5-gVirtualXRay_vs_Gate-detector_energy_response

March 2, 2022

[1]:
```python
from IPython.display import display
from IPython.display import Image
from utils import * # Code shared across more than one notebook
```

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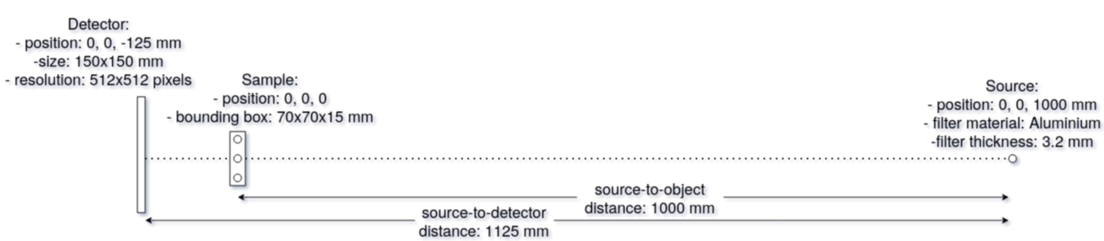
Purpose: In this notebook, we aim to demonstrate that gVirtualXRay is able to generate analytic simulations on GPU comparable to images generated with the state-of-the-art Monte Caro simulation packages. We take into account i) a realistic beam spectrum and ii) the energy response of the detector.

Material and Methods: We simulate an image with gVirtualXRay and compare it with a ground truth image. For this purpose, we use Gate, a wrapper for CERN's state-of-the-art Monte Caro simulation tool: Geant4. The number of tracked particles is 1e10.

In our simulation the source-to-object distance (SOD) is 1000mm, and the source-to-detector distance (SDD) is 1125mm. The beam spectrum is polychromatic. The voltage is 90 kV and a 3.2mm filter of aluminium is used. The energy response of the detector is considered. It mimics a 600-micron thick CsI scintillator.

[2]:
```python
Image(filename="doc/setup.png")
```

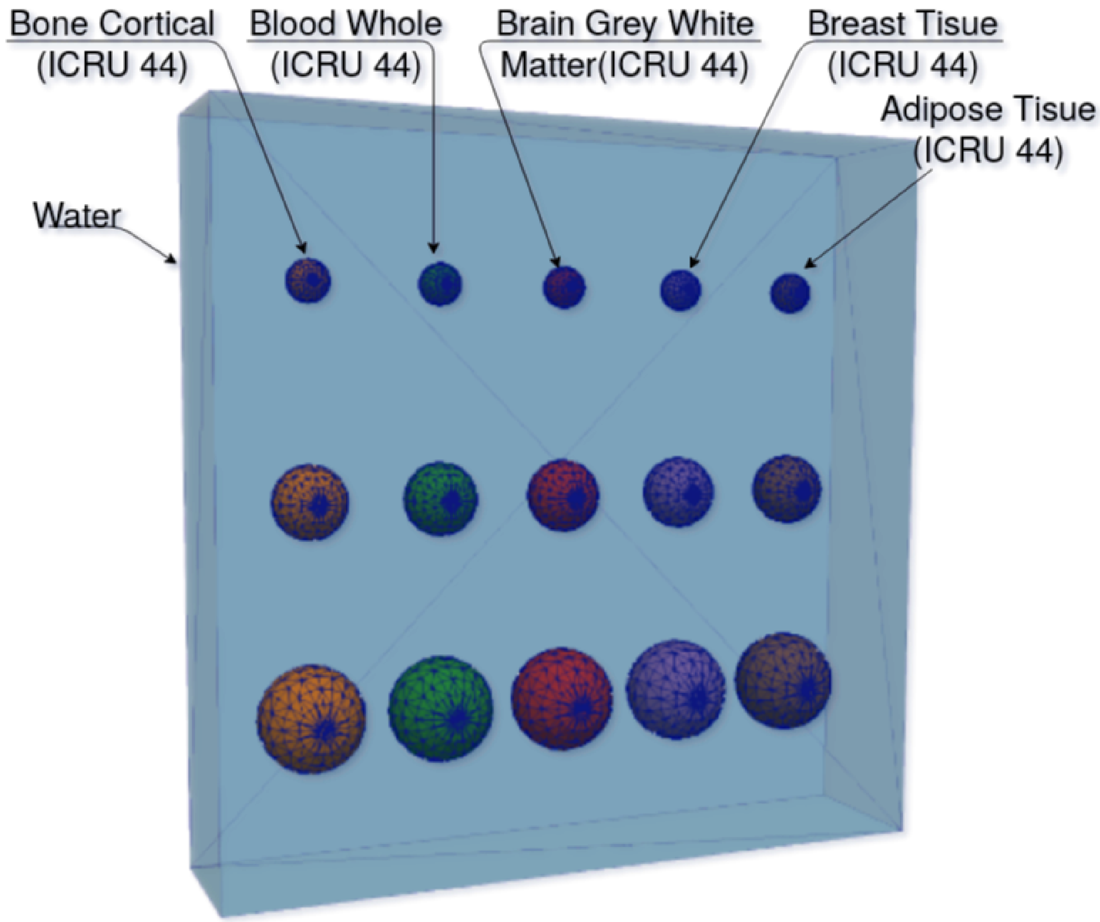
[2]:



The sample is made of a 70x70x15mm box of water, in which 5 columns of 3 spheres of different radii (2, 3.5, and 5mm) have been inserted. A given material is associated to the spheres of each column (bone (cortical), blood (whole), brain (grey/white matter), breast tissue, and adipose tissue). The columns are ordered in decreasing density. We use the definitions of tissue substitutes provided in the ICRU Report 44 by the International Commission on Radiation Units and Measurements. The material composition is available at https://physics.nist.gov/PhysRefData/XrayMassCoef/tab2.html.

[3]:
```
Image(filename="doc/sample.png", width=400)
```

[3]:



Results: The calculations were performed on the following platform:

[4]:
```
printSystemInfo()
```

```
OS:
        Linux 5.3.18-150300.59.49-default
        x86_64

CPU:
        AMD Ryzen 7 3800XT 8-Core Processor

RAM:
        63 GB
GPU:
        Name: GeForce RTX 2080 Ti
        Drivers: 455.45.01
```

```
Video memory: 11 GB
```

The Monte Carlo simulation needed 2.65e6 HS06 seconds to complete. It is equivalent to **1.15E+08** ms (i.e. ~1.3 day) on the system used. Only 24 $\pm$ 2 ms was needed with the GPU used.

The mean absolute percentage error (MAPE), also known as mean absolute percentage deviation (MAPD), between the two simulated images is **MAPE 0.69%**. The **zero-mean normalised cross-correlation is 99.85%**. The **Structural Similarity Index (SSIM) is 0.89**. As MAPE is low (close to 0), SSIM is high (close to 1), and ZNCC is high (close to 100%), we can conclude that this X-ray image simulated with gVirtualXRay on GPU in milliseconds is comparable to the same Monte Carlo simulation that ran for days.

1 Import packages

[5]:

```python
%matplotlib inline

import os # Locate files

import math
import numpy as np # Who does not use Numpy?
import pandas as pd # Load/Write CSV files

import matplotlib

from matplotlib.cm import get_cmap
import matplotlib.pyplot as plt # Plotting
from matplotlib.colors import LogNorm # Look up table
from matplotlib.colors import PowerNorm # Look up table
import matplotlib.colors as mcolors

font = {'family' : 'serif',
         #'weight' : 'bold',
          'size'   : 22
        }
matplotlib.rc('font', **font)
# matplotlib.rc('text', usetex=True)

from scipy.stats import pearsonr # Compute the correlatio coefficient

from skimage.util import compare_images # Checkboard comparison between two␣
↪images
from skimage.metrics import structural_similarity as ssim
from sklearn.metrics import mean_absolute_percentage_error as mape
from skimage.metrics import structural_similarity as ssim

from tifffile import imread, imwrite # Load/Write TIFF files
```

```
import datetime # For the runtime

import viewscad # Use OpenSCAD to create STL files

import gvxrPython3 as gvxr # Simulate X-ray images

import json2gvxr # Set gVirtualXRay and the simulation up
from utils import * # Code shared across more than one notebook
```

```
SimpleGVXR 1.0.1 (2022-02-22T14:00:25) [Compiler: GNU g++] on Linux
gVirtualXRay core library (gvxr) 1.1.5 (2022-02-22T14:00:25) [Compiler: GNU g++]
on Linux
```

2 Reference image

We first load the reference image that has been simulated using Gate wrapper for CERN's Geant4. Here we ignore scattering.

[6]:
```
Image = imread("Gate_data/energy_1e10_flat2.tif") # Already corrected
Full_field = np.ones(Image.shape) # Perfect full field image
Dark_field = np.zeros(Full_field.shape) # Perfect dark field image
```

Projections are then corrected to account for variations in beam homogeneity and in the pixel-to-pixel sensitivity of the detector. This is the projection with flat-field correction (**Proj**):

$$\mathbf{Proj} = \frac{I - D}{F - D} \tag{1}$$

where F (full fields) and D (dark fields) are projection images without sample and acquired with and without the X-ray beam turned on respectively.

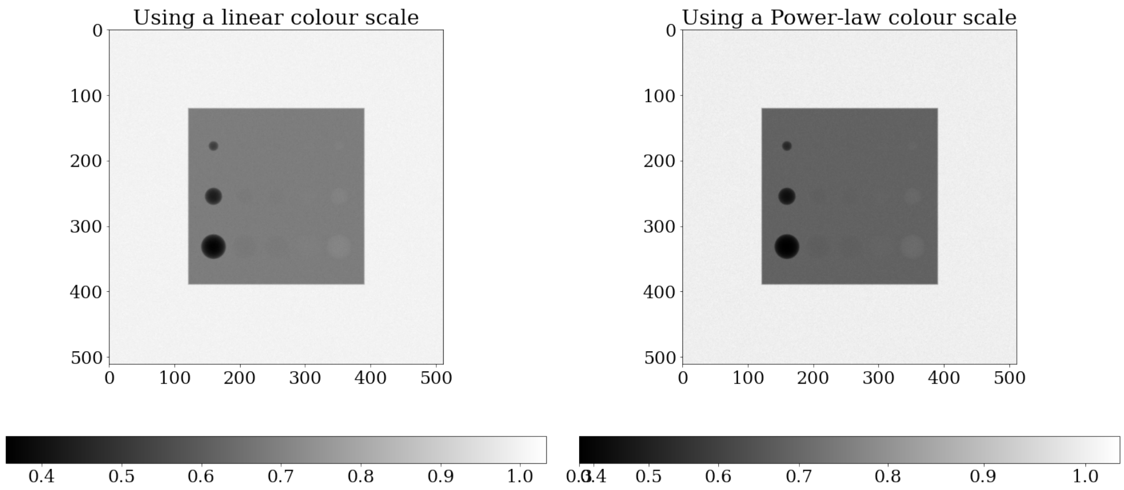
We now apply the flat-field correction to `Image`.

[7]:
```
gate_image = (Image - Dark_field) / (Full_field - Dark_field)
# gate_image = Image / np.mean(Full_field)
```

We plot the image using a linear look-up table and a power-law normalisation.

[8]:
```
displayLinearPowerScales(gate_image,
                         "Image simulated using Gate wrapper for CERN's Geant4",
                         "plots/reference_from_Gate-detResponse")
```

Image simulated using Gate wrapper for CERN's Geant4



3 Setting up gVirtualXRay

Before simulating an X-ray image using gVirtualXRay, we must create an OpenGL context.

[9]:
```
json2gvxr.initGVXR("notebook-5.json", "EGL")
```

```
Create an OpenGL context: 800x450
Wed Mar  2 12:43:40 2022 ---- Create window gvxrStatus: Create window

0
1.5
4.5.0 NVIDIA 455.45.01


Wed Mar  2 12:43:40 2022 ---- EGL version: Wed Mar  2 12:43:40 2022 ---- OpenGL
version supported by this platform OpenGL renderer:   GeForce RTX 2080
Ti/PCIe/SSE2
OpenGL version:    4.5.0 NVIDIA 455.45.01
OpenGL vender:     NVIDIA Corporation
Wed Mar  2 12:43:40 2022 ---- Use OpenGL 4.5.0 0 500 500
0 0 800 450
```

3.1 X-ray source

We create an X-ray source. It is a point source.

[10]:
```
json2gvxr.initSourceGeometry()
```

```
Set up the beam
        Source position: [0.0, 0.0, 1000.0, 'mm']
        Source shape: PointSource
```

3.2 Spectrum

The spectrum is polychromatic.

[11]:
```
spectrum, unit, k, f = json2gvxr.initSpectrum(verbose=1)
energy_set = sorted(spectrum.keys())

count_set = []

for energy in energy_set:
    count_set.append(spectrum[energy])
```

```
kVp (kV): 90
tube angle (degrees): 12
params["Source"]["Beam"] {'kvp': 90, 'tube angle': 12, 'filter': [['Al', 3.2]]}
['Al', 3.2]
Filter 3.2 mm of Al
/gate/source/mybeam/gps/emin 11.0 keV
/gate/source/mybeam/gps/emax 90.0 keV
/gate/source/mybeam/gps/histpoint 0.011 3
/gate/source/mybeam/gps/histpoint 0.0115 12
/gate/source/mybeam/gps/histpoint 0.012 40
/gate/source/mybeam/gps/histpoint 0.0125 148
/gate/source/mybeam/gps/histpoint 0.013 519
/gate/source/mybeam/gps/histpoint 0.0135 1565
/gate/source/mybeam/gps/histpoint 0.014 4090
/gate/source/mybeam/gps/histpoint 0.0145 9474
/gate/source/mybeam/gps/histpoint 0.015 19789
/gate/source/mybeam/gps/histpoint 0.0155 37826
/gate/source/mybeam/gps/histpoint 0.016 67047
/gate/source/mybeam/gps/histpoint 0.0165 111380
/gate/source/mybeam/gps/histpoint 0.017 174907
/gate/source/mybeam/gps/histpoint 0.0175 261254
/gate/source/mybeam/gps/histpoint 0.018 373324
/gate/source/mybeam/gps/histpoint 0.0185 513706
/gate/source/mybeam/gps/histpoint 0.019 684248
/gate/source/mybeam/gps/histpoint 0.0195 885574
/gate/source/mybeam/gps/histpoint 0.02 1116396
/gate/source/mybeam/gps/histpoint 0.0205 1374186
/gate/source/mybeam/gps/histpoint 0.021 1657270
/gate/source/mybeam/gps/histpoint 0.0215 1963696
/gate/source/mybeam/gps/histpoint 0.022 2288428
/gate/source/mybeam/gps/histpoint 0.0225 2625825
```

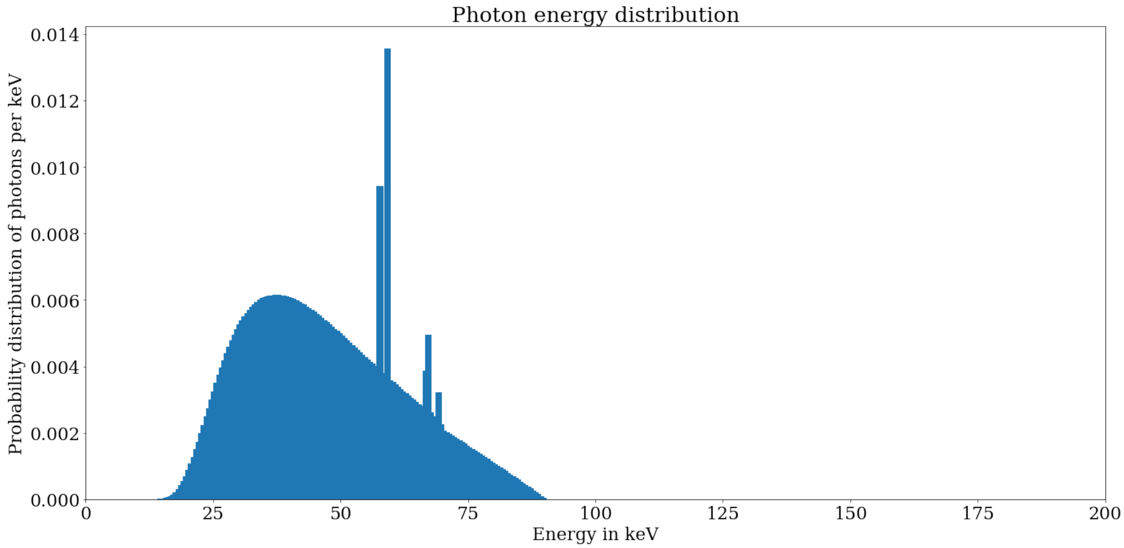
```
/gate/source/mybeam/gps/histpoint 0.023 2973622
/gate/source/mybeam/gps/histpoint 0.0235 3329919
/gate/source/mybeam/gps/histpoint 0.024 3691254
/gate/source/mybeam/gps/histpoint 0.0245 4054238
/gate/source/mybeam/gps/histpoint 0.025 4413597
/gate/source/mybeam/gps/histpoint 0.0255 4764178
/gate/source/mybeam/gps/histpoint 0.026 5105678
/gate/source/mybeam/gps/histpoint 0.0265 5438146
/gate/source/mybeam/gps/histpoint 0.027 5759789
/gate/source/mybeam/gps/histpoint 0.0275 6063438
/gate/source/mybeam/gps/histpoint 0.028 6345801
/gate/source/mybeam/gps/histpoint 0.0285 6611838
/gate/source/mybeam/gps/histpoint 0.029 6862872
/gate/source/mybeam/gps/histpoint 0.0295 7098600
/gate/source/mybeam/gps/histpoint 0.03 7314860
/gate/source/mybeam/gps/histpoint 0.0305 7507984
/gate/source/mybeam/gps/histpoint 0.031 7682269
/gate/source/mybeam/gps/histpoint 0.0315 7841800
/gate/source/mybeam/gps/histpoint 0.032 7986870
/gate/source/mybeam/gps/histpoint 0.0325 8117696
/gate/source/mybeam/gps/histpoint 0.033 8234764
/gate/source/mybeam/gps/histpoint 0.0335 8338316
/gate/source/mybeam/gps/histpoint 0.034 8428981
/gate/source/mybeam/gps/histpoint 0.0345 8507251
/gate/source/mybeam/gps/histpoint 0.035 8569366
/gate/source/mybeam/gps/histpoint 0.0355 8612137
/gate/source/mybeam/gps/histpoint 0.036 8640866
/gate/source/mybeam/gps/histpoint 0.0365 8660454
/gate/source/mybeam/gps/histpoint 0.037 8671256
/gate/source/mybeam/gps/histpoint 0.0375 8673875
/gate/source/mybeam/gps/histpoint 0.038 8668661
/gate/source/mybeam/gps/histpoint 0.0385 8656161
/gate/source/mybeam/gps/histpoint 0.039 8636823
/gate/source/mybeam/gps/histpoint 0.0395 8611011
/gate/source/mybeam/gps/histpoint 0.04 8576366
/gate/source/mybeam/gps/histpoint 0.0405 8530744
/gate/source/mybeam/gps/histpoint 0.041 8477772
/gate/source/mybeam/gps/histpoint 0.0415 8420667
/gate/source/mybeam/gps/histpoint 0.042 8359784
/gate/source/mybeam/gps/histpoint 0.0425 8295281
/gate/source/mybeam/gps/histpoint 0.043 8227457
/gate/source/mybeam/gps/histpoint 0.0435 8156546
/gate/source/mybeam/gps/histpoint 0.044 8082912
/gate/source/mybeam/gps/histpoint 0.0445 8006737
/gate/source/mybeam/gps/histpoint 0.045 7926479
/gate/source/mybeam/gps/histpoint 0.0455 7840686
/gate/source/mybeam/gps/histpoint 0.046 7751514
/gate/source/mybeam/gps/histpoint 0.0465 7661091
```

```
/gate/source/mybeam/gps/histpoint 0.047 7569425
/gate/source/mybeam/gps/histpoint 0.0475 7476829
/gate/source/mybeam/gps/histpoint 0.048 7383252
/gate/source/mybeam/gps/histpoint 0.0485 7288972
/gate/source/mybeam/gps/histpoint 0.049 7193968
/gate/source/mybeam/gps/histpoint 0.0495 7098483
/gate/source/mybeam/gps/histpoint 0.05 7001512
/gate/source/mybeam/gps/histpoint 0.0505 6901928
/gate/source/mybeam/gps/histpoint 0.051 6801288
/gate/source/mybeam/gps/histpoint 0.0515 6700538
/gate/source/mybeam/gps/histpoint 0.052 6599991
/gate/source/mybeam/gps/histpoint 0.0525 6499522
/gate/source/mybeam/gps/histpoint 0.053 6399365
/gate/source/mybeam/gps/histpoint 0.0535 6299498
/gate/source/mybeam/gps/histpoint 0.054 6199931
/gate/source/mybeam/gps/histpoint 0.0545 6100829
/gate/source/mybeam/gps/histpoint 0.055 6001327
/gate/source/mybeam/gps/histpoint 0.0555 5901063
/gate/source/mybeam/gps/histpoint 0.056 5800552
/gate/source/mybeam/gps/histpoint 0.0565 5700728
/gate/source/mybeam/gps/histpoint 0.057 5601473
/gate/source/mybeam/gps/histpoint 0.0575 9420198
/gate/source/mybeam/gps/histpoint 0.058 9322295
/gate/source/mybeam/gps/histpoint 0.0585 5307697
/gate/source/mybeam/gps/histpoint 0.059 12194183
/gate/source/mybeam/gps/histpoint 0.0595 12098117
/gate/source/mybeam/gps/histpoint 0.06 5019438
/gate/source/mybeam/gps/histpoint 0.0605 4923665
/gate/source/mybeam/gps/histpoint 0.061 4828291
/gate/source/mybeam/gps/histpoint 0.0615 4733613
/gate/source/mybeam/gps/histpoint 0.062 4639626
/gate/source/mybeam/gps/histpoint 0.0625 4546434
/gate/source/mybeam/gps/histpoint 0.063 4453955
/gate/source/mybeam/gps/histpoint 0.0635 4362293
/gate/source/mybeam/gps/histpoint 0.064 4271171
/gate/source/mybeam/gps/histpoint 0.0645 4180785
/gate/source/mybeam/gps/histpoint 0.065 4090597
/gate/source/mybeam/gps/histpoint 0.0655 4000614
/gate/source/mybeam/gps/histpoint 0.066 3911251
/gate/source/mybeam/gps/histpoint 0.0665 4668514
/gate/source/mybeam/gps/histpoint 0.067 6222942
/gate/source/mybeam/gps/histpoint 0.0675 5331495
/gate/source/mybeam/gps/histpoint 0.068 3602495
/gate/source/mybeam/gps/histpoint 0.0685 3474545
/gate/source/mybeam/gps/histpoint 0.069 3982533
/gate/source/mybeam/gps/histpoint 0.0695 3862004
/gate/source/mybeam/gps/histpoint 0.07 3059564
/gate/source/mybeam/gps/histpoint 0.0705 2892527
```

```
/gate/source/mybeam/gps/histpoint 0.071 2820640
/gate/source/mybeam/gps/histpoint 0.0715 2748965
/gate/source/mybeam/gps/histpoint 0.072 2677389
/gate/source/mybeam/gps/histpoint 0.0725 2605965
/gate/source/mybeam/gps/histpoint 0.073 2534576
/gate/source/mybeam/gps/histpoint 0.0735 2463286
/gate/source/mybeam/gps/histpoint 0.074 2391944
/gate/source/mybeam/gps/histpoint 0.0745 2320609
/gate/source/mybeam/gps/histpoint 0.075 2249241
/gate/source/mybeam/gps/histpoint 0.0755 2177874
/gate/source/mybeam/gps/histpoint 0.076 2106502
/gate/source/mybeam/gps/histpoint 0.0765 2034998
/gate/source/mybeam/gps/histpoint 0.077 1963461
/gate/source/mybeam/gps/histpoint 0.0775 1891761
/gate/source/mybeam/gps/histpoint 0.078 1820012
/gate/source/mybeam/gps/histpoint 0.0785 1748038
/gate/source/mybeam/gps/histpoint 0.079 1675960
/gate/source/mybeam/gps/histpoint 0.0795 1603727
/gate/source/mybeam/gps/histpoint 0.08 1531245
/gate/source/mybeam/gps/histpoint 0.0805 1458517
/gate/source/mybeam/gps/histpoint 0.081 1385508
/gate/source/mybeam/gps/histpoint 0.0815 1312412
/gate/source/mybeam/gps/histpoint 0.082 1239070
/gate/source/mybeam/gps/histpoint 0.0825 1165607
/gate/source/mybeam/gps/histpoint 0.083 1091859
/gate/source/mybeam/gps/histpoint 0.0835 1017894
/gate/source/mybeam/gps/histpoint 0.084 943704
/gate/source/mybeam/gps/histpoint 0.0845 869238
/gate/source/mybeam/gps/histpoint 0.085 794564
/gate/source/mybeam/gps/histpoint 0.0855 719522
/gate/source/mybeam/gps/histpoint 0.086 644162
/gate/source/mybeam/gps/histpoint 0.0865 568383
/gate/source/mybeam/gps/histpoint 0.087 492199
/gate/source/mybeam/gps/histpoint 0.0875 415628
/gate/source/mybeam/gps/histpoint 0.088 338714
/gate/source/mybeam/gps/histpoint 0.0885 261405
/gate/source/mybeam/gps/histpoint 0.089 183351
/gate/source/mybeam/gps/histpoint 0.0895 98409
/gate/source/mybeam/gps/histpoint 0.09 26369
```

Plot the spectrum

[12]:
```
plotSpectrum(k, f, 'plots/spectrum-detResponse')
```



3.3 Detector

Create a digital detector

[13]:
```
json2gvxr.initDetector()
```

```
Set up the detector
        Detector position: [0.0, 0.0, -125.0, 'mm']
        Detector up vector: [0, 1, 0]
        Detector number of pixels: [512, 512]
        Energy response: Gate_data/responseDetector.txt in MeV
        Pixel spacing: [0.29296875, 0.29296875, 'mm']
```

3.4 Model the energy response of the detector

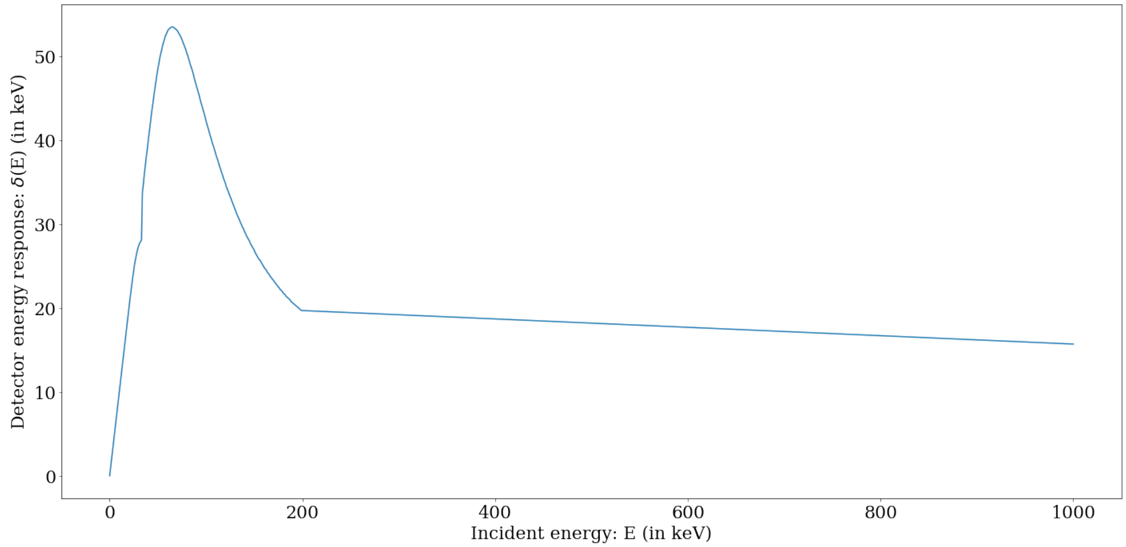
Load the energy response

[14]:
```
detector_response = np.loadtxt("Gate_data/responseDetector.txt")
```

Display the energy response

[15]:
```
plt.figure(figsize= (20,10))
# plt.title("Detector response")
plt.plot(detector_response[:,0] * 1000, detector_response[:,1] * 1000)
plt.xlabel('Incident energy: E (in keV)')
plt.ylabel('Detector energy response: $\\delta$(E) (in keV)')
```

```
plt.tight_layout()

plt.savefig('plots/detector_response.pdf')
plt.savefig('plots/detector_response.png')
```



3.5 Sample

We now create CAD models using OpenSCAD and extract the corresponding STL files.

[16]:
```
openscad_make_spheres_str = """

module make_column_of(sphere_radius, height, count)
{
    step = height / (count - 1);
    for (a = [0 : count - 1]) {
        offset = -height / 2 + step * a ;
        translate([0, offset, 0])
            sphere(sphere_radius[a], $fn=25);
    }
}

module make_row_of(radius, count, id)
{
    step = radius / (count - 1);
    for (a = [0 : count - 1]) {
        if (id == -1 || id == a) {
            offset = -radius / 2 + step * a ;
```

```
            translate([offset, 0, 0])
                children();
        }
    }
}

module make_spheres(sphere_radius, ring_radius, ring_count, column_height,␣
 ↪column_count, id = -1)
{
    make_row_of(radius = ring_radius, count = ring_count, id = id)
        make_column_of(sphere_radius, height = column_height, count =␣
 ↪column_count);
}
"""
```

The matrix

[17]:
```
openscad_matrix_str = """

color("red")
    difference() {
        scale([70, 70, 15])
            cube(1, center = true);
        make_spheres([2, 3.5, 5], 50, 5, 40, 3, -1);
}

"""
```

[18]:
```
fname = 'CAD_models/matrix.stl'
if not os.path.isfile(fname):

    r = viewscad.Renderer()
    r.render(openscad_matrix_str + openscad_make_spheres_str, outfile=fname)
```

[19]:
```
openscad_cube_str = """

color("red")
    scale([70, 70, 15])
        cube(1, center = true);

"""
```

[20]:
```
fname = 'CAD_models/cube.stl'
if not os.path.isfile(fname):

    r = viewscad.Renderer()
    r.render(openscad_cube_str, outfile='gvxr/input/cube.stl')
```

The spheres

[21]:
```
openscad_col_str_set = []

for i in range(5):
    openscad_col_str_set.append("""
    color("blue")
        make_spheres([2, 3.5, 5], 50, 5, 40, 3, """ + str(i) + ");")

    fname = 'CAD_models/col_' + str(i) + '.stl'
    if not os.path.isfile(fname):

        r = viewscad.Renderer()
        r.render(openscad_col_str_set[-1] + openscad_make_spheres_str,␣
 ↪outfile=fname)
```

Load the samples. `verbose=2` is used to print the material database for Gate. To disable it, use `verbose=0` or `verbose=1`.

[22]:
```
json2gvxr.initSamples(verbose=1)
```

```
Load the 3D data

        Load Bone_Cortical_ICRU_44 in CAD_models/col_0.stl using mm
        Load Blood_Whole_ICRU_44 in CAD_models/col_1.stl using mm
        Load Brain_Grey_White_Matter_ICRU_44 in CAD_models/col_2.stl using mm
        Load Breast_Tissue_ICRU_44 in CAD_models/col_3.stl using mm
        Load Adipose_Tissue_ICRU_44 in CAD_models/col_4.stl using mm
        Load H2O in CAD_models/cube.stl using mm

CAD_models/col_0.stl    nb_faces:       1938    nb_vertices:    5814
bounding_box (in cm):   (-2.99606, -2.19961, -0.496354) (-2, 2.49901, 0.496354)
CAD_models/col_1.stl    nb_faces:       1938    nb_vertices:    5814
bounding_box (in cm):   (-1.74606, -2.19961, -0.496354) (-0.75, 2.49901,
0.496354)
CAD_models/col_2.stl    nb_faces:       1938    nb_vertices:    5814
bounding_box (in cm):   (-0.496057, -2.19961, -0.496354)        (0.5, 2.49901,
0.496354)
CAD_models/col_3.stl    nb_faces:       1938    nb_vertices:    5814
bounding_box (in cm):   (0.753943, -2.19961, -0.496354) (1.75, 2.49901,
0.496354)
CAD_models/col_4.stl    nb_faces:       1938    nb_vertices:    5814
bounding_box (in cm):   (2.00394, -2.19961, -0.496354)  (3, 2.49901, 0.496354)
CAD_models/cube.stl     nb_faces:       12      nb_vertices:    36
bounding_box (in cm):   (-3.5, -3.5, -0.75)     (3.5, 3.5, 0.75)
```

4 Run the simulation

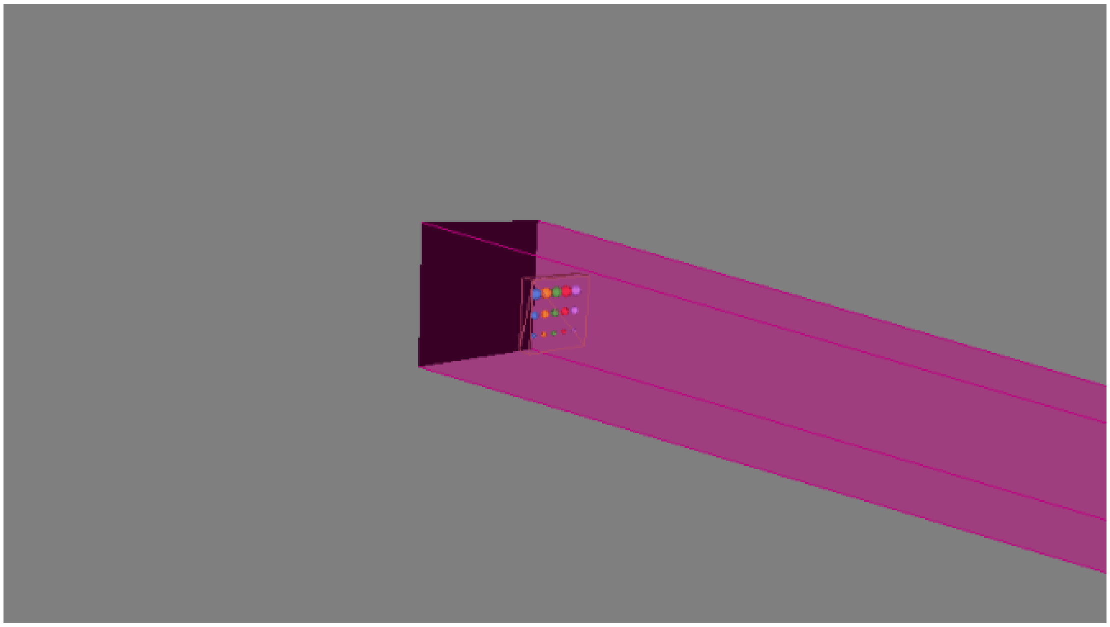
Update the 3D visualisation and take a screenshot

[23]:
```
gvxr.displayScene()

gvxr.useLighing()
gvxr.useWireframe()
gvxr.setZoom(719.6787109375)
gvxr.setSceneRotationMatrix([0.7624880075454712, 0.09040657430887222, -0.
 ↪6406543850898743, 0.0,
                             0.05501500517129898, 0.9775413870811462, 0.
 ↪20342488586902618, 0.0,
                             0.6446591019630432, -0.190354123711586, 0.
 ↪7403913140296936, 0.0,
                             0.0, 0.0, 0.0, 1.0])

gvxr.displayScene()
```

[24]:
```
screenshot = gvxr.takeScreenshot()
```

[25]:
```
plt.figure(figsize= (10,10))
plt.title("Screenshot")
plt.imshow(screenshot)
plt.axis('off')

plt.tight_layout()

plt.savefig('plots/screenshot-beam-off-detResponse.pdf')
plt.savefig('plots/screenshot-beam-off-detResponse.png')
```

Screenshot

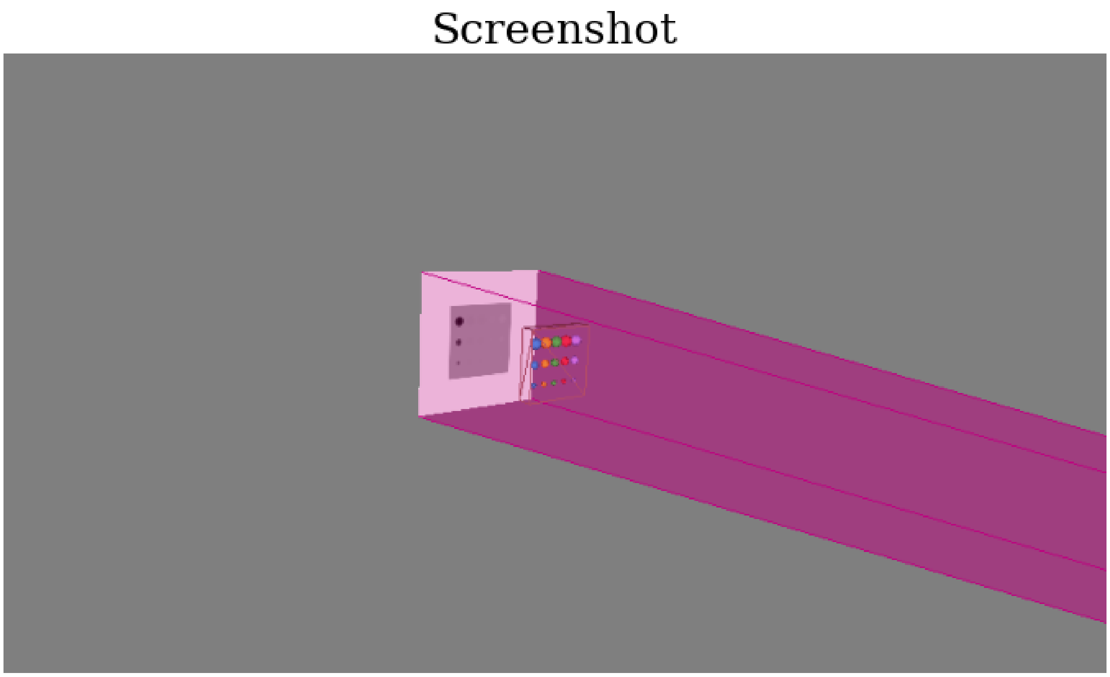


Compute an X-ray image 100 times (to gather performance statistics)

[26]:
```
# gvxr.enableArtefactFilteringOnCPU()
gvxr.enableArtefactFilteringOnGPU()
# gvxr.disableArtefactFiltering() # Spere inserts are missing with GPU␣
↪integration when a outer surface is used for the matrix


runtimes = []

for i in range(100):
    start_time = datetime.datetime.now()
    gvxr.computeXRayImage()
    end_time = datetime.datetime.now()
    delta_time = end_time - start_time
    runtimes.append(delta_time.total_seconds() * 1000)

gvxr.displayScene()
```

[27]:
```
screenshot = gvxr.takeScreenshot()

plt.figure(figsize= (10,10))
plt.title("Screenshot")
plt.imshow(screenshot)
plt.axis('off')
```

```
plt.tight_layout()

plt.savefig('plots/screenshot-beam-on-detResponse.pdf')
plt.savefig('plots/screenshot-beam-on-detResponse.png')
```



Save an X-ray image

[28]:
```
# Compute the L-buffers on the GPU and integrate on the GPU
x_ray_image_integration_GPU = np.array(gvxr.computeXRayImage())
imwrite('gVirtualXRay_output_data/projection_raw_integration_GPU_detResponse.
 ↪tif', x_ray_image_integration_GPU.astype(np.single))
```

Flat-field correction

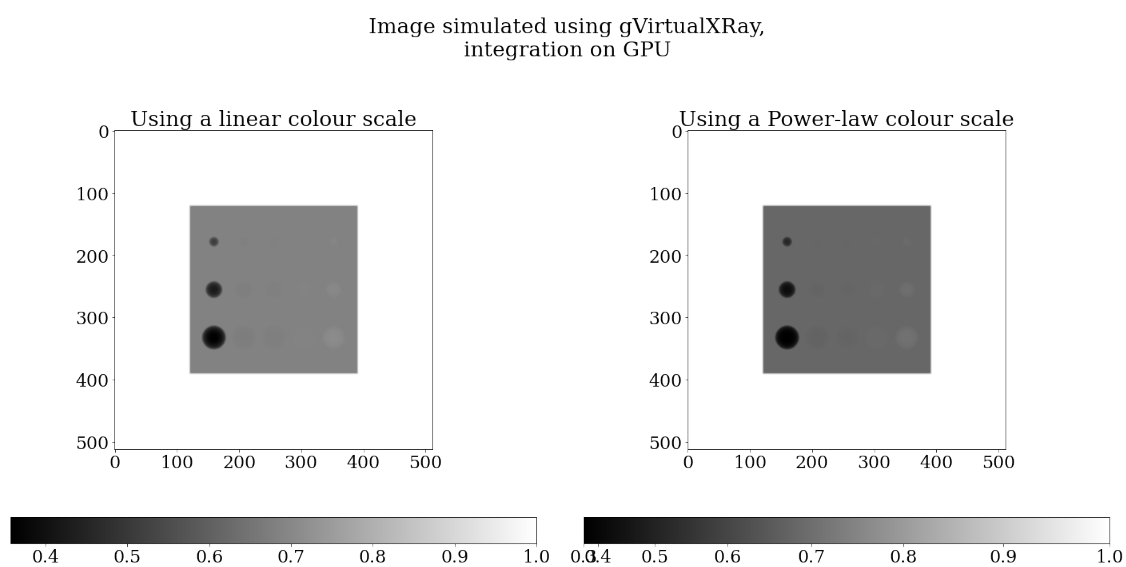
[29]:
```
total_energy_in_keV = 0.0
for energy, count in zip(energy_set, count_set):
    total_energy_in_keV += energy * count

total_energy_in_MeV = gvxr.getTotalEnergyWithDetectorResponse()
```

[30]:
```
white = np.ones(x_ray_image_integration_GPU.shape) * total_energy_in_MeV
dark = np.zeros(x_ray_image_integration_GPU.shape)

x_ray_image_integration_GPU = (x_ray_image_integration_GPU - dark) / (white -␣
 ↪dark)
```

Save the corresponding image

[31]:
```
imwrite('gVirtualXRay_output_data/
↪projection_corrected_integration_GPU_detResponse.tif',␣
↪x_ray_image_integration_GPU.astype(np.single))
```

[32]:
```
plt.figure(figsize= (20,10))

plt.suptitle("Image simulated using gVirtualXRay,\nintegration on GPU", y=1.02)

plt.subplot(121)
plt.imshow(x_ray_image_integration_GPU, cmap="gray")
plt.colorbar(orientation='horizontal')
plt.title("Using a linear colour scale")

plt.subplot(122)
plt.imshow(x_ray_image_integration_GPU, norm=PowerNorm(gamma=1./0.75),␣
↪cmap="gray")
plt.colorbar(orientation='horizontal')
plt.title("Using a Power-law colour scale")

plt.tight_layout()

plt.savefig('plots/x_ray_image_integration_GPU-detResponse.pdf')
plt.savefig('plots/x_ray_image_integration_GPU-detResponse.png')
```



5 Comparison the analytic simulation with the Monte Carlo simulation

5.1 Quantitative validation

Compute image metrics between the two simulated images:

1. mean absolute percentage error (MAPE), also known as mean absolute percentage deviation (MAPD),
2. zero-mean normalised cross-correlation (ZNCC), and
3. Structural Similarity Index (SSIM).

We use these three metrics as one is a disimilarity measurement (MAPE), two are similarity measurement (ZNCC & SSIM). MAPE and ZNCC can be expressed as a percentage, which eases the interpretation of the numerical values. SSIM is a number between 0 and 1. A good value of MAPE s 0%; of ZNCC 100%, and SSIM 1.

[33]:
```
MAPE_integration_GPU = mape(gate_image, x_ray_image_integration_GPU)
ZNCC_integration_GPU = np.mean((gate_image - gate_image.mean()) / gate_image.
 ↪std() * (x_ray_image_integration_GPU - x_ray_image_integration_GPU.mean()) /␣
 ↪x_ray_image_integration_GPU.std())
SSIM_integration_GPU = ssim(gate_image, x_ray_image_integration_GPU,␣
 ↪data_range=gate_image.max() - gate_image.min())

print("MAPE_integration_GPU:", "{0:0.2f}".format(100 * MAPE_integration_GPU) +␣
 ↪"%")
print("ZNCC_integration_GPU:", "{0:0.2f}".format(100 * ZNCC_integration_GPU) +␣
 ↪"%")
print("SSIM_integration_GPU:", "{0:0.2f}".format(SSIM_integration_GPU))
```

```
MAPE_integration_GPU: 0.69%
ZNCC_integration_GPU: 99.85%
SSIM_integration_GPU: 0.89
```

Get the total number of triangles

[34]:
```
number_of_triangles = 0

for mesh in json2gvxr.params["Samples"]:
    label = mesh["Label"]
    number_of_triangles += gvxr.getNumberOfPrimitives(label)
```

[35]:
```
runtime_avg = round(np.mean(runtimes))
runtime_std = round(np.std(runtimes))
```

Print a row of the table for the paper

```
[36]: print("Sphere inserts -- polychromatic (90 kV), detector energy response & Gate␣
    ↪& " +
          "{0:0.2f}".format(100 * MAPE_integration_GPU) + "\\%     &     " +
          "{0:0.2f}".format(100 * ZNCC_integration_GPU) + "\\%     &     " +
          "{0:0.2f}".format(SSIM_integration_GPU) + "     &     $" +
          str(json2gvxr.params["Detector"]["NumberOfPixels"][0]) + " \\pm " +␣
    ↪str(json2gvxr.params["Detector"]["NumberOfPixels"][1]) + "$     &     " +
          str(number_of_triangles) + "     &     " +
          "1.15E+08     &     " +
          "$" + str(runtime_avg) + " \\pm " + str(runtime_std) + "$ \\\\")
```

```
Sphere inserts -- polychromatic (90 kV), detector energy response & Gate &
0.69\%     &     99.85\%     &     0.89     &     $512 \pm 512$     &     9702     &
1.15E+08     &     $26 \pm 5$ \\
```

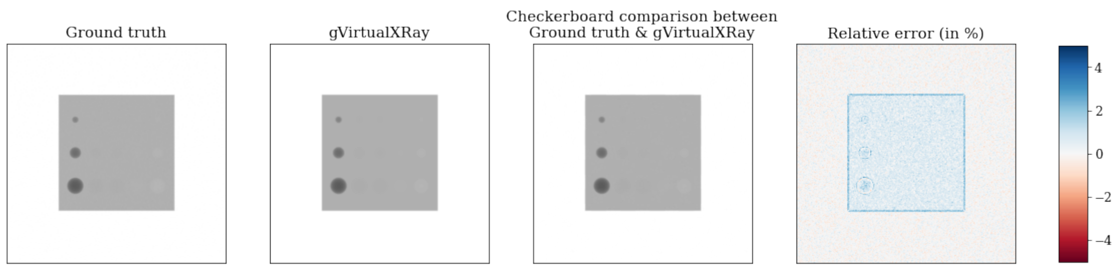
In both cases, MAPE is very small (less than 1%), ZNCC is very high (more than 99%), and SSIM is very high (almost 1). We can conclude that the two images are similar. The main difference lie in the Poisson noise affecting the Monte Carlo simulation.

5.2 Qualitative validation

Checkboard comparison

```
[37]: font = {'size'    : 12.5
              }
      matplotlib.rc('font', **font)
```

```
[38]: fullCompareImages(gate_image,
                        x_ray_image_integration_GPU,
                        "gVirtualXRay",
                        "plots/full_comparison_integration_GPU-detResponse",
                        False,
                        0,
                        1,
                        avoid_div_0=False)
```



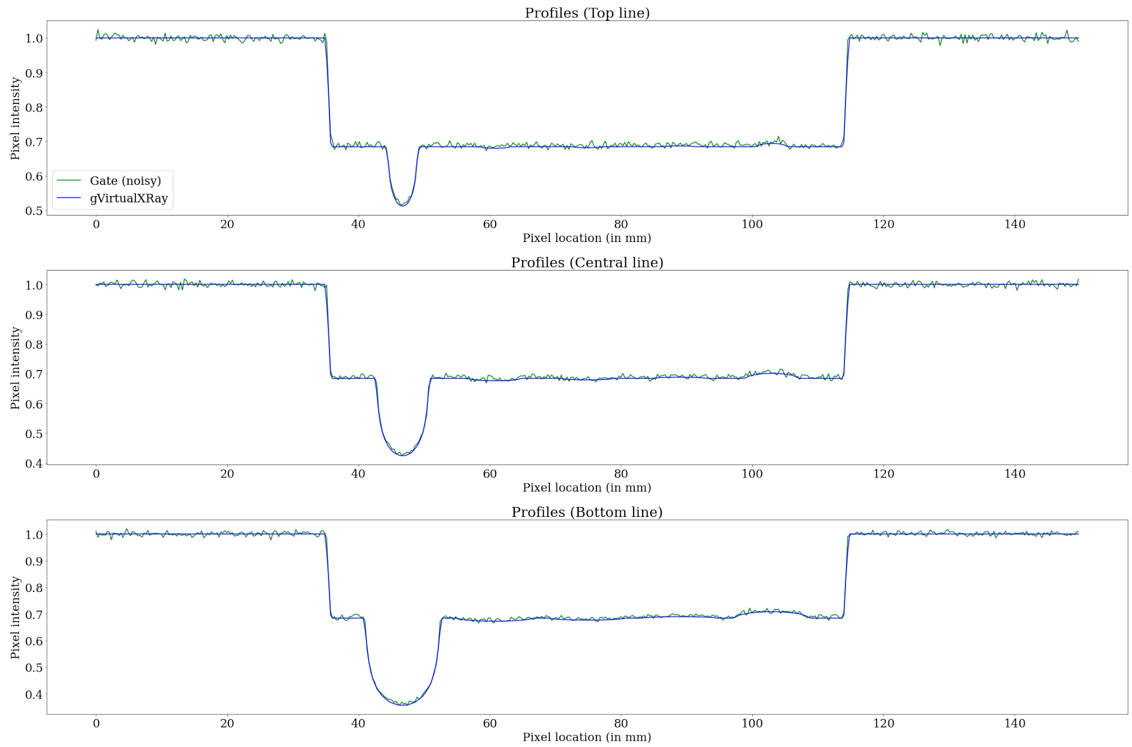
Plot the profiles

[39]:

```
font = {'size'   : 22
       }
matplotlib.rc('font', **font)
```

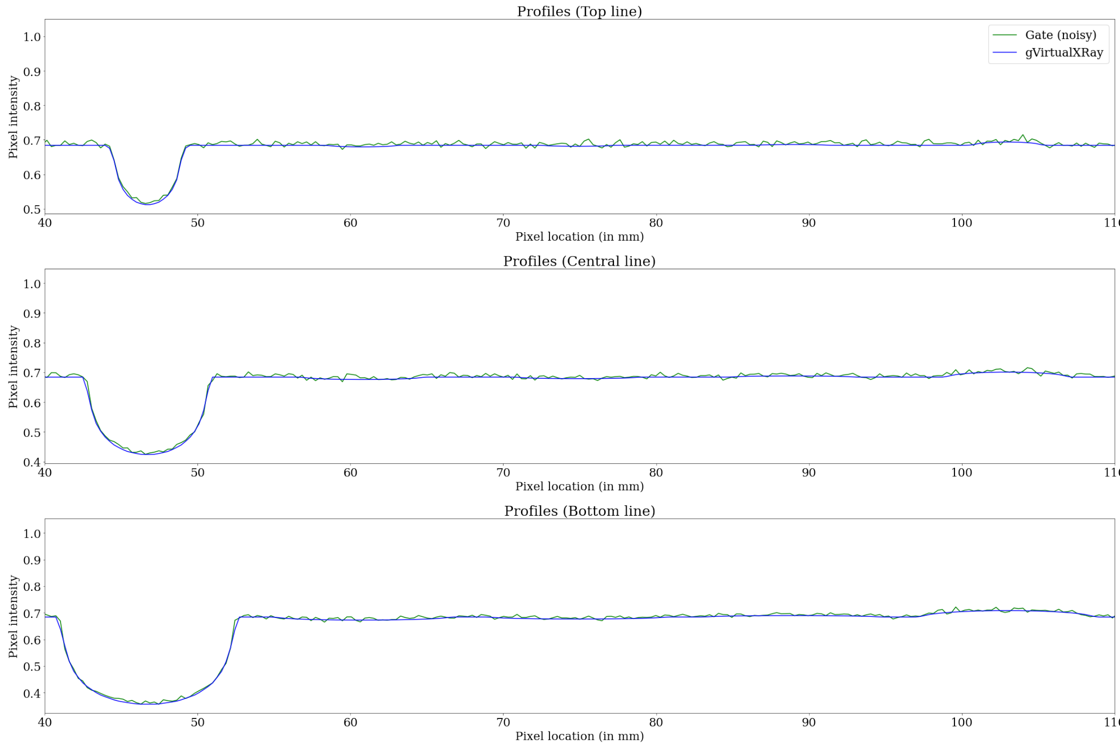
[40]:

```
plotTwoProfiles(json2gvxr, gate_image, x_ray_image_integration_GPU, "plots/
  ↪profiles-checkerboard-detResponse")
```



[41]:

```
spacing = json2gvxr.params["Detector"]["Size"][0] / json2gvxr.
  ↪params["Detector"]["NumberOfPixels"][0]
min_limit = round(40)
max_limit = round(512 * spacing - 40)
plotTwoProfiles(json2gvxr, gate_image, x_ray_image_integration_GPU, "plots/
  ↪profiles-zoom-checkerboard-detResponse", [min_limit, max_limit])
```



6 All done

Destroy the window

[42]:
```
gvxr.destroyAllWindows()
```

0(0x562da2367950)