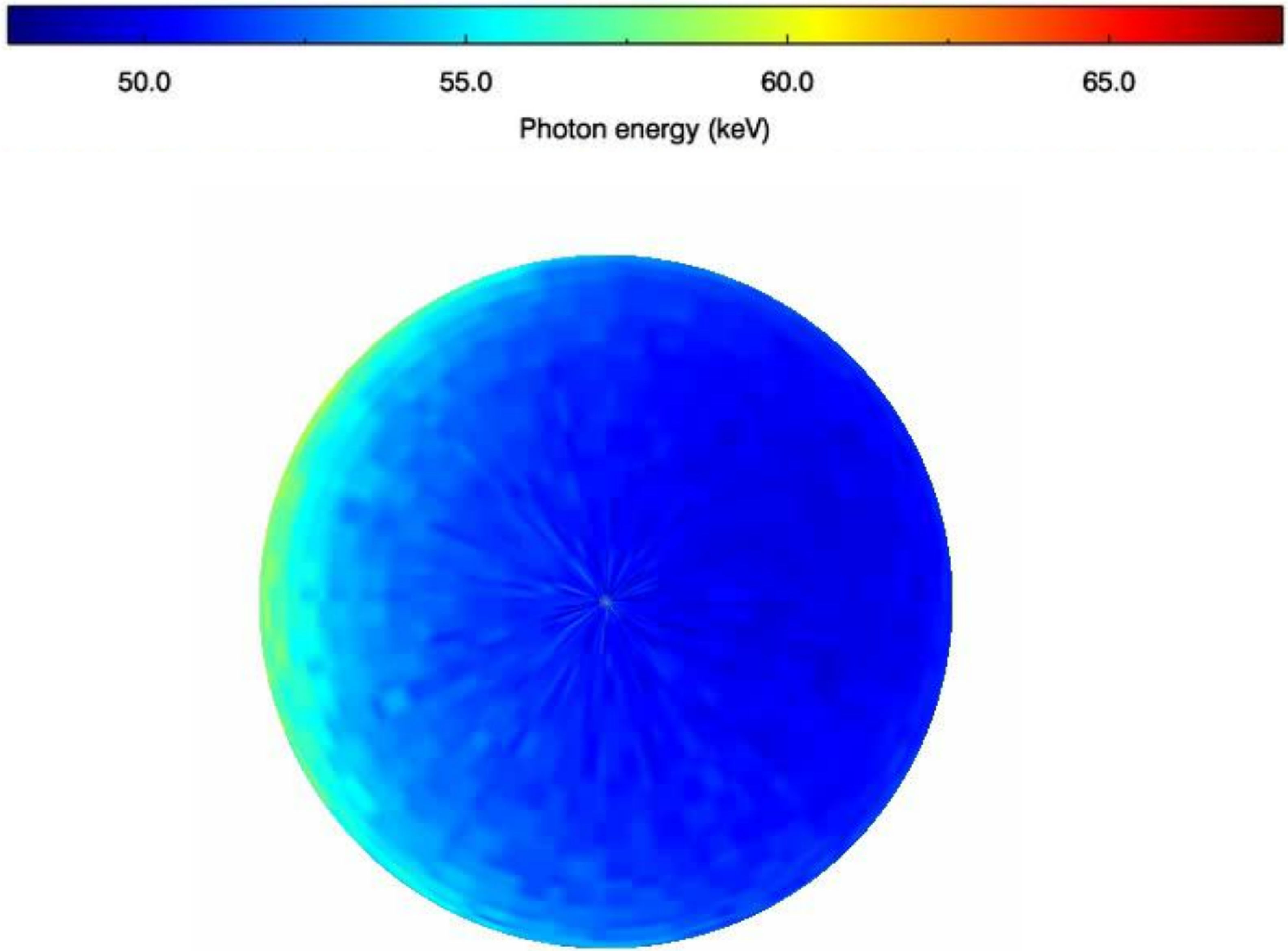
Output files log each photon that leaves the simulation geometry.

Single Compton; single Rayleigh; multiple scatter; primary; total photons

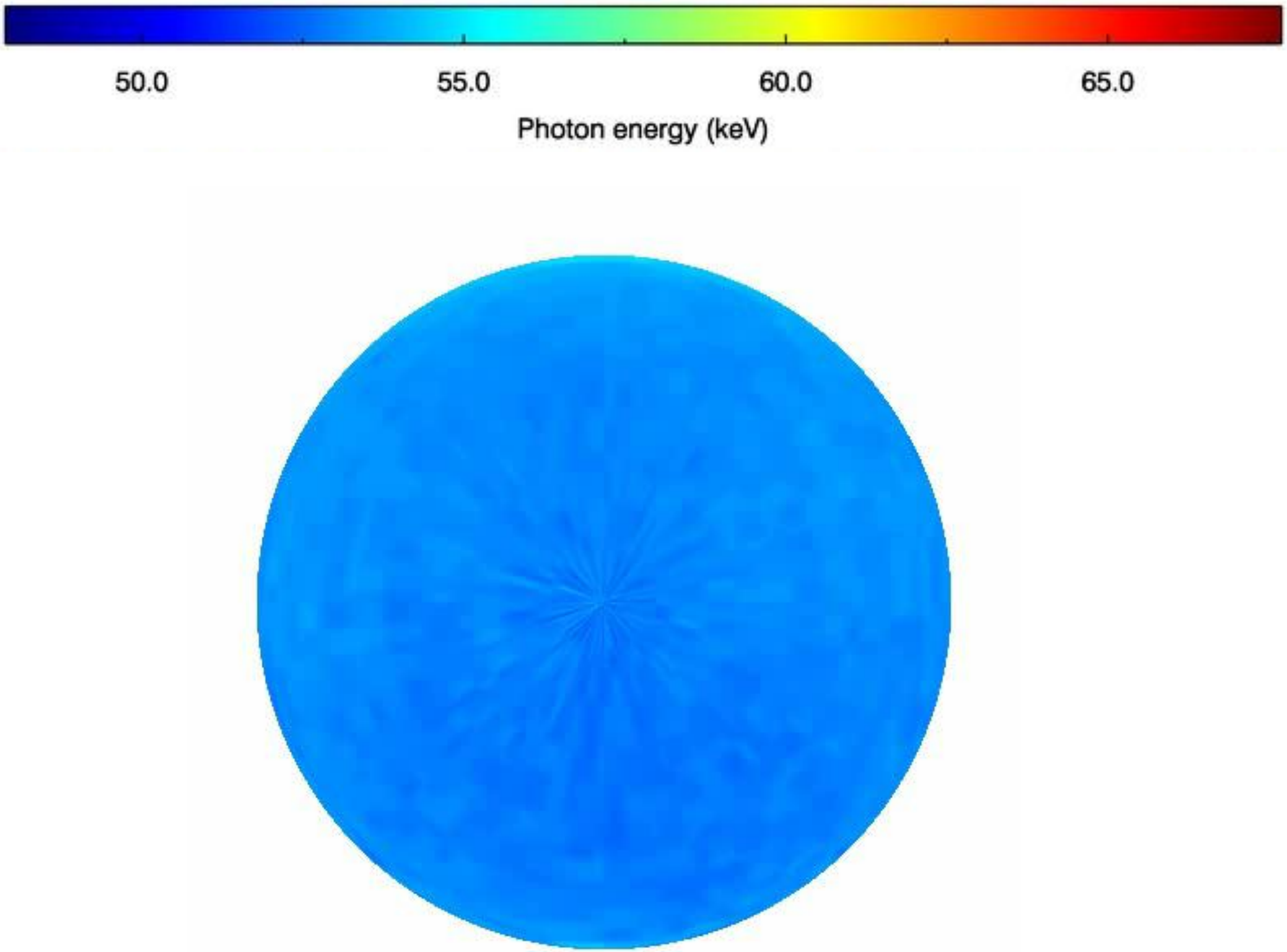
Histogram of scattered photon energies calculated to provide energy spectrum



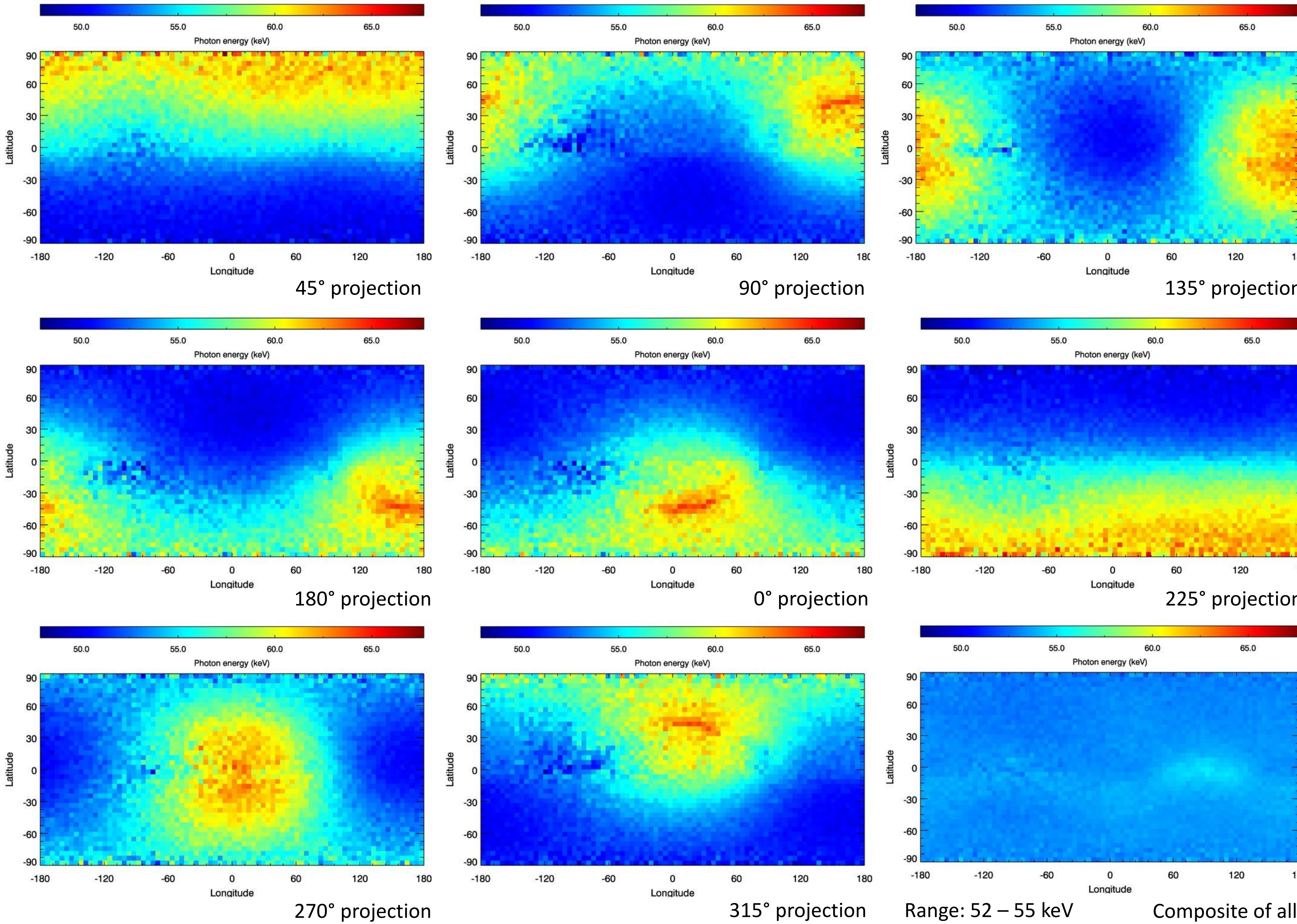

0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
20
40
60
80
100
120
Photon energy (keV)
120 kV, 9.8 mm Al
Scatter from 120 kV, 9.8 mm Al
54.3 vs. 64.7 keV mean energy
6.1 vs. 8.3 mm Al HVL



135°



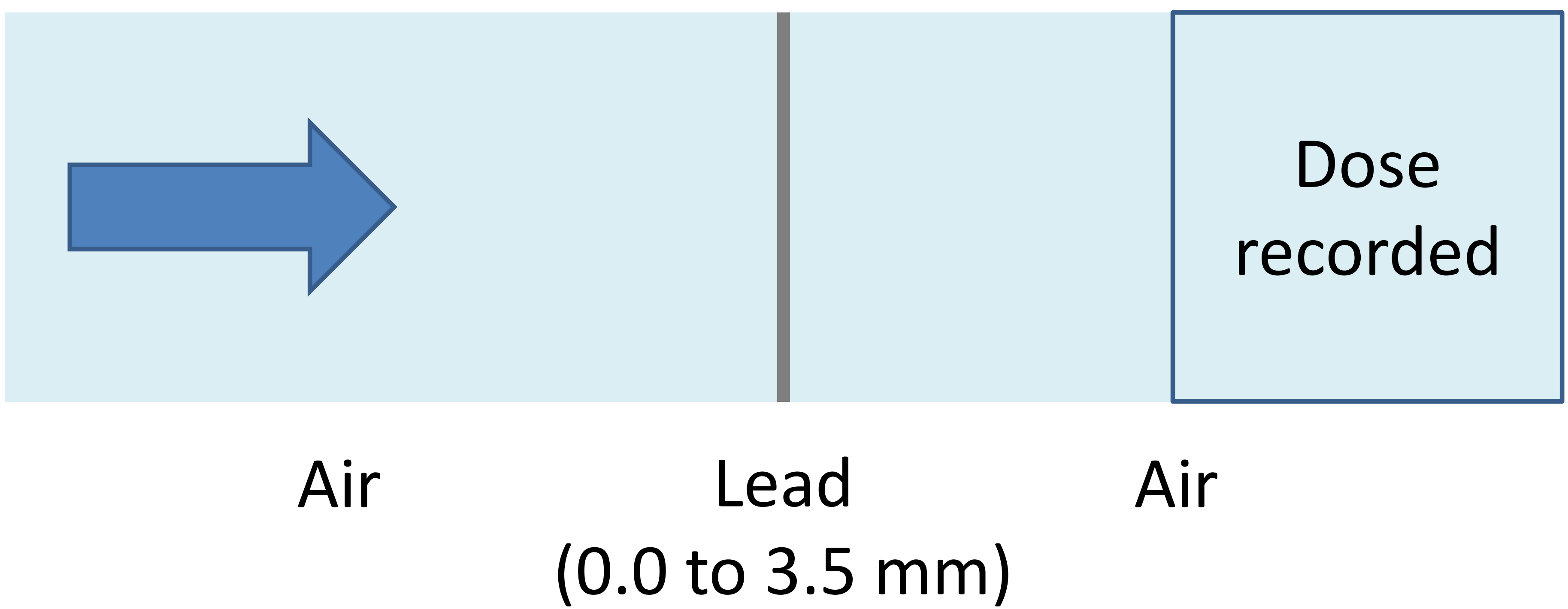
Composite of all



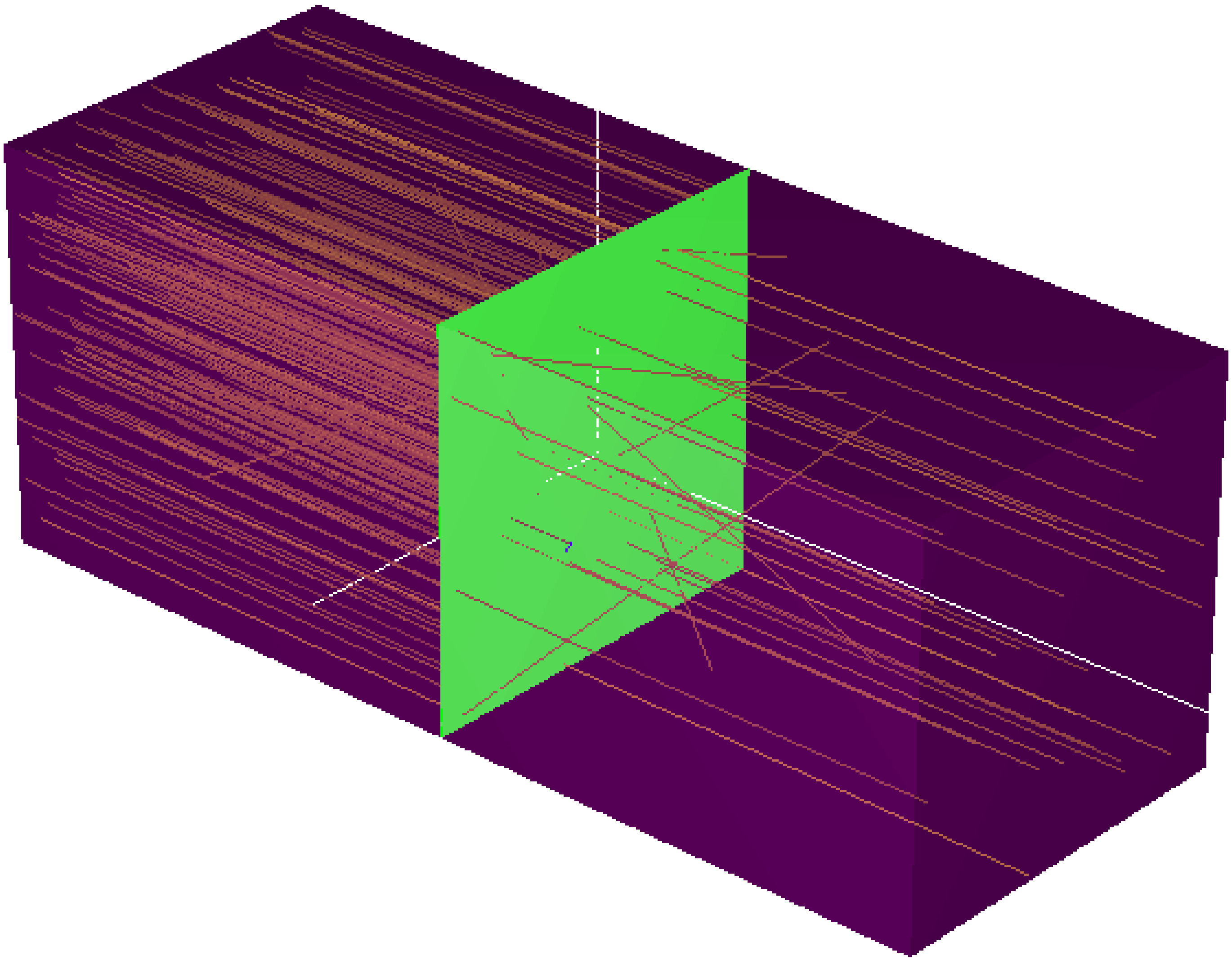
50.0
55.0
60.0
65.0
Photon energy (keV)
Latitude
Longitude
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
45° projection
90° projection
135° projection
180° projection
0° projection
225° projection
270° projection
315° projection
Range: 52 – 55 keV
Composite of all

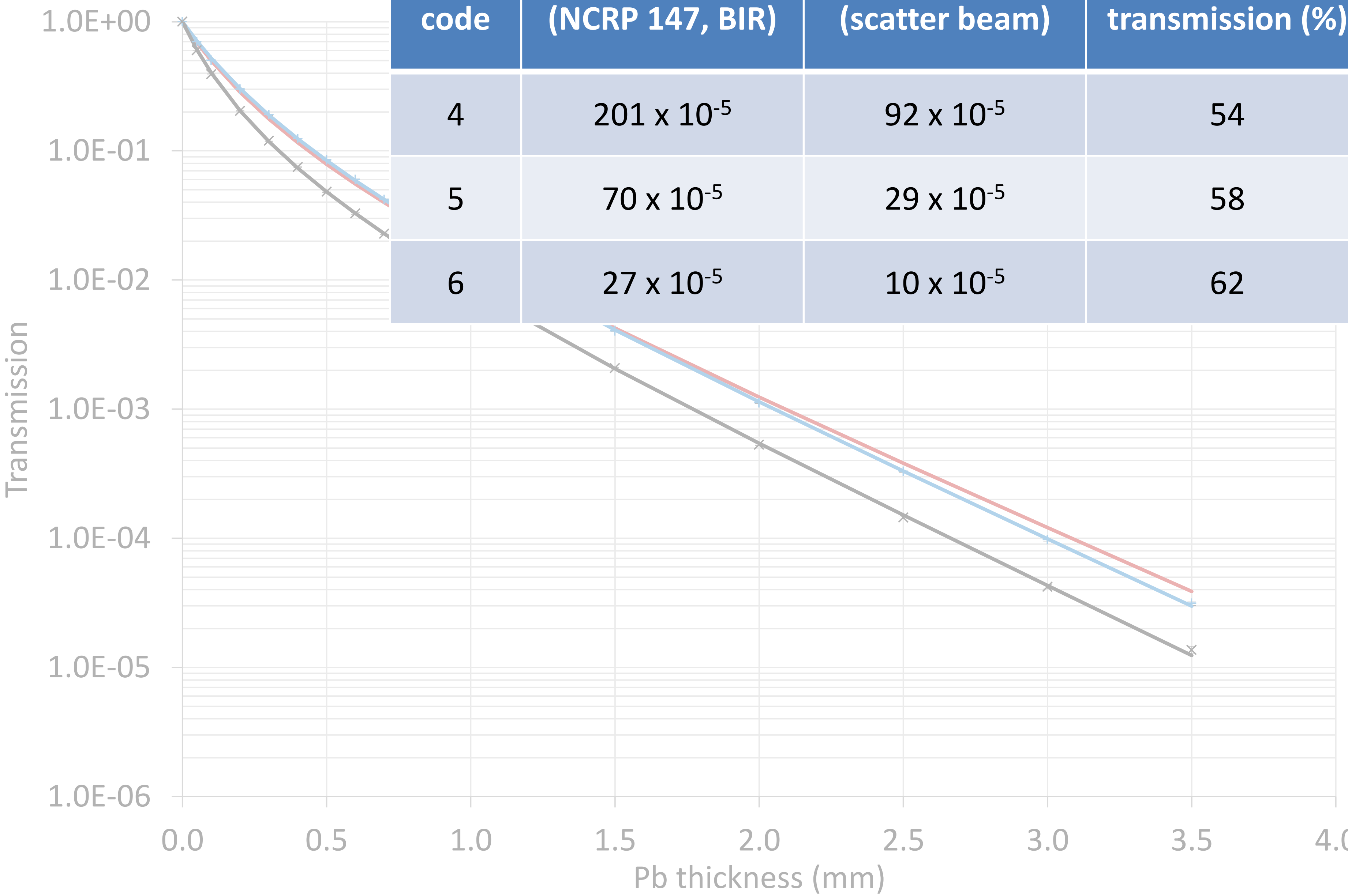
How? Transmission simulation

$1x10^7$ to $5x10^9$ photons



How? Transmission simulation





Lead code	Transmission (NCRP 147, BIR)	Transmission (scatter beam)	Reduction in transmission (%)
4	201×10^{-5}	92×10^{-5}	54
5	70×10^{-5}	29×10^{-5}	58
6	27×10^{-5}	10×10^{-5}	62

Results: Transmission coefficients

kVp	Filtration (mm Al)	α (mm^{-1})	β (mm^{-1})	γ	Limiting HVL (mm Pb)
120	NCRP 147, BIR	2.246	5.73	0.547	0.31
120	6.8	2.488 ± 0.011	9.99 ± 0.17	0.574 ± 0.012	0.28
120	9.8	2.479 ± 0.012	8.68 ± 0.15	0.569 ± 0.013	0.28
140	NCRP 147, BIR	2.009	3.99	0.342	0.35
140	6.8	2.432 ± 0.011	8.61 ± 0.16	0.616 ± 0.014	0.29
140	9.8	2.417 ± 0.012	7.41 ± 0.14	0.598 ± 0.015	0.29

Results: Does it matter?

kVp	Lead code	Transmission (NCRP 147)	Transmission (scatter beam)	Reduction in transmission (%)
120	4	201×10^{-5}	92×10^{-5}	54
120	5	70×10^{-5}	29×10^{-5}	58
120	6	27×10^{-5}	10×10^{-5}	62
140	4	205×10^{-5}	136×10^{-5}	34
140	5	71×10^{-5}	45×10^{-5}	37
140	6	28×10^{-5}	16×10^{-5}	41

Data shown for 9.8 mm Al filtration primary beams and associated scatter spectra
Change in transmission is larger for the 6.8 mm Al filtration primary beam data

Results: Does it matter?

- Room-dependent

- Two existing installations investigated

- Retrospectively shown to make a 1- or 2-code difference to the lead shielding required for some barriers

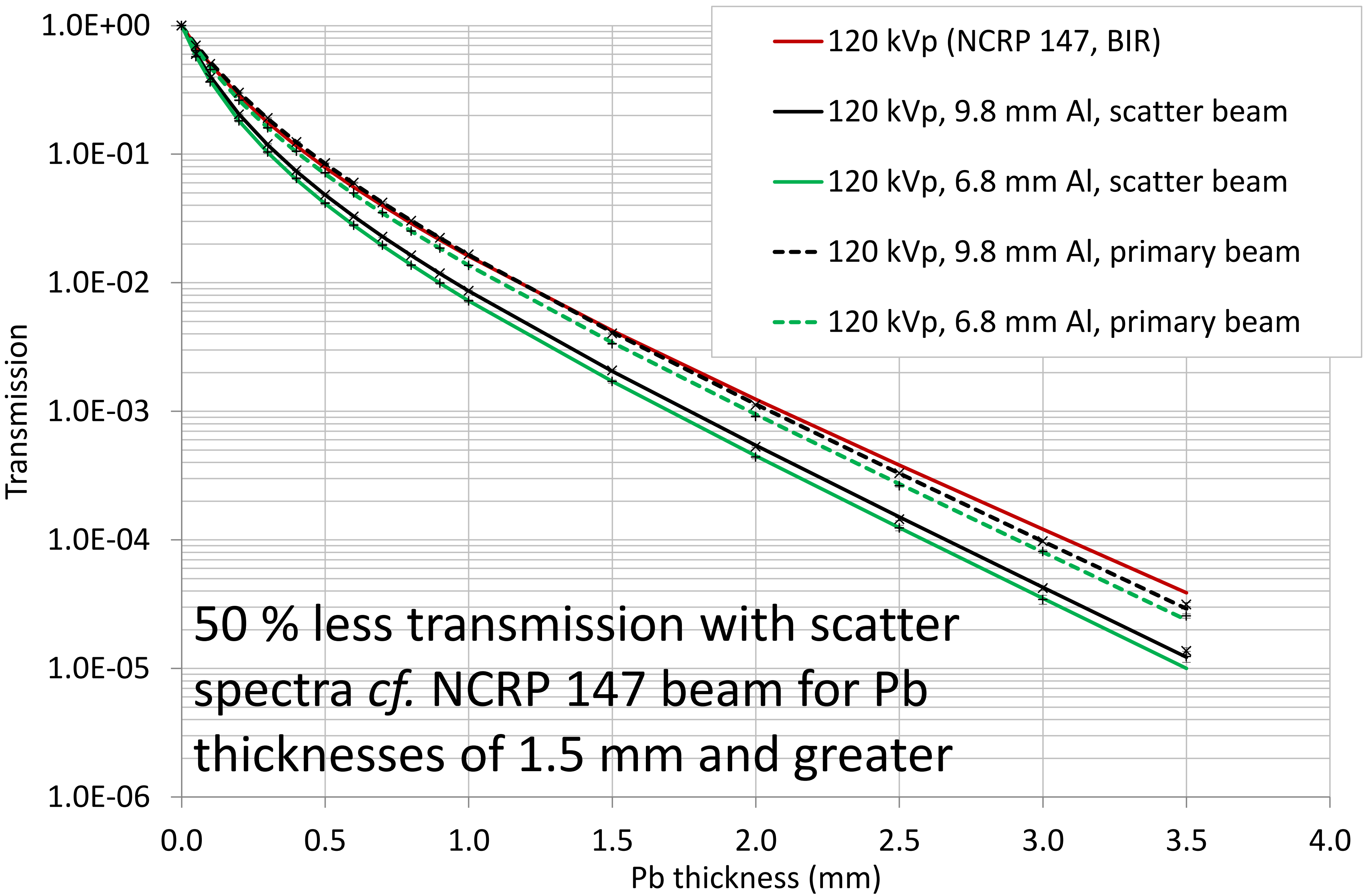
Limitations

- Scatter spectrum calculation:
  - Beam-shaping filter not considered
  - Gantry will shield against some scatter
  - Mean over chest, abdomen, pelvis
- Leakage radiation not considered
- Patient size variation not considered

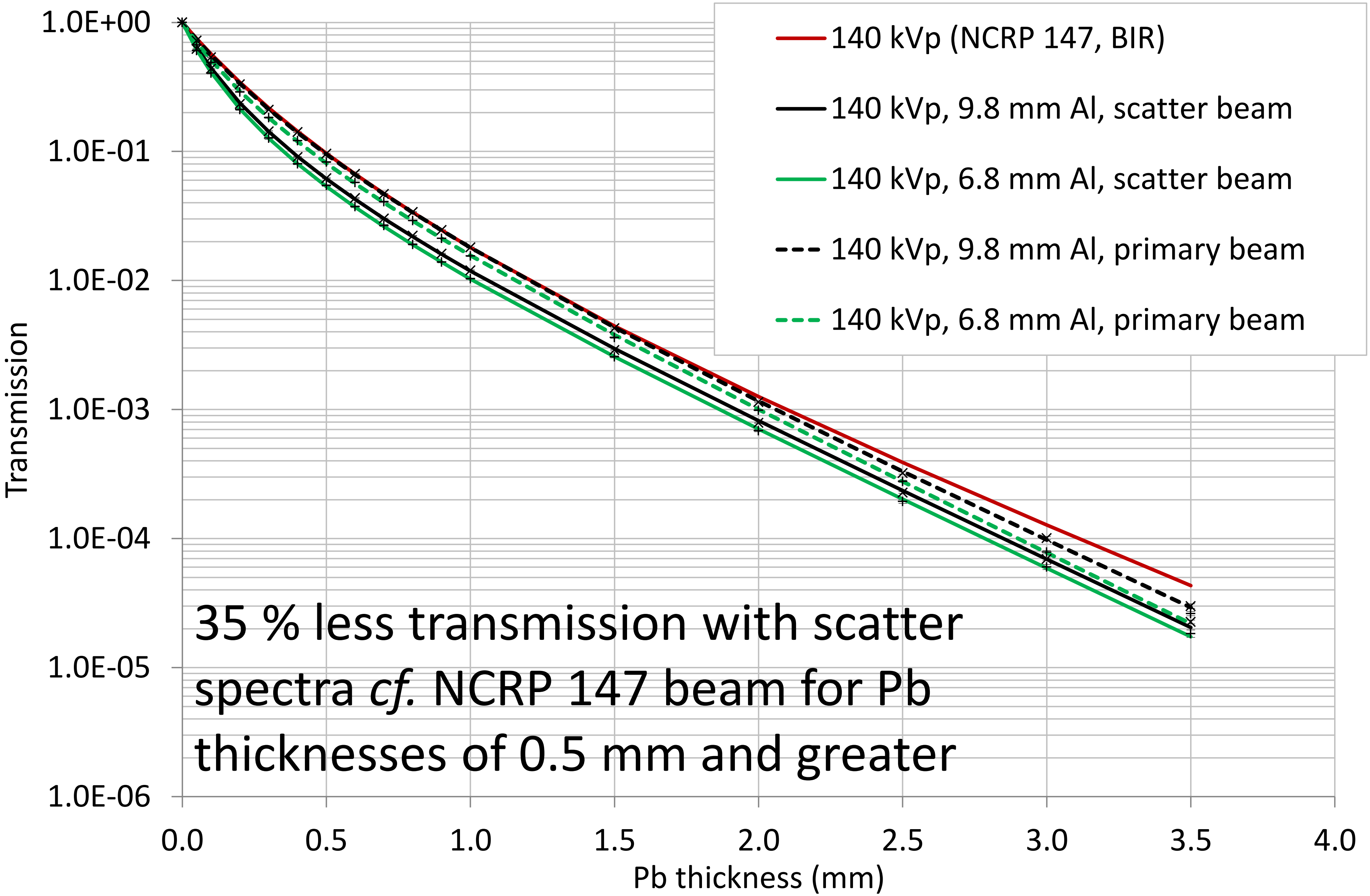
Conclusions

- Lead attenuates CT scatter spectra more than primary CT spectra by a factor of up to 2.6 for a 120 kVp, 9.8 mm Al filtration beam
- The CT scatter transmission data used in NCRP report 147 and BIR’s “Radiation shielding in diagnostic radiology” are overly cautious
- The data from this work may result in less shielding being required for CT installations

Any questions?



1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
Transmission
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Pb thickness (mm)
120 kVp (NCRP 147, BIR)
120 kVp, 9.8 mm Al, scatter beam
120 kVp, 6.8 mm Al, scatter beam
120 kVp, 9.8 mm Al, primary beam
120 kVp, 6.8 mm Al, primary beam
50 % less transmission with scatter spectra *cf.* NCRP 147 beam for Pb thicknesses of 1.5 mm and greater



140 kVp (NCRP 147, BIR)
140 kVp, 9.8 mm Al, scatter beam
140 kVp, 6.8 mm Al, scatter beam
140 kVp, 9.8 mm Al, primary beam
140 kVp, 6.8 mm Al, primary beam
Transmission
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Pb thickness (mm)
35 % less transmission with scatter spectra *cf.* NCRP 147 beam for Pb thicknesses of 0.5 mm and greater