GateParamterisedPinholeCollimator class for simulation of preclinical SPECT

Olga Kochebina (kochebina@gmail.com)

May 31, 2022

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1 Introduction

The GateParametrisedPinholeCollimator class was developed for GATE simulations of a multiple pinhole collimator for preclinical SPECT imaging. In the simulation we use analytical model for the collimator geometry description.

An example of preclinical SPECT with a multipinhole collimator is a nanoSPECT/CT by Mediso shown in Figure 1 and macros can be found in macros on github. It is a four head system with exchangeable collimators adapted to imagning subject. An example of pinhole collimator simulated with GATE is presented in Figure 2.

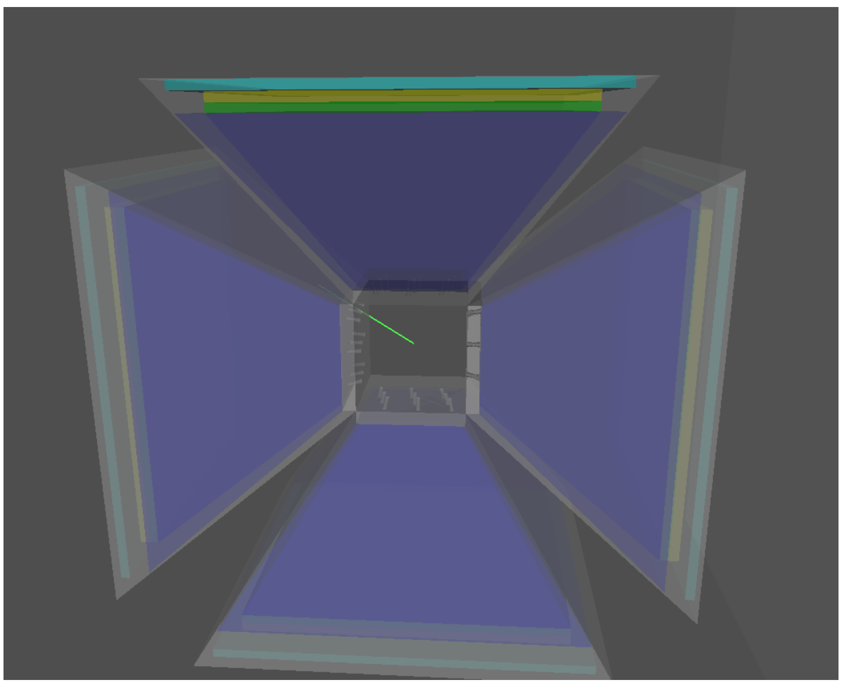


Figure 1: Illustration for simulated nanoSPECT

2 Options and input data

The geometry of pinhole is defined from a G4-pyramid with a subtracted cones (G4Cons) in order to have pinholes drilled from both sides of a colli-

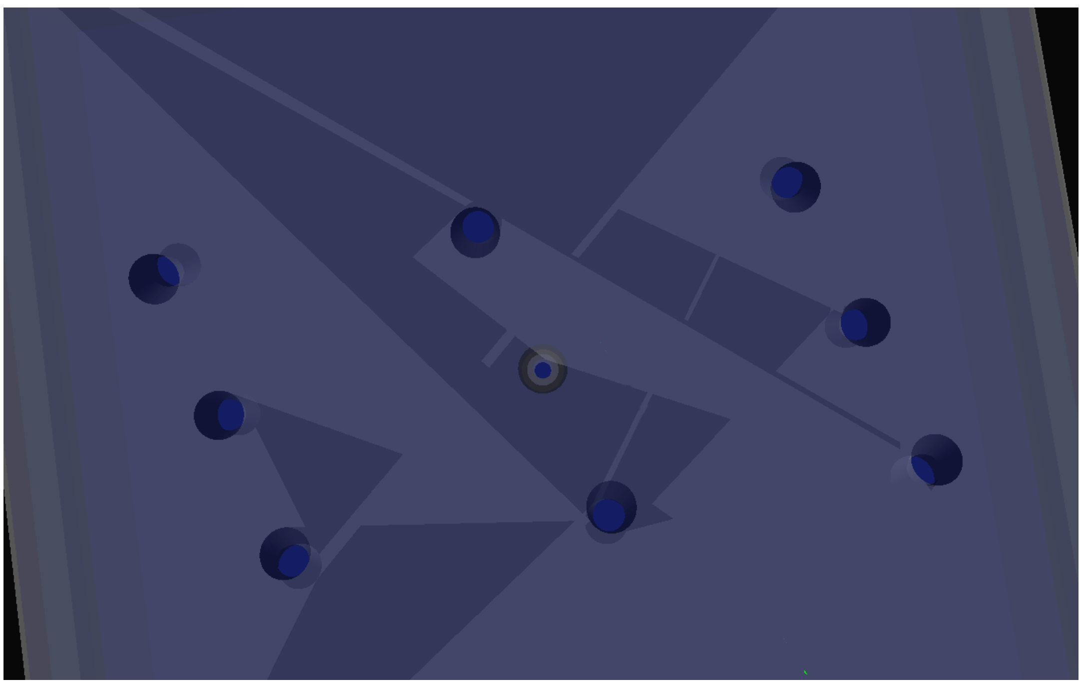


Figure 2: Illustration for pinhole collimator

mator plane.

The pyramid is defied with mac options:

```
/gate/colli/geometry/setDimensionX1 80 mm
/gate/colli/geometry/setDimensionY1 84 mm
/gate/colli/geometry/setDimensionX2 80 mm
/gate/colli/geometry/setDimensionY2 84 mm
/gate/colli/geometry/setHeight 10 mm
```

The collimator rotation radius, i.e. distance from the center of field of view to the pinholes center (see Figure 3 and Figure 4) is defined as:

```
/gate/colli/geometry/setRotRadius 45 mm
```

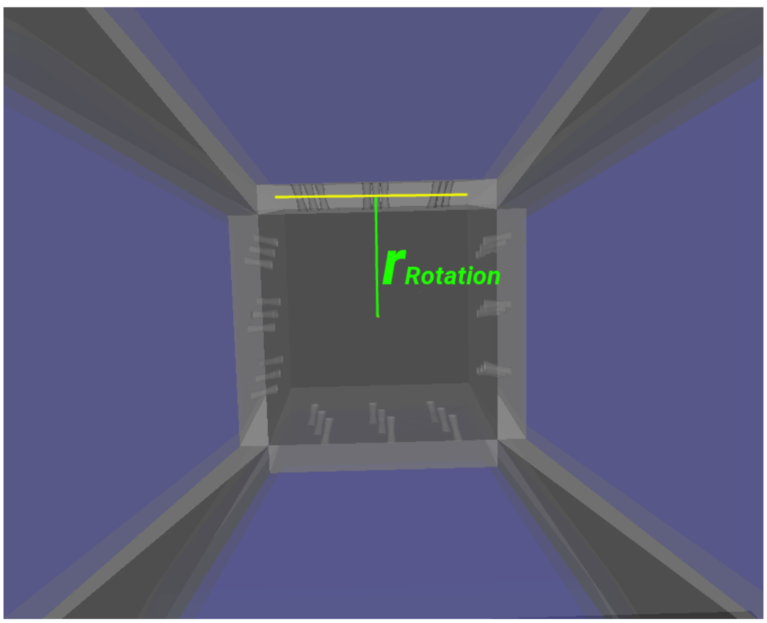


Figure 3: Definition of the rotation radius

The the pinhole geometry is defined with an option file:

```
/gate/colli/geometry/input mac/APT2.pin
```

The stricture of the option file, APT2.pin, is the following (an example could be found in Table 1):

# x	y	dia	alpha cone	x_{focal}	y_{focal}
[APT2]					
9					
28.898	11.949	2.5	7.5	20.0002	0
25.19	0	2.5	7.5	15.0274	0
21.464	-11.949	2.5	7.5	10.0315	0
3.743	11.949	2.5	7.5	5.01876	0
0	0	2.5	7.5	0	0
-3.743	-11.949	2.5	7.5	-5.01876	0
-21.464	11.949	2.5	7.5	-10.0315	0
-25.19	0	2.5	7.5	-15.0274	0
-28.898	-11.949	2.5	7.5	-20.0002	0

Table 1: Example of APT2.pin option file

```
Number of pinholes
y z diameter cone_angle focal_point_y focal_point_z
```

In Table 1 one can find a description of a collimator called "APT2" with 9 holes. The diameter of pinholes (at the center) is 2.5 mm, the opening cone angle (α) is 7.5 degree. The y and z coordinates are the centers of the pinholes. The focal coordinates are illustrated in Figure 4.

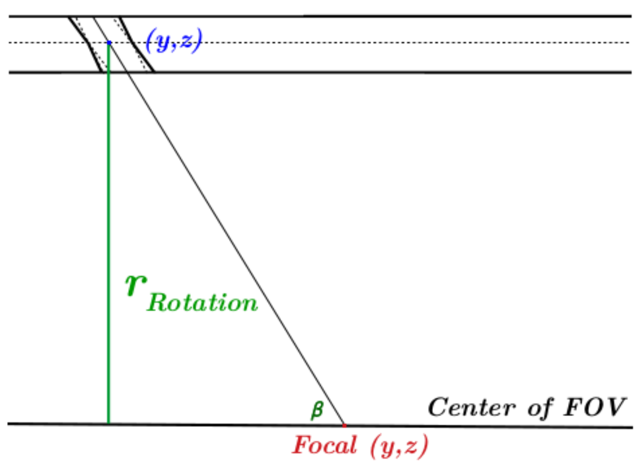


Figure 4: Illustration of parameters defined in APT2.pin option file

3 Pinhole geometry calculations

The result of the following calculations are implemented in GateParametrised-PinholeCollimator class.

The names of the variables in the class are the same as in Figures 5 and 6 and the calculations below. The final results used in the GateParametrised-PinholeCollimator are framed.

The drilled cones of pinholes are simulated as G4Cons. The required and nontrivial parameters are:

- Geometrical cone parameters
  - height of the cone, Dz
  - radius of the cone basis, $rmax$
- Cone tilt
- Displacement correction due to tilt
  - on x (x = the first column read from .pin file) : $x + \Delta x$ for "down cone" or $x - \Delta x$ for "upper cone"
  - on y (y = the second column read from .pin file): $y + \Delta y$ for "down cone" or $y - \Delta y$ for "upper cone"
  - on z (z = collimator rotation radius, Figure 3) : $-\Delta z$ for "down cone" or Δz for "upper cone"

3.1 Geometrical cone parameters

The known parameters are: ***d (= dia)*** – diameter of the pinhole, α = cone opening angle, x and y – center of pinhole, x_{focal} and y_{focal} – focal coordinates, z = rotation radius, h = half of a thickness of collimator plate.

1. Calculation of β

$$\boxed{\beta = |\pi/2 - atan(|x - x_{focal}/z|)|} \tag{1}$$

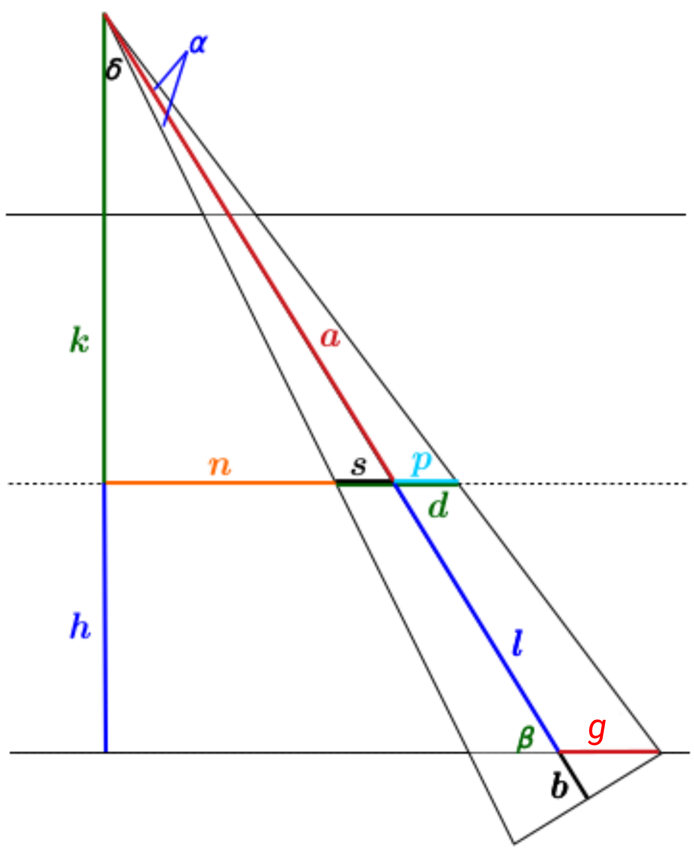


Figure 5: Illustration for pinhole size parameter definitions

2. Calculation of l

$$l = \frac{h}{\cos(\delta + \alpha)} = \frac{h}{\sin\beta}$$

$$\boxed{l = \frac{h}{\sin\beta}} \tag{2}$$

3. Calculation of k and n

$$\delta = 90^o - (\alpha + \beta)$$

$$\begin{cases} \tan\delta = \frac{1}{\tan(\alpha+\beta)} = \frac{n}{k} \\ \tan(\delta + 2\alpha) = \frac{1}{\tan(\beta-\alpha)} = \frac{n+d}{k} \end{cases}$$

$$\begin{cases} \tan(\alpha+\beta) = \frac{k}{n} \\ \tan(\beta-\alpha) = \frac{k}{n+d} \end{cases}$$

$$\boxed{k = \frac{d \cdot \tan(\beta - \alpha) \cdot \tan(\alpha + \beta)}{\tan(\alpha + \beta) - \tan(\beta - \alpha)}} \tag{3}$$

$$\boxed{n = \frac{k}{\tan(\beta - \alpha)} - d} \tag{4}$$

4. Calculation of a from k

$$a = \frac{k}{\cos(\delta + \alpha)} = \frac{k}{\sin\beta}$$

$$\boxed{a = \frac{k}{\sin\beta}} \tag{5}$$

5. Calculation of s and b

$$\tan(\delta + \alpha) = \frac{1}{\tan\beta} = \frac{n + s}{k}$$

$$\boxed{s = \frac{k}{\tan\beta} - n} \tag{6}$$

$$
\begin{gathered}
p = d - s \\
\frac{p}{g} = \frac{a}{a+l} \\
g = \frac{(d-s)\cdot(a+l)}{a} \\
\cos\beta = \frac{b}{g}
\end{gathered}
$$

$$\boxed{b = \frac{(d-s)\cdot(a+l)\cdot\cos\beta}{a}} \tag{7}$$

6. Calculation of Dz for a chosen direction (x or y)

$$\boxed{Dz_x = a + l + b} \tag{8}$$

$$\boxed{Dz_y = \frac{y - y_{focal}}{\cos\left((y - y_{focal})/z\right)}} \tag{9}$$

7. In 3D:

$$\boxed{Dz = \sqrt{Dz_x^2 + Dz_y^2}} \tag{10}$$

8. Cone radius:

$$\boxed{rmax = Dz \cdot \tan\alpha} \tag{11}$$

3.2 Cone tilt

The tilt is defined with G4RotationMatrix by methods rotateX($rotX$) and rotateY($rotY$).

1. Definitions of t

$$t = (x - x_{focal})^2 + (y - y_{focal})^2 + z^2 \tag{12}$$

2. Definitions of normal x, y and z

$$x_{normal} = (x - x_{focal})/\sqrt{t} \tag{13}$$

$$y_{normal} = (y - y_{focal})/\sqrt{t} \tag{14}$$

$$z_{normal} = z/\sqrt{t} \tag{15}$$

3. Definitions of $rotX$ and $rotY$

$$\boxed{rotX = atan(x_{normal}/z_{normal})} \tag{16}$$

$$\boxed{rotY = -atan(y_{normal}/z_{normal})} \tag{17}$$

3.3 Displacement correction due to tilt

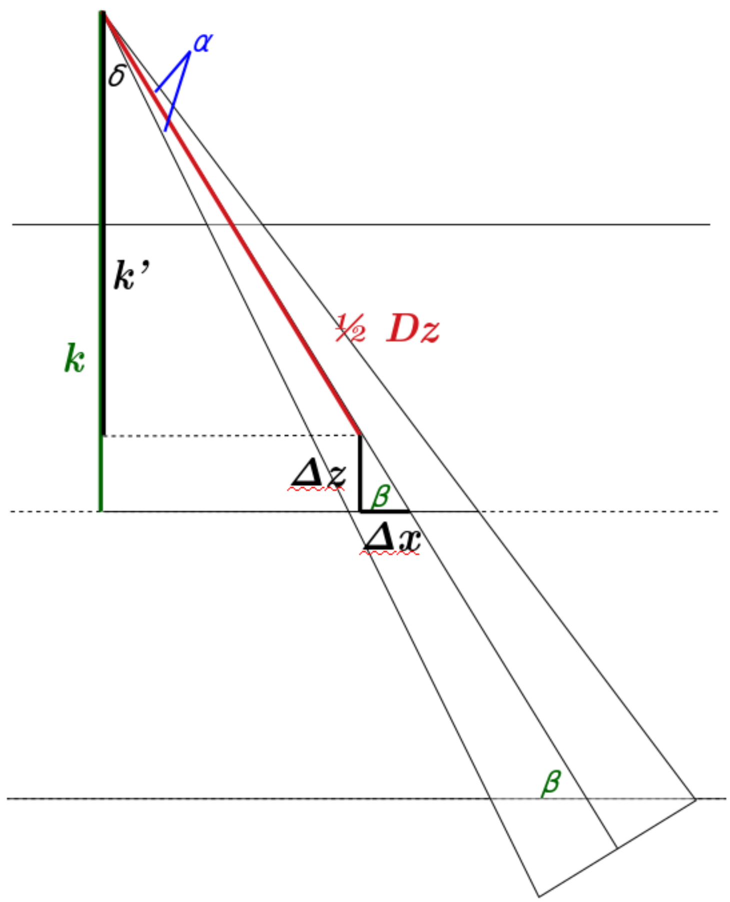


Figure 6: Illustration for pinhole positions definitions

According to illustration in Figure 6 one obtains:

1. Calculation of Δz

$$\Delta z = k - k' \tag{18}$$

$$\cos(\delta + \alpha) = \sin\beta = \frac{k'}{Dz/2} \tag{19}$$

$$k' = (Dz/2) \cdot \sin\beta \tag{20}$$

$$\boxed{\Delta z = k - (Dz/2) \cdot \sin\beta} \tag{21}$$

2. Calculation of Δx or Δy in 3D with ϕ as an azimuthal angle:

$$\boxed{\Delta x = \sin\phi \frac{\Delta z}{\tan\beta}} \tag{22}$$

$$\boxed{\Delta y = \cos\phi \frac{\Delta z}{\tan\beta}} \tag{23}$$

4 How to obtain .pin file

One of tricky steps is to obtain the .pin file, i.e. pinhole parameters: positions, diameters, cone opening angles and focal points positions.

4.1 Input from HiSPECT reconstruction software

Here one can find a description of how it was done for one of projects where the simulation of nanoSPECT/CT by Mediso was done with GATE. It is four head camera with several pinhole exchangeable collimators. In our case we were interested in APT1, a collimator for mouse imagning, and APT2, a collimator for rat imagning.

The best way that we found was to search information in integrated reconstruction software of the scanner. In our case it was **HiSPECT**. The pinhole information was stored in (Figure 7)

```
Scivis/HiSPECT/SQL/Install/NanoSPECT_Aperture_4det.sql
```

In Figure 7, the lines corresponding to APT1 and APT2 apertures are highlighted.

The explanations of corresponding table structures were located in

```
Scivis/HiSPECT/SQL/Install/HiSPECT.sql
```

and also given in Figure 8.

The pinhole definitions are shown in Figure 9. The most interesting parameters in our case are: yPosition, zPosition, Diameter, ApexAngle, phi and theta.

However, in .pin file one should have focal points positions and not angles phi and theta and, thus, conversion should be done. This conversion is necessary for historical reason: we have in-house reconstruction software developed much earlier than GATE simulations, where .pin files with the defined structure and parameters are used. In order to have the same parameterization files for simulation and reconstruction, we recalculate the focal position from phi and theta. It is done with a tool `HiSPECTtoGATE` described below.

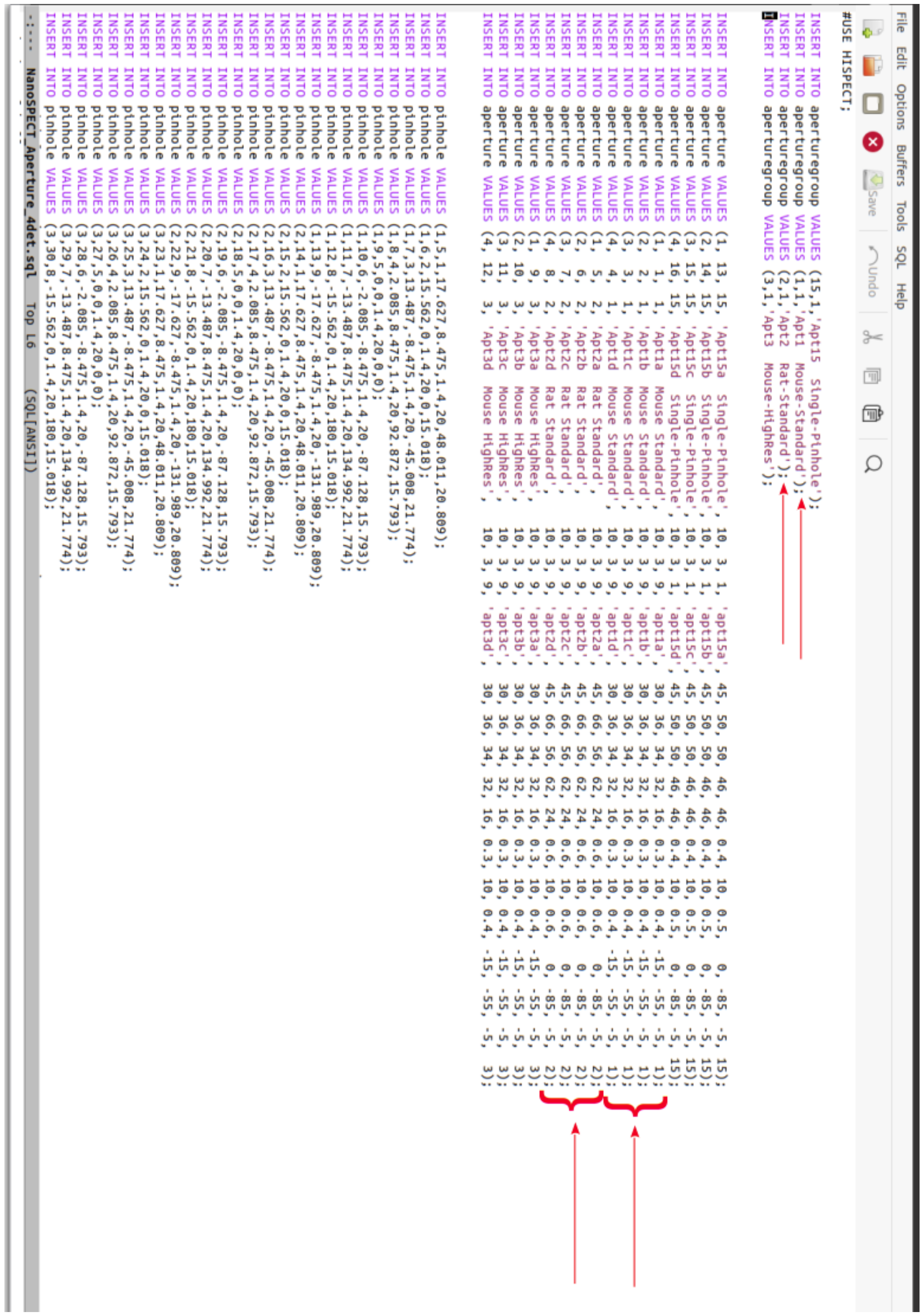
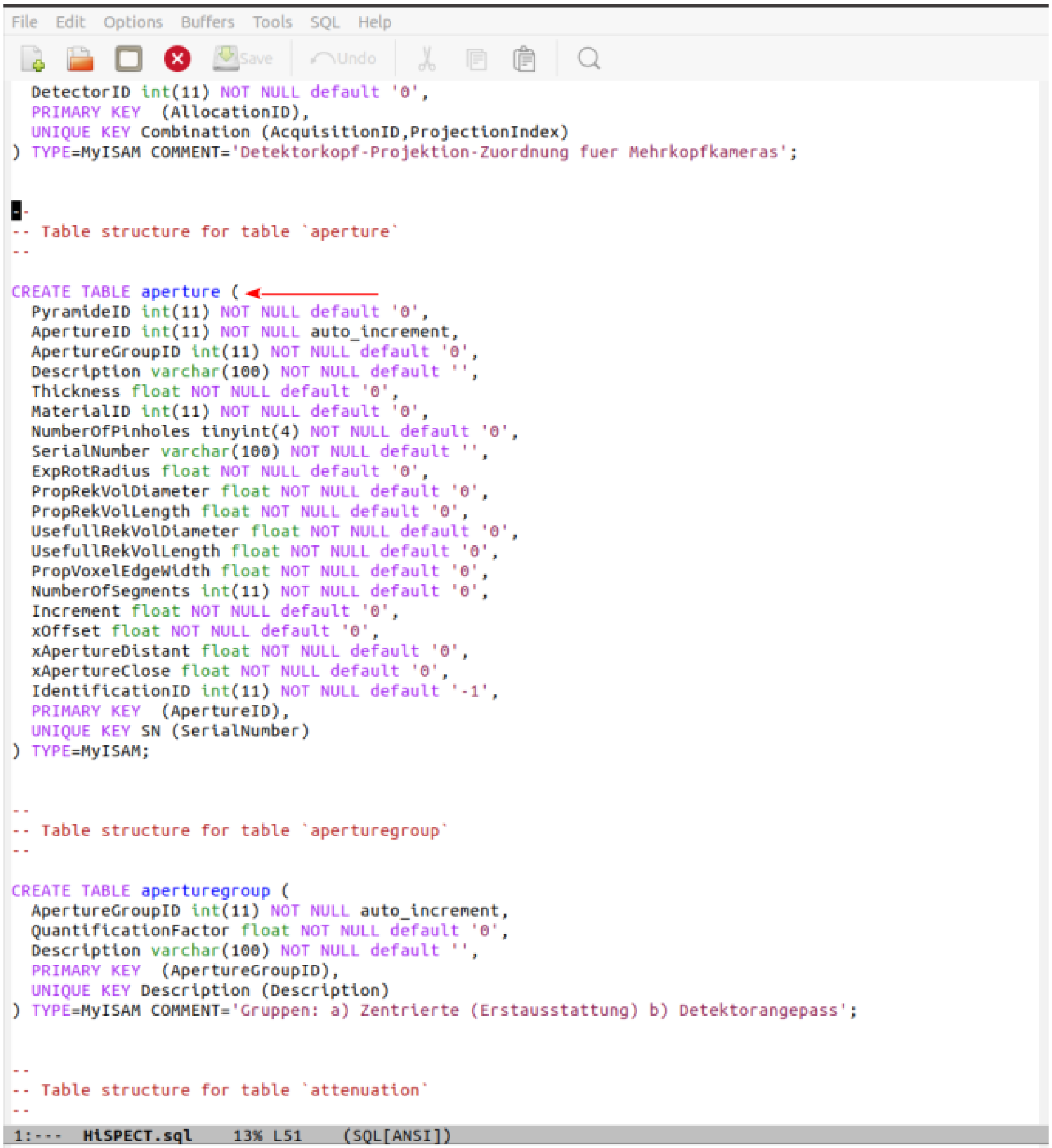


Figure 7: Part of `NanoSPECT_Aperture_4det.sql` file with important lines highlighted



File Edit Options Buffers Tools SQL Help

```sql
  DetectorID int(11) NOT NULL default '0',
  PRIMARY KEY  (AllocationID),
  UNIQUE KEY Combination (AcquisitionID,ProjectionIndex)
) TYPE=MyISAM COMMENT='Detektorkopf-Projektion-Zuordnung fuer Mehrkopfkameras';


--
-- Table structure for table `aperture`
--

CREATE TABLE aperture (
  PyramideID int(11) NOT NULL default '0',
  ApertureID int(11) NOT NULL auto_increment,
  ApertureGroupID int(11) NOT NULL default '0',
  Description varchar(100) NOT NULL default '',
  Thickness float NOT NULL default '0',
  MaterialID int(11) NOT NULL default '0',
  NumberOfPinholes tinyint(4) NOT NULL default '0',
  SerialNumber varchar(100) NOT NULL default '',
  ExpRotRadius float NOT NULL default '0',
  PropRekVolDiameter float NOT NULL default '0',
  PropRekVolLength float NOT NULL default '0',
  UsefullRekVolDiameter float NOT NULL default '0',
  UsefullRekVolLength float NOT NULL default '0',
  PropVoxelEdgeWidth float NOT NULL default '0',
  NumberOfSegments int(11) NOT NULL default '0',
  Increment float NOT NULL default '0',
  xOffset float NOT NULL default '0',
  xApertureDistant float NOT NULL default '0',
  xApertureClose float NOT NULL default '0',
  IdentificationID int(11) NOT NULL default '-1',
  PRIMARY KEY  (ApertureID),
  UNIQUE KEY SN (SerialNumber)
) TYPE=MyISAM;


--
-- Table structure for table `aperturegroup`
--

CREATE TABLE aperturegroup (
  ApertureGroupID int(11) NOT NULL auto_increment,
  QuantificationFactor float NOT NULL default '0',
  Description varchar(100) NOT NULL default '',
  PRIMARY KEY  (ApertureGroupID),
  UNIQUE KEY Description (Description)
) TYPE=MyISAM COMMENT='Gruppen: a) Zentrierte (Erstausstattung) b) Detektorangepass';


--
-- Table structure for table `attenuation`
--
```

1:--- HiSPECT.sql 13% L51 (SQL[ANSI])

Figure 8: Part of HiSPECT.sql file with important lines highlighted

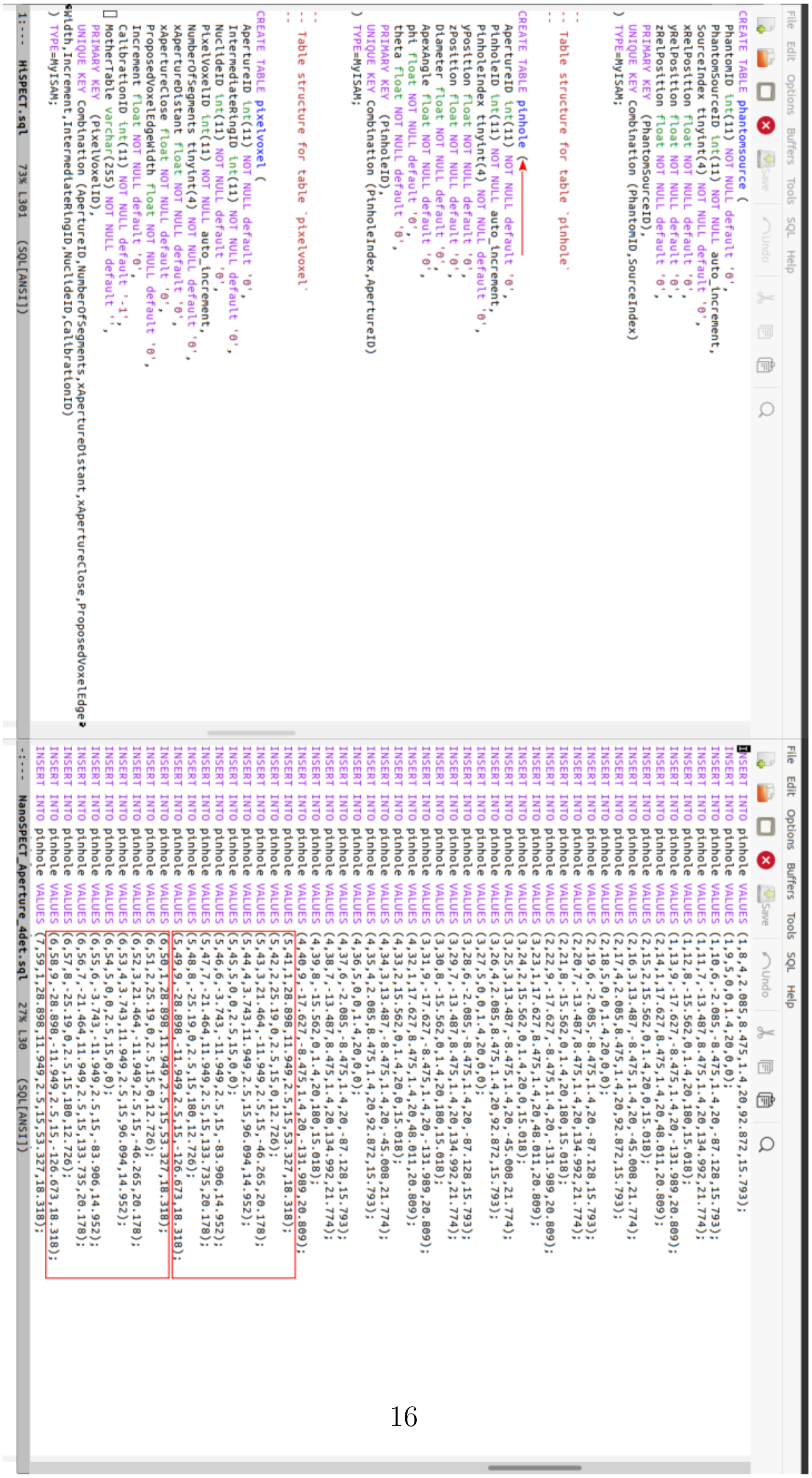


Figure 9: Part of `HiSPECT.sql` and `NanoSPECT_Aperture_4det.sql` file with important lines highlighted: parameters for APT1 are in blue rectangles and in red for APT2.

4.2 HiSPECTtoGate tool

This tool can be found on github: HiSPECTtoGATE on github. We decided to keep this script as simple as possible and not introduce the previous parameters as input options, thus, the script doesn't need a compilation. It is most probably will be used for inspiration.

It is important to notice that one should change some of lines of the script in order to adapt it for specific needs:

- line 16: give the name of your input file
- line 22: give the rotation radius

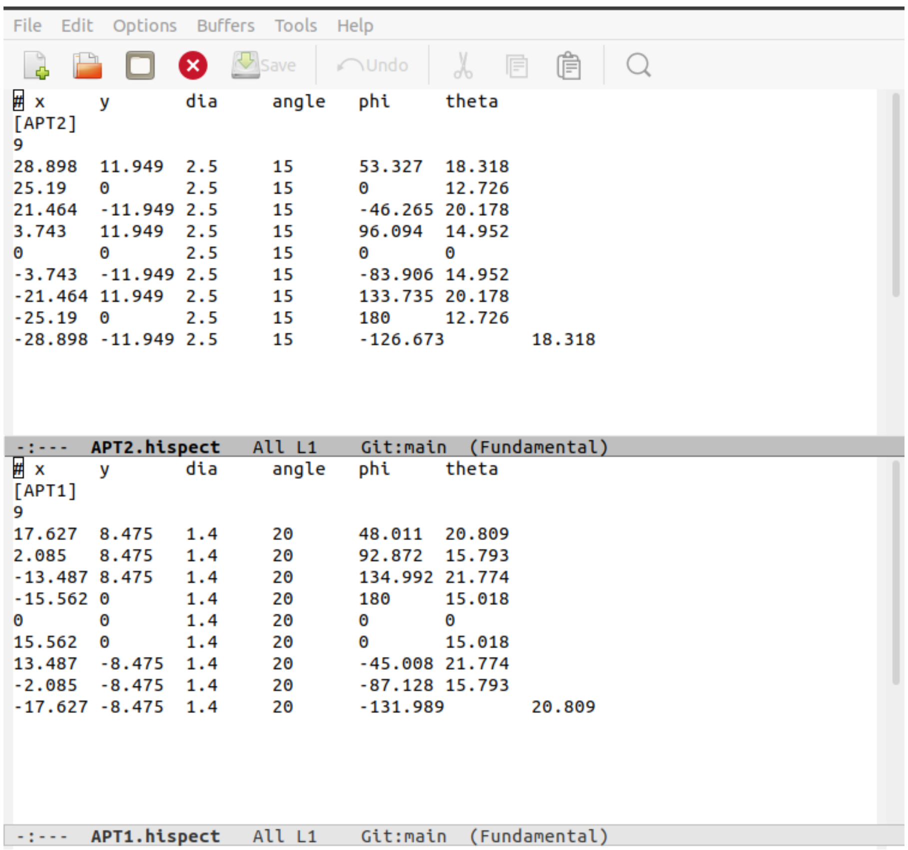
In order to run the script one can simple does: The pyramid is defied with mac options:

```
root -l HiSPECTtoGate.C
```

4.3 Input file

As input one should provide information from a text file obtained from HiSPECT (Figure 9) ApertureName.hispect, for example APT1.hispect and APT2.hispect. These are text files produced "by hand". APT1.hispect and APT2.hispect are presented in Figure 10.

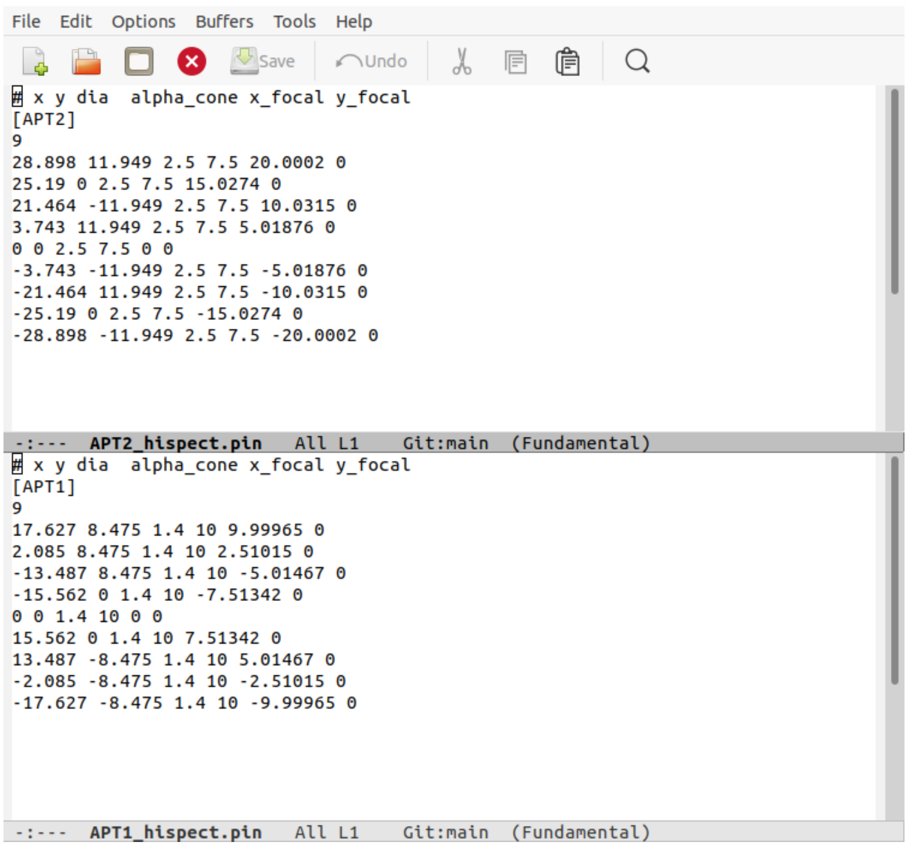
The output files, APT1_hispect.pin and APT2_hispect.pin (Figure 11), can be used directly in GATE macros.




```
# x     y       dia     angle   phi     theta
[APT2]
9
28.898  11.949  2.5     15      53.327  18.318
25.19   0       2.5     15      0       12.726
21.464  -11.949 2.5     15      -46.265 20.178
3.743   11.949  2.5     15      96.094  14.952
0       0       2.5     15      0       0
-3.743  -11.949 2.5     15      -83.906 14.952
-21.464 11.949  2.5     15      133.735 20.178
-25.19  0       2.5     15      180     12.726
-28.898 -11.949 2.5     15      -126.673        18.318
-:---  APT2.hispect   All L1    Git:main  (Fundamental)
```

```
# x     y       dia     angle   phi     theta
[APT1]
9
17.627  8.475   1.4     20      48.011  20.809
2.085   8.475   1.4     20      92.872  15.793
-13.487 8.475   1.4     20      134.992 21.774
-15.562 0       1.4     20      180     15.018
0       0       1.4     20      0       0
15.562  0       1.4     20      0       15.018
13.487  -8.475  1.4     20      -45.008 21.774
-2.085  -8.475  1.4     20      -87.128 15.793
-17.627 -8.475  1.4     20      -131.989        20.809
-:---  APT1.hispect   All L1    Git:main  (Fundamental)
```

Figure 10: APT1.hispect and APT2.hispect




```
# x y dia  alpha_cone x_focal y_focal
[APT2]
9
28.898 11.949 2.5 7.5 20.0002 0
25.19 0 2.5 7.5 15.0274 0
21.464 -11.949 2.5 7.5 10.0315 0
3.743 11.949 2.5 7.5 5.01876 0
0 0 2.5 7.5 0 0
-3.743 -11.949 2.5 7.5 -5.01876 0
-21.464 11.949 2.5 7.5 -10.0315 0
-25.19 0 2.5 7.5 -15.0274 0
-28.898 -11.949 2.5 7.5 -20.0002 0
```

```
-:---  APT2_hispect.pin   All L1    Git:main  (Fundamental)
```

```
# x y dia  alpha_cone x_focal y_focal
[APT1]
9
17.627 8.475 1.4 10 9.99965 0
2.085 8.475 1.4 10 2.51015 0
-13.487 8.475 1.4 10 -5.01467 0
-15.562 0 1.4 10 -7.51342 0
0 0 1.4 10 0 0
15.562 0 1.4 10 7.51342 0
13.487 -8.475 1.4 10 5.01467 0
-2.085 -8.475 1.4 10 -2.51015 0
-17.627 -8.475 1.4 10 -9.99965 0
```

```
-:---  APT1_hispect.pin   All L1    Git:main  (Fundamental)
```

Figure 11: APT1_hispect.pin and APT2_hispect.pin produced by HiSPECT-toGate script and used in macros examples here.