

# GamBet Tutorials

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# 1 Electron backscatter from a gold sheet

This introductory section gives a detailed description of a simulation to calculate the backscatter fraction for energetic electrons incident on a planar gold sheet. The simple geometry does not utilize the full resources of **GamBet** – instead, the intention is to illustrate useful techniques and the accuracy of the code. The two required input files are `BACKSCAT.MIN` (definition of the solution volume geometry) and `BACKSCAT.GIN` (specification of incident electron properties and control parameters for the Monte Carlo calculation). Move the files to a convenient working directory such as `/PATH/GAMBET/BUFFER`. The run also accesses Penelope data files with information on the physical properties of gold. These files are located in the directory `/PATH/GAMBET/REFERENCE`. If you encounter any problems, check the setup procedure described in the *GamBet Reference Manual*.

Figure 1 shows measurements reported in T. Tabata, R. Ito and S. Okabe, Nucl. Instrum. and Methods **94**, 509 (1971). The graph plots the backscatter ratio for gold as a function of the kinetic energy of electrons at normal incidence. The small black circles are data points, while the line represents the best fit. The backscatter ratio is the number of electrons that emerge from the front face divided by the number of incident electrons assuming that the foil is thick enough so that there are no transmitted electrons. In our simulation we shall check the ratio at energies of 1.0, 3.0 and 10.0 MeV. To plan the run we need information on electron ranges in gold. The following Internet site is a useful source of information:

<http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html>

The interactive site gives information on the interactions of energetic electrons with matter including the total range. The first data column of Table 3 shows the EStar results.

The planar 2D approximation applies when the transverse dimension of the sheet is large compared to the extent of the incident beam and backscattered electrons. We assume that electrons initially move in the  $+x$  direction. The script to define the geometry mesh is shown in Table 1. The solution volume consists of a single material region with 0.5 cm thickness in the  $x$  direction. The depth is sufficient to prevent electron loss by transmission at the highest energy. Electrons that leave the solution volume are included in run statistics and the particle escape file. We shall use this information to

Table 1: File BACKSCAT.MIN to create the geometry file

```
* File: BACKSCAT.MIN
* Dimensions in cm
* -----
GLOBAL
  XMESH
    0.000  0.100  0.002
    0.100  0.500  0.010
  END
  YMESH
    -0.300  0.300  0.010
  END
END
* -----
REGION  FILL  SolnVolume
  L    0.00 -0.30  0.50 -0.30
  L    0.50 -0.30  0.50  0.30
  L    0.50  0.30  0.00  0.30
  L    0.00  0.30  0.00 -0.30
END
* -----
ENDFILE
```

determine the backscatter ratio. The mesh has variable resolution in  $x$  with small elements near the entrance at  $x = 0.0$  cm. The element division could be used to study dose distributions for electrons of different energies. The element size is not critical for the backscatter calculation. A mesh with a single layer of elements in  $x$  would yield the same accuracy with little difference in run speed. The system has dimensions  $\pm 0.3$  cm in the  $y$  direction. The width is sufficient to ensure that scattered electrons are not lost from the top and bottom boundaries. The first step in the run is the creation of the geometry input file `BACKSCAT.MOU`. Start **GBLaunch** and check that the data directory points to the working directory. Start the **Mesh** program, click on *FILE/LOAD SCRIPT (MIN)*, choose `BACKSCAT.MIN` and click *OK*. Choose the *PROCESS* command to generate the mesh and then click on *FILE/SAVE MESH (MOU)*.

Table 2 shows the contents of the file `BACKSCAT.GIN`. The *GFILE2D* command of the *GEOMETRY* section directs **GamBet** to load node and element information from `BACKSCAT.MOU` and to interpret the system as planar (variations in  $x$  and  $y$  with infinite length in  $z$ ). The *DUNIT* command specifies that coordinate dimensions are in centimeters. The commands of the *COMPOSITION* section define Material 1 as gold ( $Z = 79$ ) and associates Region 1 (the complete solution volume) with the material. The *SLIST* command in the *SOURCE* section lists a single primary electron with kinetic energy 1.0 MeV moving in the  $+x$  direction. Notice that the start position (0.0001, 0.0, 0.0) is just inside the solution volume close the left boundary. The position ensures that **GamBet** will find a valid element within the geometry mesh to start the particle orbits. There are three lines for the energies that we shall study – two of the lines are deactivated with comment symbols. The *NPMULT* command instructs the program to generate 50,000 showers (instances of the primary particle) for good statistics. Finally, the commands of the *PROCESS* section control the Monte Carlo calculation. A cutoff energy of 100 keV is applied to all types of particles. The value is also used for the parameters  $W_{cc}$  and  $W_{cr}$  (transition energies between continuous and discrete calculations). The value is high enough to ensure fast calculations but relatively low compared to initial electron energy. The final *PLOTON* command instructs **GamBet** to generate a plot file of primary and secondary particle orbits for 50 showers.

Run **GamBet** from **GBLaunch**, click on *RUN/START RUN* and choose `BACKSCAT.GIN`. Following the script instructions, the program loads information on geometry and material properties and then begins the Monte Carlo

Table 2: File BACKSCAT.GIN to control the **GamBet** calculation

```
* File: BACKSCAT.GIN
GEOMETRY
  DUnit 100.0
  GFile2D BackScat.MOU  Rect
END
COMPOSITION
  Material 79
  Region(1) = 1
END
SOURCE
  SList
    E 1.0E6 0.0001 0.00 0.00 1.00 0.00 0.00
  * E 3.0E6 0.0001 0.00 0.00 1.00 0.00 0.00
  * E 10.0E6 0.0001 0.00 0.00 1.00 0.00 0.00
  End
  NPMult = 50000
END
PROCESS
  EAbs Electron 1.0E5
  EAbs Photon 1.0E5
  EAbs Positron 1.0E5
  C1 0.10
  C2 0.10
  WCc 1.0E5
  WCr 1.0E5
  PlotOn 50
END
ENDFILE
```

simulation for 1.0 MeV electrons. The run with 50,000 showers takes about 57 seconds on a 3.4 GHz computer. Upon completion **GamBet** displays two important pieces of status information. The programs states that no particle histories terminated early because they exceeded *NStep* and displays the energy conservation factor. The quantity equals the difference between the energy input and the sum of deposited and escape energies divided by the input energy. The factor should be small compared to unity – for this run it equals about 0.025%.

The listing file contains the primary information for the backscatter calculation. Click on *FILE/EDIT LISTING FILES*, choose **BACKSCAT.GLS** and click *OK*. **GamBet** opens the file in its internal editor. The first section of the listing file records input parameters and details of the run setup. The run statistics section (near the end of file) contains the following information:

Primary electrons

```
Escape fraction:      0.4429
Average energy of escape electrons:  7.2382E+05 (eV)
Average pathlength of escape electrons:  1.5234E-02 (cm)
Average pathlength of absorbed electrons:  3.8197E-02 (cm)
```

The code predicts that 44.29% of primary electrons leave the solution volume with average kinetic energy of 0.7238 MeV after traveling an average distance of 0.0152 cm through the material. Because particles can leave only through the front face, the escape fraction equals the backscatter fraction for primary electrons. The average pathlength for absorbed electrons is 0.0382 cm, close to the EStar range value. The backscatter fraction of primary electrons is not exactly equal to the experimental results which include the contribution of knock-on electrons. The region flux listing (shown below) gives the total number of electrons that leave the solution volume per incident primary particle. The energy flux is the energy crossing the region boundary per incident primary. Therefore, the average energy of all electrons leaving the front face of the solution volume is  $322.43/0.4510 = 714.92$  keV.

```
--- Region fluxes ---
  NReg NReg   Electron      Electron
  From To     flux         eng. flux
                   (p/p)         (eV/p)
=====
    1   0   4.509800E-01  3.224274E+05
```

Table 3: Backscatter example results

| Energy<br>(MeV) | Range<br>(cm) | Primary<br>fraction | Total<br>fraction |
|-----------------|---------------|---------------------|-------------------|
| 1.0             | 0.0402        | 0.443               | 0.451             |
| 3.0             | 0.1228        | 0.317               | 0.331             |
| 10.0            | 0.3185        | 0.113               | 0.139             |

Table 3 lists values of the primary and total backscatter fraction for energies of 1.0, 3.0 and 10.0 MeV. **GamBet** calculations of the total backscatter fraction are plotted as red circles in Fig. 1. The values at high energy are quite close to the experimental results, while the 1.0 MeV point is slightly low. The most likely cause of the discrepancy is the relatively high choice of electron cutoff energy – the value of  $EAbs$  is equal to 10% of the incident energy for 1 MeV electrons. We can check the effect by re-running the simulation with electron absorption energy  $EAbs = 10$  keV. In this case the run time increases to 124 seconds and the total backscatter fraction equals 0.456, moving the point closer to the experimental line. This example illustrates one effect of the Penelope control parameters and the trade-off between run time and accuracy. There is no way to make *a priori* estimates of accuracy for complex Monte Carlo calculations. In critical calculations you must experiment with the number of showers and the Penelope parameters to determine the effects on the results.

During course of a run **GamBet** records extensive information on the orbits and dose distribution. Run **GBView2** from **GBLaunch**. Click on *FILE/LOAD DOSE FILE* and choose `BACKSCAT.G2D`. The program loads information and creates a default dose plot. To add orbits, click on *FILE/LOAD TRAJECTORIES* and choose `BACKSCAT.GPL`. Figure 2 shows trajectories of 1.0 MeV electrons. In order to replicate the plot, use the *SPATIAL PLOTS/ZOOM WINDOW* command to narrow the view. Dose information is not particularly useful in the present calculation because of the relatively large element size and the spatial singularity of the input distribution. Therefore, click on *SPATIAL PLOTS/PLOT TYPE* and uncheck the DOSE box in the dialog. In this case, the dose file is used only to supply boundaries for the plot.

Besides spatial plots, **GBView2** can be used to analyze the distributions

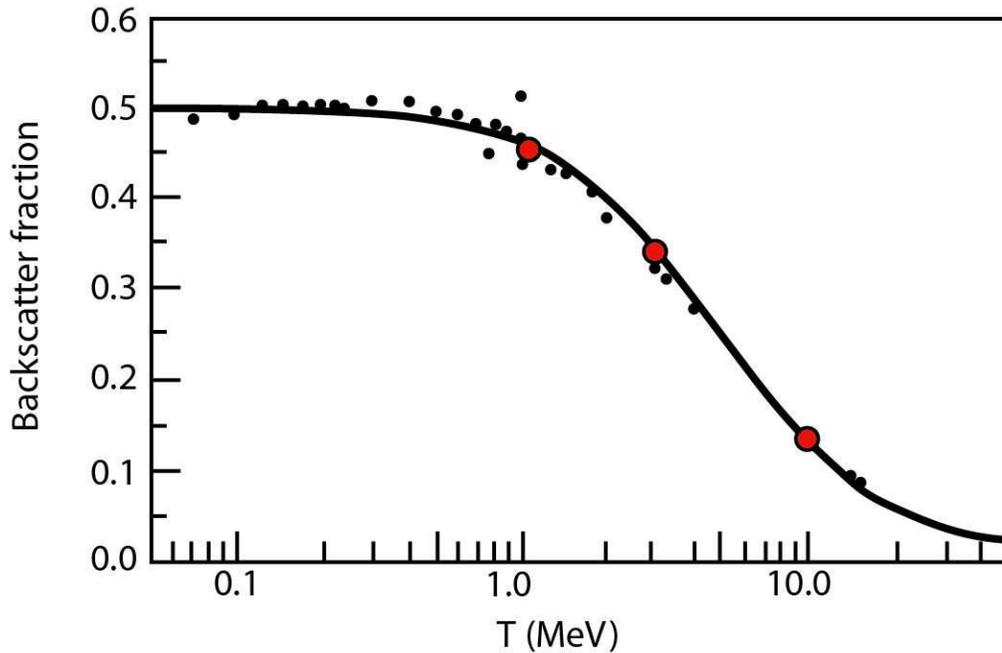


Figure 1: Electron backscatter from a gold foil – comparison of experimental results and GamBet calculations

of particles contained in the escape file. Click on *FILE/LOAD SOURCE FILE* and choose *BACKSCATESC.SRC*. Then click on *SOURCE ANALYSIS* to switch to the distribution menu. Figure 3 shows a plot of the relative number of electrons leaving the front face of the solution volume in terms of kinetic energy. There is a peak around 300 keV – the additional peak near zero results from contributions of knock-on electrons. The following operations were used to create the plot. Click on *PLOT/SET PLOT TYPE* and choose *1D BINS* in the dialog. In the dialog initiated by *PLOT/SET PLOT QUANTITY* choose  $f(T)$ . To ensure that the plot contains only electrons leaving the front face, click on *ANALYSIS/SET PARTICLE FILTER*. In the dialog, check the box for electrons and set  $XMax = 0.001$  and  $UxMax = 0.0$ .

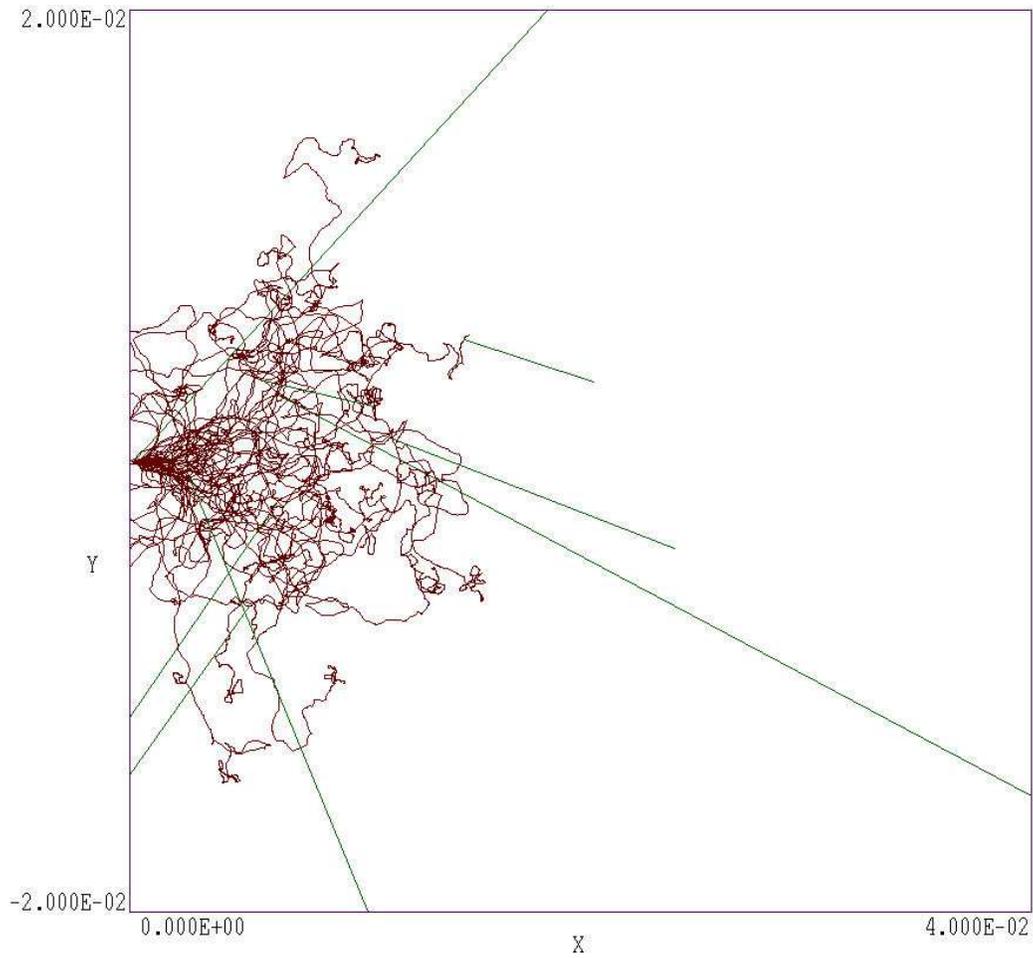


Figure 2: Representative orbits for electrons incident at 1.0 MeV, zoomed view of the entrance region. Brown: primary and secondary electrons. Green: photons.

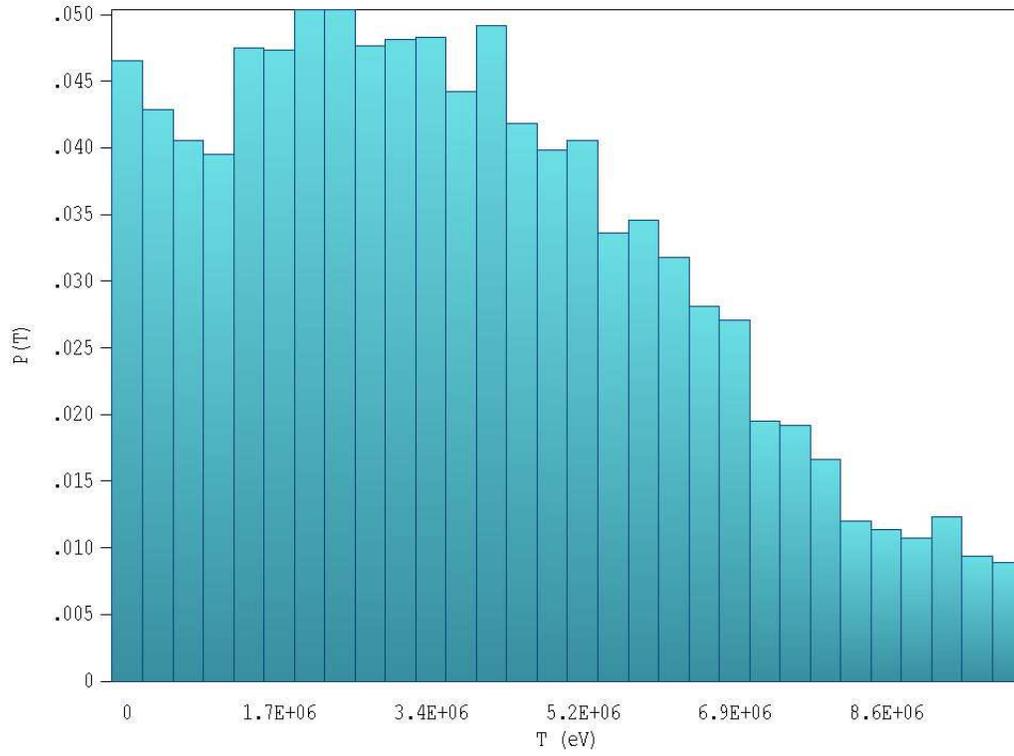


Figure 3: Energy distribution of electrons escaping through the front face of the solution volume.

## 2 Dose from a uniform electron beam incident on an aluminum block

The calculation discussed in this tutorial treats a 1 MeV sheet electron beam incident on an aluminum block. The calculation has three goals:

1. Demonstrate how to define an incident electron beam.
2. Show how to interpret dose units in **GamBet** and **GBView2**.
3. Compare the results and run times to those of the PenSlab program supplied with the Penelope package.

The two required input files are `ALUMBEAM.MIN` and `ALUMBEAM.GIN`. The simple planar 2D system consists of an aluminum block of thickness 0.20 cm in the beam direction. The beam has a height  $h = 0.11$  cm and the solution volume extends from  $y = -0.15$  cm to 0.15 cm in this direction. The mesh element size is about 0.01 cm.

The first step in planning the simulation is to consult the EStar database at:

<http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html>

The site lists the following information on the interactions of 1 MeV electrons with aluminum (density  $\rho = 2.6989$  gm/cm<sup>3</sup>).

```
ESTAR: Stopping Powers and Range Tables for Electrons
ALUMINUM
Kinetic      Collision Radiative Total      CSDA      Radiation
Energy      Stp. Pow. Stp. Pow. Stp. Pow. Range      Yield
MeV         MeV cm2/g MeV cm2/g MeV cm2/g g/cm2
=====
1.000E+00 1.465E+00 2.119E-02 1.486E+00 5.546E-01 7.636E-03
```

The physical range is 0.205 cm. Therefore, the aluminum slab is sufficiently thick to stop the strongly-scattered distribution of electrons.

The incident sheet beam is represented by 21 primary particles with a uniform spacing of 0.05 cm along  $y$ . Table 4 contains an extract from the SLIST structure of `ALUMBEAM.GIN` showing some of the particle data lines.

Table 4: Source section from the file ALUMBEAM.GIN

```

SOURCE
  SList
    E 1.0E6 0.0001 0.050 0.00 1.00 0.00 0.00 1.0E-4
    E 1.0E6 0.0001 0.045 0.00 1.00 0.00 0.00 1.0E-4
    E 1.0E6 0.0001 0.040 0.00 1.00 0.00 0.00 1.0E-4
    . . .
    E 1.0E6 0.0001 -0.045 0.00 1.00 0.00 0.00 1.0E-4
    E 1.0E6 0.0001 -0.050 0.00 1.00 0.00 0.00 1.0E-4
  End
  NPMult = 500
END

```

All particles start just inside the left-hand boundary of the slab and move in the  $+x$  direction. The run includes 500 showers for each primary for good dose statistics. Each primary particle carries  $1.0 \times 10^{-4}$  A/m of current, so the linear current of the beam is  $J = 2.1 \times 10^{-3}$  A/m. The average beam current density is therefore  $j = J/h = 1.909$  A/m<sup>2</sup>. Ignoring the contributions of backscattered electrons, the dose rate at the slab entrance can be calculated from the EStar total stopping power,  $S = 4.01 \times 10^8$  eV/m. The dose rate is given by

$$D = \frac{Sj}{\rho} = 2.836 \times 10^5 \text{ Gy/s.}$$

Note that the SI unit of dose is the Gray, where  $1 \text{ Gy} = 1 \text{ J/kg}$ .

The files ALUMBEAM.GLS and ALUMBEAM.G2D are created by running **Mesh** and then **GamBet**. Entries in the statistics section of ALUMBEAM.GLS can be compared to equivalent quantities calculated by PenSlab (a basic 1D program) for the same number of showers. Results are summarized in Table 5. Quantitative values agree within statistic limits, confirming that **GamBet** correctly implements the Penelope package. The run time for **GamBet** is about three times longer. The reason is that PenSlab makes no geometric decisions beyond whether the next interaction occurs between the front and back faces of the slab. In contrast, **GamBet** performs extensive geometric operations such as identification of arbitrary boundaries on the conformal mesh. The payoff from this effort is that **GamBet** provides detailed informa-

Table 5: ALUMBEAM example – code comparison

| Quantity                                   | PenSlab               | GamBet               |
|--|-----------------------|----------------------|
| Run time (s)                               | 28                    | 93                   |
| Backscatter fraction                       | 0.0897                | 0.0924               |
| Avg. energy, backscattered particles (eV)  | $4.54266 \times 10^5$ | $4.5371 \times 10^5$ |
| Avg. track length, backscattered (cm)      | 0.1338                | 0.1385               |
| Avg. track length, absorbed particles (eV) | 0.2057                | 0.2058               |

tion on dose distributions that cannot be obtained with PenSlab and other Monte Carlo codes based on simple zoning structures.

Running **GBView2** and loading `ALUMBEAM.G2D` gives the default contour plot of dose rate in the  $x$ - $y$  plane shown on the left-hand side of Fig. 4. Inspection of the figure shows that the dose rate at the entrance face is close to the theoretical value. The **GamBet** calculation is slightly higher because of power deposition by backscattered electrons. The dose rate is enhanced at a depth of about 0.05 cm because of the effect of electron scattering in the  $z$  direction. The electrons fan out and deposit energy over a tree-shaped region with size comparable to the electron range. The effect of statistical variations of deposited power between the small element is visible in the figure. Smoothing the distribution is equivalent to increasing element size – statistical noise is reduced at the expense of some loss of resolution. The right-hand side of Fig. 4 shows the modified dose distribution after one application of the `SMOOTH DOSE` command in **GBView2**.

To conclude, we can check **GamBet** calculations of flux through region boundaries for a planar geometry in the continuous beam mode. The code predicts a backscatter ratio for primary electrons striking aluminum of 0.1125. The average energy of the backscattered primaries is 424.0 keV. With the beam linear current  $J = 2.1 \times 10^3$  A/m, the expected return energy flux through the front face of the slab is 100.2 J/s/m. The value reported in the region flux table of `ALUMBEAM.GLS` for power flow from Region 1 to Region 0 is 101.4 J/s/m. The value is slightly higher because of the contribution of knock-on electrons.

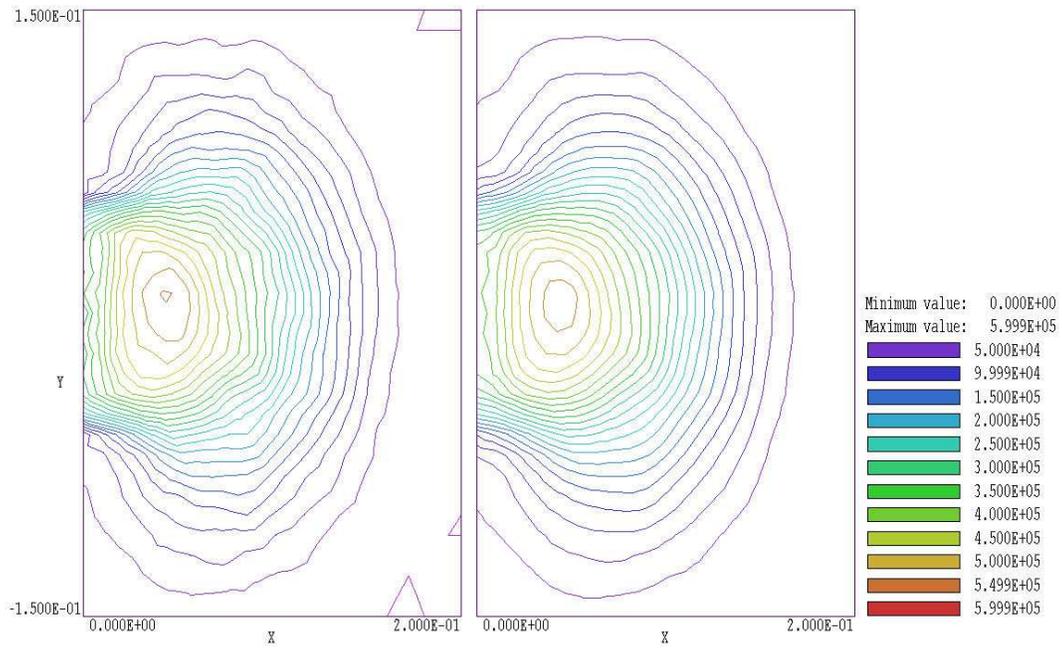


Figure 4: Dose rate distribution from an electron beam striking an aluminum block. Beam properties:  $T = 1.0$  MeV,  $h = 0.11$  cm and  $J = 2.1 \times 10^{-3}$  A/m. Left: raw data. Right: Smoothed data.

### 3 Photon benchmark simulations

This tutorial discuss two simulations of gamma ray generation and transport in a lead slab. The intention is to show useful **GamBet** techniques and diagnostic capabilities in **GBView2**. The simple planar 2D geometry facilitates comparison to theory.

In the first example, 1.0 MeV gamma rays strike a lead slab of thickness 1.0 cm at normal incidence. The calculation demonstrates some capabilities of the *SOURCE ANALYSIS* menu in **GBView2**. The input files are `LEADSLAB.MIN` and `LEADSLAB.GIN`. The geometry file defines a single region with length 1.0 cm along  $x$  and height  $\pm 5.0$  cm along  $y$ . The large extent in  $y$  and infinite width in  $z$  ensure that no photons are lost through the transverse faces. The goal of the calculation is to find the total attenuation coefficient  $\mu$ . The parameter gives the fractional flux of full-energy photons that emerge from a target of thickness  $L$  through the equation:

$$F(L)/F_0 = \exp(-\mu L).$$

The strategy is to initiate 10,000 showers and to record the parameters of particles that leave the solution volume in the escape file `LEADSLABESC.SRC`. The file is then loaded into **GBView2**. A filter is added to restrict particles to full-energy photons that exit the downstream face. A modified `SRC` file is generated and reloaded to count the particles included in the filtered class.

We use the NIST XCom site to find quantities for a theoretical comparison. The site, located at

<http://physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html>

is an invaluable resource for planning runs involving photons. XCom generates graphs and listings of attenuation coefficients for coherent and incoherent scattering, photoelectric absorption and pair production. Figure 5 illustrates an XCom plot. The site provides the following values for the normalized total attenuation coefficient for 1.0 MeV gamma rays in lead:  $\mu_n = 0.071$  cm<sup>2</sup>/gm with coherent scattering and  $\mu_n = 0.068$  cm<sup>2</sup>/gm without coherent scattering. The process of *coherent scattering* changes the direction of photons but not their energy. Because we do not intend to filter by angle, we use the value of  $\mu_n$  that does not include coherent scattering. Multiplication by density of lead ( $\rho = 11.35$  gm/cm<sup>3</sup>) gives the total attenuation coefficient:

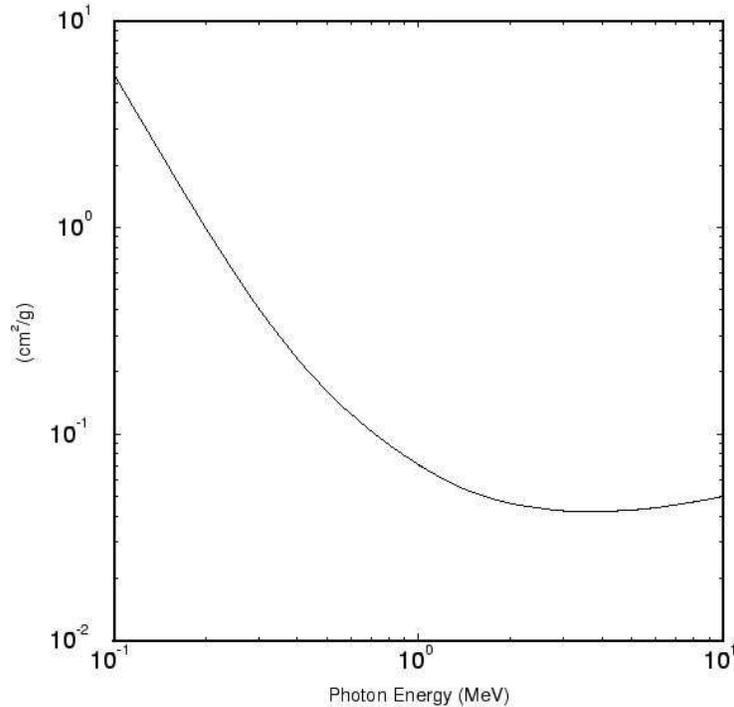


Figure 5: Total attenuation coefficient (with coherent scattering) for gamma rays in lead. Data generated by the NIST XCom site.

$$\mu = \rho\mu_n = (0.068)(11.35) = 0.772 \text{ cm}^{-1}.$$

Inserting the value in the previous equation with  $L = 1.0$  cm yields  $F(x)/F_0 = 0.462$ .

To carry out the calculation, run **Mesh** and **GamBet** to create the file `LEADSLABESC.SRC`. Run **GBView2** and pick the command `FILE/LOAD SOURCE FILE` and choose the file in the dialog. Go to the `SOURCE ANALYSIS MENU` and choose the command `ANALYSIS/SET PARTICLE FILTER`. In the dialog, activate the `PHOTON` radio button and enter the values 0.999 for `XMIN` and  $0.999 \times 10^6$  for `KENGMIN`. Click `OK` to continue. The filter eliminates knock-on electrons and backscattered or reduced-energy photons. Choose the command `ANALYSIS/WRITE SOURCE FILE` and supply the prefix `LEADSLABMOD`. Return to the main menu and load the new source file. The information dialog shows that the file contains 4612

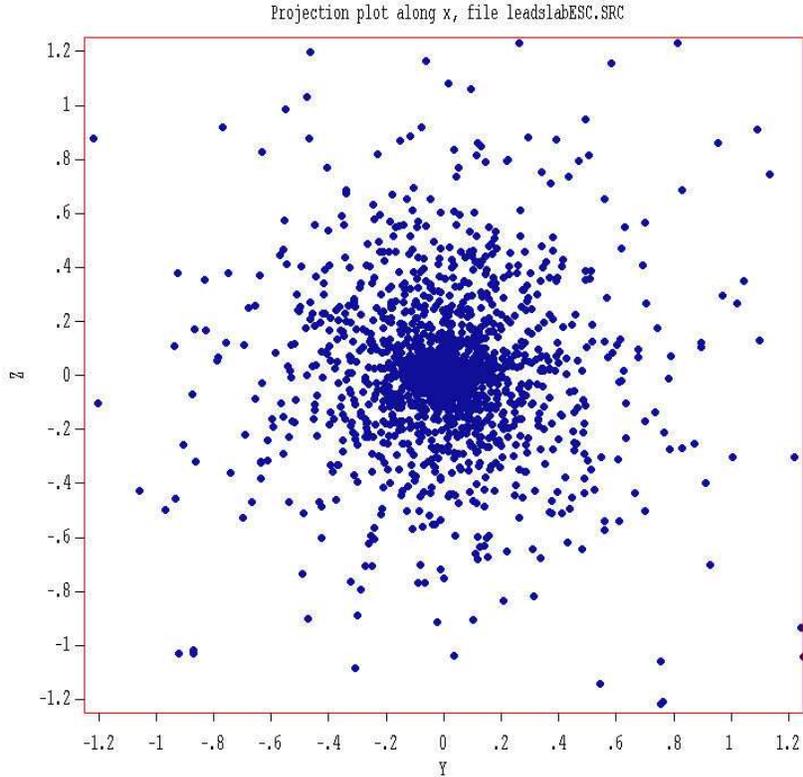


Figure 6: Example LEADSLAB – transverse spatial distribution of photons at the exit plane.

particles. The implied value  $F(L)/F_0 = 0.461$  is in good agreement with the prediction.

As a final activity, we shall generate a plot of the transverse distribution of scattered photons at the downstream face of the slab. Reload LEADSLABESC.SRC, go the *SOURCE ANALYSIS MENU* and return to the *SET PARTICLE FILTER* dialog. Leave the constraints on particle type and *XMIN* in place, but remove the filter on kinetic energy. Choose the command *PLOT/SET PLOT QUANTITY* and pick the option *Y-Z*. In the default *AUTOSCALE* mode, a few photons with large angles give a skewed plot with a large field of view. To improve the appearance of the plot, click on *PLOT/SET PLOT LIMITS* to bring up a dialog. The active fields depend on the type of distribution plot. In this case, uncheck the *AUTOSCALE* boxes and supply limits for the *Y* and *Z* axes. Figure 6 was generated with the

choices  $YMin = -1.25$ ,  $YMax = 1.25$ ,  $ZMin = -1.25$  and  $ZMax = 1.25$ .

The second example treats generation of bremsstrahlung X-rays by an electron beam striking a thin target. The calculation demonstrates interaction forcing to improve output statistics. The input files are `BREMSFORCE.MIN` and `BREMSFORCE.GIN`. A 5.0 MeV electron beam is normally incident on a lead sheet of thickness 0.324 mm in  $x$  with extents  $\pm 0.150$  mm in  $y$ . The sheet thickness is about 1/10 the electron range, so we can make approximate comparisons to theory. The following information for 5.0 MeV electrons in lead was generated by the NIST EStar site:

| Kinetic Energy MeV | Collision Stp. MeV | Radiative Stp. cm2/g | Total Stp. MeV | CSDA Range cm2/g | Radiation Yield g/cm2 |
|--------------------|--------------------|----------------------|----------------|------------------|-----------------------|
| 5.000E+00          | 1.120E+00          | 5.773E-01            | 1.698E+00      | 3.673E+00        | 2.045E-01             |

Table 6 shows the **GamBet** control script `BREMSFORCE.GIN`. The cut-off energies are set to 50.0 keV to give a short run time. As a result, the spectrum of escaping gamma rays will contain no data for lower energies. An initial run was performed without interaction forcing. A total of 20,000 electrons were injected and the run time was 22.0 s. Because the probability of bremsstrahlung interactions is low compared to scattering and collisional energy loss, the escape file contains only 6279 photons. The top plot in Fig.7 of the energy spectrum of downstream photons shows a high level of statistical noise. The plot was created in the *SOURCE* menu of **GBView2** with the following options: 1) the plot type is *1D BINS*, 2) the plot quantity is  $T$  and 3) energy weighting is applied. With energy weighting, the vertical axis shows the relative photon energy-flux per kinetic-energy interval.

The statistical variations of output quantities can be significantly reduced by adding the command

```
Force Brems 50.0
```

In this case, **GamBet** raises the probability of bremsstrahlung interactions by 50.0 but reduces the energy-deposition weight of resulting photons by a factor of 0.02. This technique increases the number of bremsstrahlung photons but ensures that their effect on materials in the solution volume is unchanged. With interaction forcing, the total number of photons in the

Table 6: Control script BREMSFORCE.GIN

```
GEOMETRY
  DUnit 1000.0
  GFile2D BREMSFORCE.MOU Rect
END
COMPOSITION
  Material Pb
  Region(1) = 1
END
SOURCE
  SList
    E 5.0E6 0.00001 0.00 0.00 1.00 0.00 0.00
  End
  NPMult = 20000
END
PROCESS
  EAbs Electron 5.0E4
  EAbs Photon 5.0E4
  EAbs Positron 5.0E4
  C1 0.10
  C2 0.10
  Wc 5.0E4
  WCr -5.0E4
  DsMax(1) = 0.01
  Force Brems 50.0
END
ENDFILE
```

escape file increases to 288708. The improvement in statistics is evident in the bottom plot of Fig. 7. The run time is 59 s. Although the number of photons increases by a factor of 50, the run time rises by only a factor of 2.7. **Gambet** performs much less work tracking a photon (which undergo only discrete interactions) than an electron. Therefore interaction forcing is highly effective in modelling bremsstrahlung targets.

To conclude, we can make some other comparisons of code results to theory. Using the total stopping power from the EStar data, the predicted change in electron kinetic energy is

$$\Delta T_e \cong -(1.698 \text{ MeV-cm}^2/\text{g}) (11.350 \text{ g/cm}^3) (0.034 \text{ cm}) = 0.655 \text{ MeV}.$$

The predicted average electron energy at the downstream boundary of the sheet is 4.345 MeV. The radiative stopping power value implies that the average energy lost to photons by an incident electron is

$$\Delta T_e \cong -(0.577 \text{ MeV-cm}^2/\text{g}) (11.35 \text{ g/cm}^3) (0.034 \text{ cm}) = 0.223 \text{ MeV}.$$

For comparison the following entries appear in the file `BREMSFORCE.GLS`:

```
Average input energy: 5.0 MeV
Average output electron energy: 4.310 MeV
Average energy lost to photons per primary: 0.231 MeV
```

The output energy is slightly lower than the prediction because of elongation of electron paths by small-angle scattering. The code gives a thin-target radiation conversion efficiency of 4.6%. Figure 8 shows a plot generated by **GBView2** of the angular distribution of forward-directed bremsstrahlung photons.

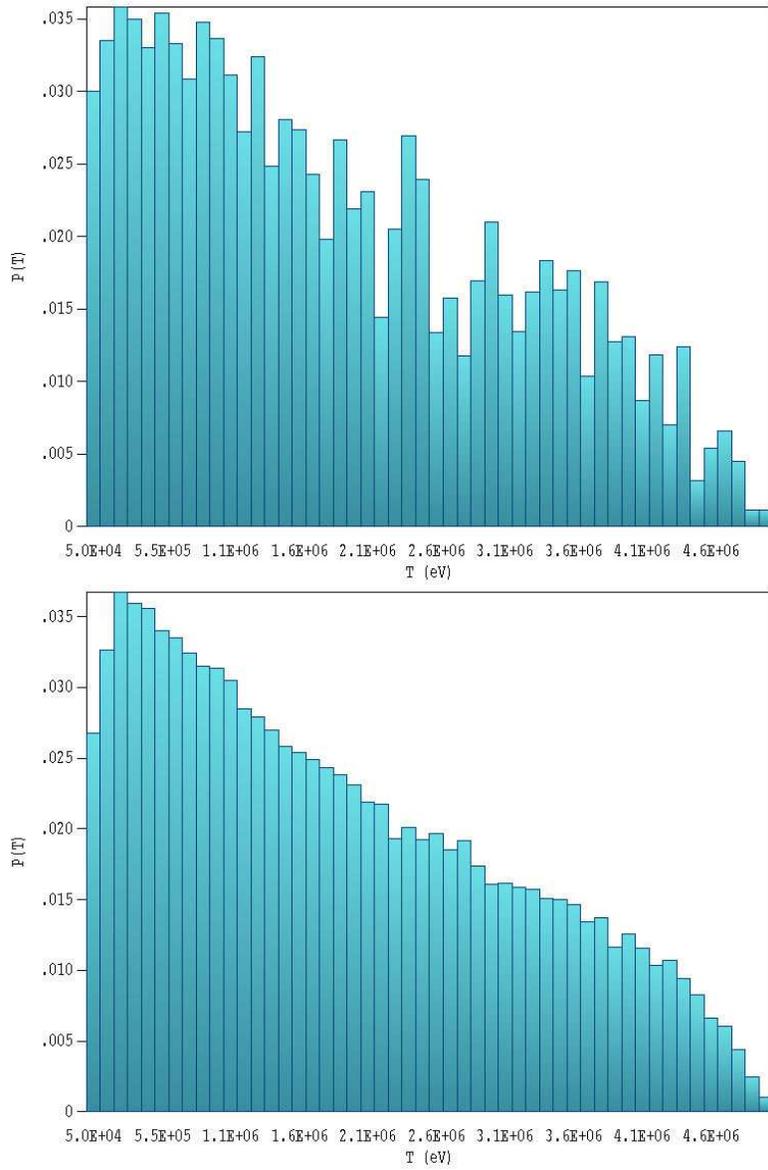


Figure 7: Bremsstrahlung photon relative energy flux as a function of kinetic energy, example BREMSFORCE. Top: Without interaction forcing. Bottom: With interaction forcing.

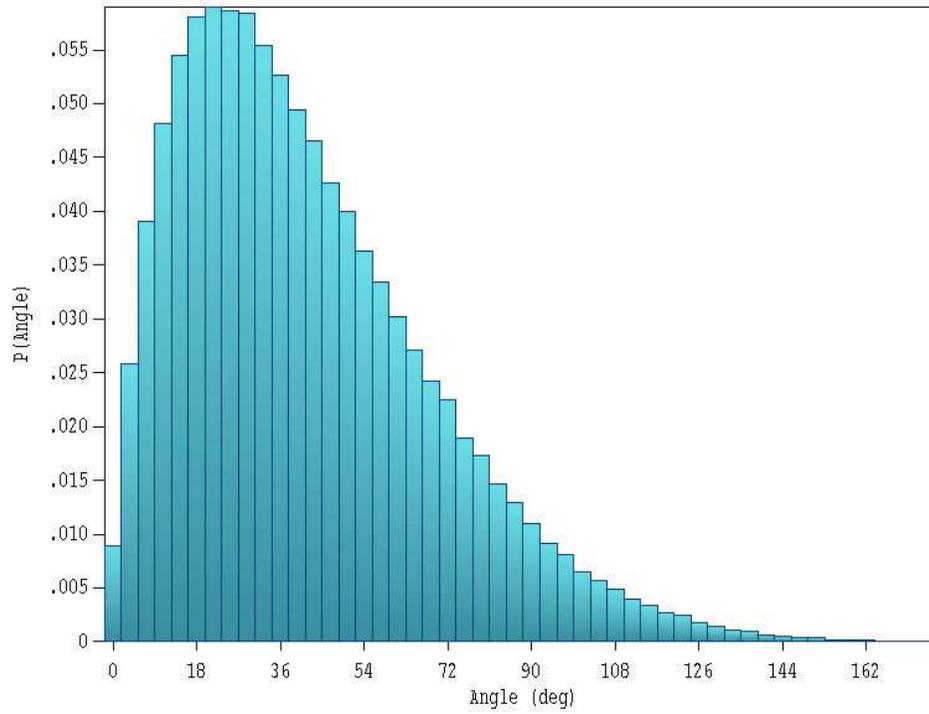


Figure 8: Bremsstrahlung photon relative energy flux as a function of angle with respect to the electron beam axis, example BREMSFORCE.

## 4 Electron beam energy deposition in a high-pressure gas

This example treats energy deposition in a high pressure gas by a pulsed electron beam, a situation that might be encountered in an ionization chamber. The system geometry is relatively simple to allow comparisons with theory. The example emphasizes the following features:

1. Interpretation of deposited dose for a pulsed beam in a 2D cylindrical geometry.
2. Modification of electron dynamics by an applied electric field.
3. Definition of a special material not included in the standard Penelope set.
4. Comparison of **GamBet** results to theory.

The incident electron beam with 0.5 cm radius, 1.0 A current, 125 keV kinetic energy and 1.0 ms pulselength enters a chamber of radius 5.0 cm and length 10.0 cm filled with 10 atmospheres of helium gas. We shall compare results with and without an applied accelerating field of  $E_z = -20.0$  kV/cm. In comparison, the NIST EStar site gives an electron stopping power in helium at 10 atmospheres of  $dE/dx = 6.192$  keV/cm. Therefore, the accelerating field counteracts the affect of collisional energy loss and we expect that the majority of electrons exit through the downstream boundary.

You can perform the complete calculation if you have the **TriComp Mesh** and **EStat** programs. Otherwise, we have supplied the electric field file **IONCHAMBER.EOU** so you can carry out the **GamBet** simulation. The input file **IONCHAMBER.MIN** (listed in Table 7) defines the mesh for the **EStat** calculation. The same mesh is used as the geometry file of the *GamBet* calculation. The first region is a cylinder that will be associated with the helium fill gas. This region is surrounded by void – the calculation does not include the effects of the chamber walls. The element size is about 0.1 cm. The two other unfilled regions (node assignment only) define fixed potentials on the left and right boundaries to create the electric field in the **EStat** calculation. These regions play no part in the **GamBet** simulation. Table 8 shows the contents of **IONCHAMBER.EIN**, the control script for the **EStat** calculation. The commands specify that units are in centimeters, cylindrical weighting

Table 7: Script to define a mesh for the **EStat** and **GamBet** calculations

```

* File: IONCHAMBER.MIN
GLOBAL
  XMesh
    0.00 10.00 0.10
  END
  YMesh
    0.00 5.00 0.10
  END
END
REGION FILL Helium
  L 0.00 0.00 10.00 0.00
  L 10.00 0.00 10.00 5.00
  L 10.00 5.00 0.00 5.00
  L 0.00 5.00 0.00 0.00
END
REGION LeftBound
  L 0.00 0.00 0.00 5.00
END
REGION RightBound
  L 10.00 0.00 10.00 5.00
END
ENDFILE

```

should be applied, and that the helium gas has a relative dielectric constant close to unity. The potential on the entrance boundary is set to  $\phi = 0.0$  V and the right-hand boundary to  $\phi = 2.0 \times 10^5$  V. Run **Mesh** to generate the file IONCHAMBER.MOU. Optionally, run **EStat** to create IONCHAMBER.EOU.

The **GamBet** calculation requires two files: IONCHAMBERINPUT.SRC and IONCHAMBER.GIN. The *CIRCULAR BEAM TOOL* of the **Trak** code was used to create a PRT file that was converted to the **GamBet** SRC format. The beam consists of 100 model electrons uniformly distributed in radius to  $r = 0.5$  cm. The current of each particle is proportional to  $r$ , giving uniform current density. The sum of particles currents equals 1.0 A. Table 9 shows the contents of the file IONCHAMBER.GIN. The script has some interesting

Table 8: Control script for the **EStat** calculation

```
* File: ION_CHAMBER.EIN
Set DUnit 100.0
Set Geometry Cylin
Region(1) Epsi = 1.0
Region(2) Potential = 0.0
Region(3) Potential = 200.0E3
ENDFILE
```

features:

- The *EFIELD2D* command is used to include effects of applied electric field. For a zero-field run, the command can be deactivated by placing an asterisk (the comment symbol) in the first column.
- The standard Penelope model for helium corresponds to atmospheric pressure. The *MATERIAL* structure is used to represent the high-pressure gas with density 10 times the value at STP.
- The *TPULSE* command signals that **GamBet** should record dose rather than dose rate.
- The command *PLOTON 2* causes the program to record two showers for each primary particle (giving a total of 200 orbit traces).
- Note that there are no material properties defined for Regions 2 and 3 which consist of nodes only. The region numbers are not assigned to elements, and therefore the regions do not play a part in the **GamBet** calculation.

The calculation of 50,000 showers takes about 227 seconds on a 3.4 GHz computer. Energy statistics are recorded in the file *IONCHAMBER.GLS*. The total input energy is 125.0 J. With no applied electric field, energy is conserved to within 0.26%. The beam deposits 91.98 joules in the gas, while electrons carrying 33.02 J escape through the boundaries. With the applied field, the energy difference parameters is 158.21%. The figure is not close to

Table 9: Control script for the GamBet calculation

```
* File: IONCHAMBER.GIN
GEOMETRY
  DUnit 100.0
  GFile2D Ion_Chamber.MOU Cylin
  EFile2D Ion_Chamber.EOU
END
COMPOSITION
  Material
    Name Helium_10atm
    Component He 1.0
    Density 1.785E-3
    Insulator
  End
  Region(1) = 1
END
SOURCE
  SFile IonChamberInput
  NPMult = 500
  TPulse = 1.0E-3
END
PROCESS
  EAbs Electron 1000.0
  EAbs Photon 1000.0
  EAbs Positron 1000.0
  C1 0.10
  C2 0.10
  Wc 5000.0
  Wcr 5000.0
  EMax 300.0E3
  DsMax(1) = 0.20
  StepMax = 5000
  PlotOn 2
END
ENDFILE
```

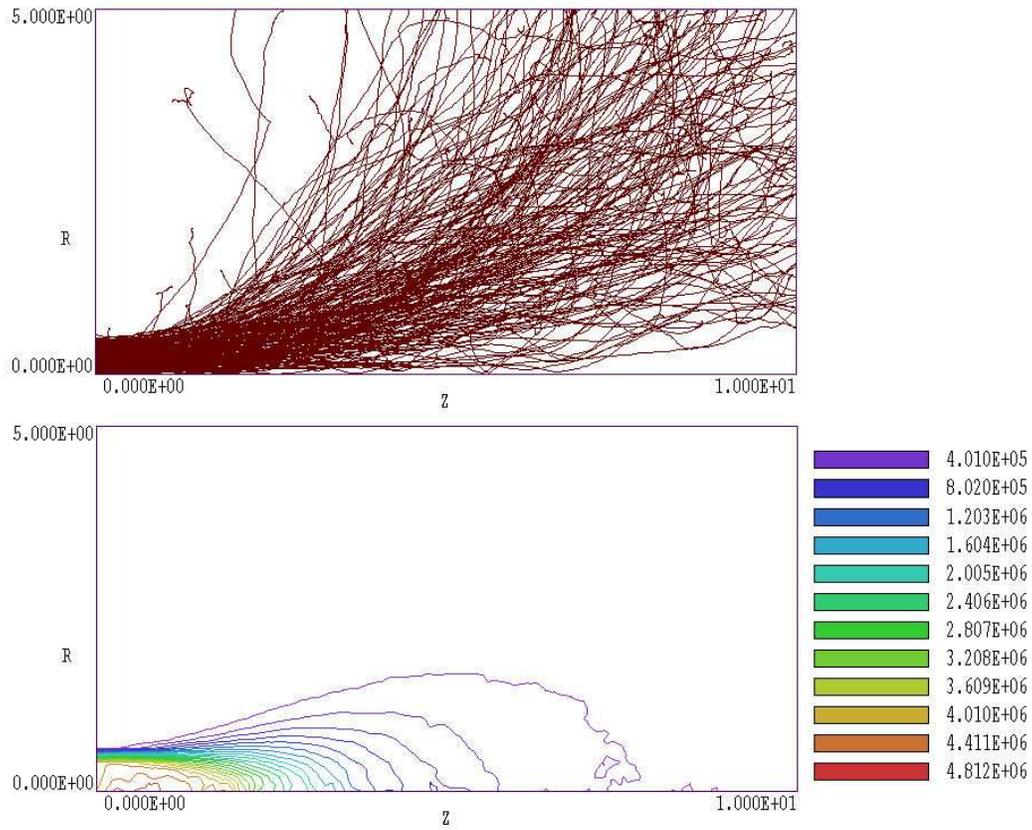


Figure 9: Results with no applied axial electric field. Top: Selected electron trajectories. Bottom: Dose distribution contours, units of Gy

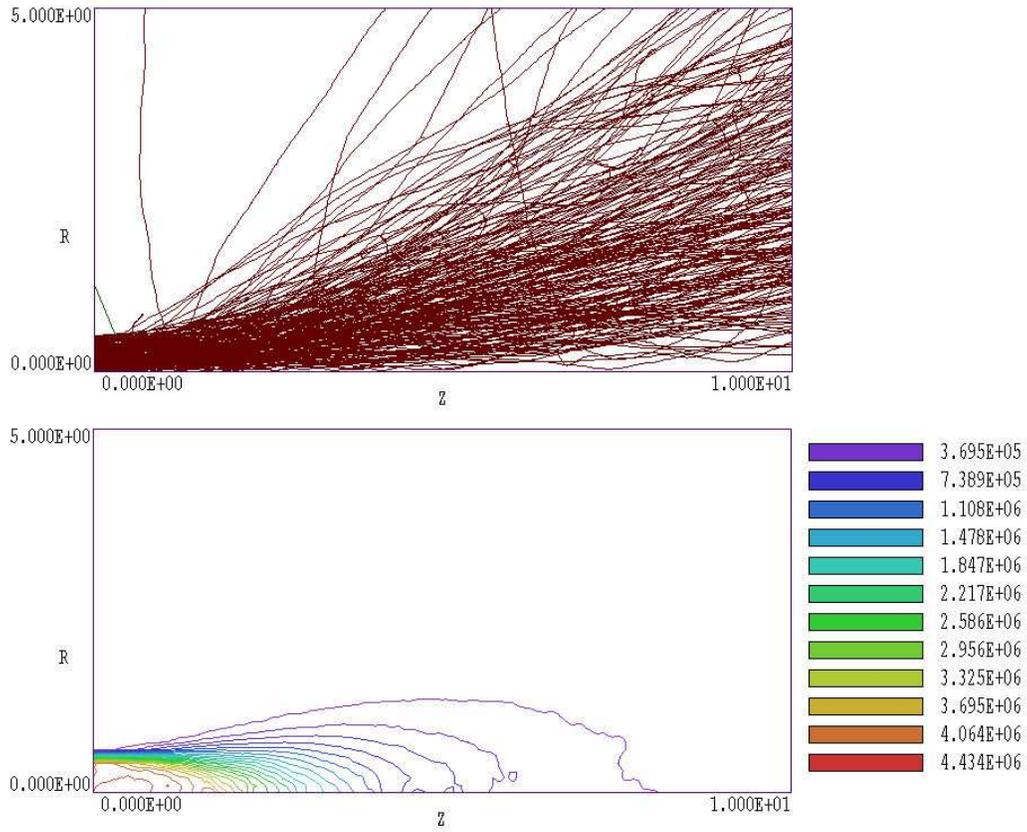


Figure 10: Results with an applied field  $E_z = 20$  kV/cm. Top: Selected electron trajectories. Bottom: Dose distribution contours, units of Gy

zero because the electric field accelerates electrons within the solution volume. In this case the energy deposited in the gas drops to 53.29 J while the energy of escape electrons increases to 269.56 J. The Energy difference parameter equals the difference between final and initial energies divided by the initial energy. Note that

$$(269.56 + 53.29 - 125.00)/125.00 = 1.5828.$$

Figure 9 shows selected electron trajectories and raw dose distributions for a run with no applied field. Given the EStar stopping power, we can calculate thin target dose at the entrance. The predicted energy loss per cm for a 1.0 A beam is 6.192 J, while the mass of helium in a cylinder of length 1.0 cm and cross-section area 0.785 cm<sup>2</sup> is  $1.401 \times 10^{-6}$  kg. The expected dose is therefore  $4.42 \times 10^6$  J/kg. For comparison, entrance value in the simulation is about  $4.85 \times 10^6$  Gy. The higher value results from the contribution of backscattered electrons. For comparison, Fig. 10 shows orbits and dose distribution with the applied field. The orbits appear smoother because of component of directed velocity in the  $+z$  direction. The volume of significant dose extends a longer distance in  $z$  and the entrance dose is closer to the theoretical prediction because of the reduction of backscattered electrons.

Finally, Fig. 11 shows the variation of dose along the axis with distance into the gas. The plot was created by employing the line scan feature of **GBView2**, recording the results in a history file and then transferring values to PsiPlot. The circles represent values calculated directly from raw data. The level of element-to-element statistical variation is apparent. The solid line shows a scan through a smoothed distribution (10 smoothing cycles).

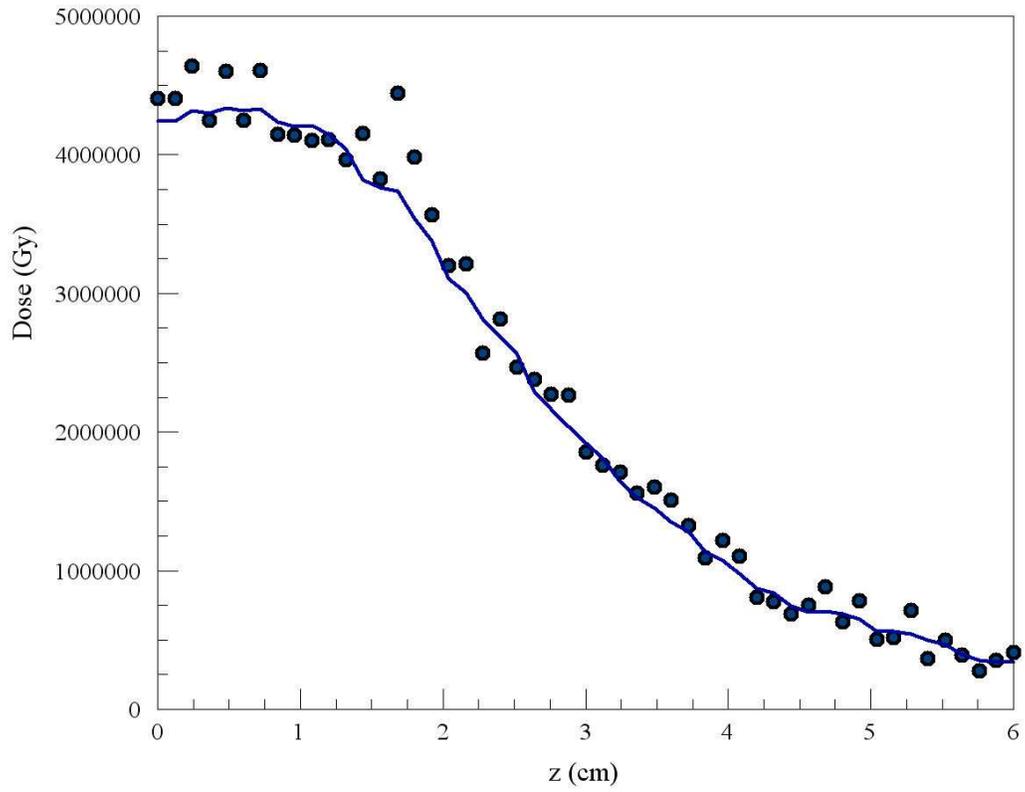


Figure 11: Variation of deposited dose along the axis. The system entrance is at  $z = 0.0$  cm. Circles: raw data. Line: data after one smoothing operation with 10 cycles.

## 5 X-ray generation by a pinched electron-beam diode

The calculations described in this tutorial demonstrate the full power of **GamBet** for 2D simulations. The program uses input from the **Trak** electron-gun code to characterize an X-ray source for pulsed radiography. An electron beam is generated in a pinched-beam diode – the term *diode* refers to a high-voltage vacuum gap that carries a large current of electrons and ions and the term *pinched-beam* implies that the electron motion is dominated by the magnetic field generated by the current. You can perform the complete simulation if you have the **Trak** package. Otherwise, we have included **Trak** output files so you can carry out the **GamBet** calculations. The files `PINCHDIODE.MIN`, `PINCHDIODE.EIN` and `PINCHDIODE.TIN` are inputs for **Trak**. The code produces two output files: `PINCHDIODEP.EOU` (data on the self-consistent electric and toroidal magnetic fields in the diode region) and `PINCHDIODE.PRT` (final parameters of model electrons and ions). The file `PINCHDIODEE.PRT` is a filtered version that contains only electrons that strike the target. The file `PINCHDIODEX.MIN` defines the geometry mesh for the **GamBet** simulation and `PINCHDIODEX.GIN` controls the run.

Figure 12 shows the diode geometry. The tungsten rod anode has a diameter of 1 mm, while the thin aluminum tube cathode has an inside diameter of 10.0 mm. The anode protrudes 4.0 mm into the cathode cavity. An applied pulsed voltage of 1.2 MV creates plasmas on the cathode and anode surfaces which act as sources for an intense flow of ions and electrons. The magnetic field generated by the current pushes electrons to a small spot on the anode tip. In the **Trak** simulation, electrons are emitted at the space-charge limit over the full exposed surface of the cathode. We assume that ion emission occurs over a 4.0 mm length near the anode tip – the ion flux illuminates most emitting regions on the cathode. Run the **Mesh** program to process and to save the electric-field mesh (`PINCHDIODE.MOU`) and run **EStat** to create an applied electric-field solution (`PINCHDIODE.EOU`). Next run **Trak** with `PINCHDIODE.TIN` as input. You can use **VTrak** to inspect particle orbits in the self-consistent electric and magnetic fields. The top part of Fig. 12 shows selected electron orbits and lines of constant electrostatic potential while the bottom part plots selected ion orbits and contours of  $B_\theta$ . Note the smooth compression of electron flow by the toroidal magnetic field with stagnation at the anode tip. Figure 13 shows that about 75% of the

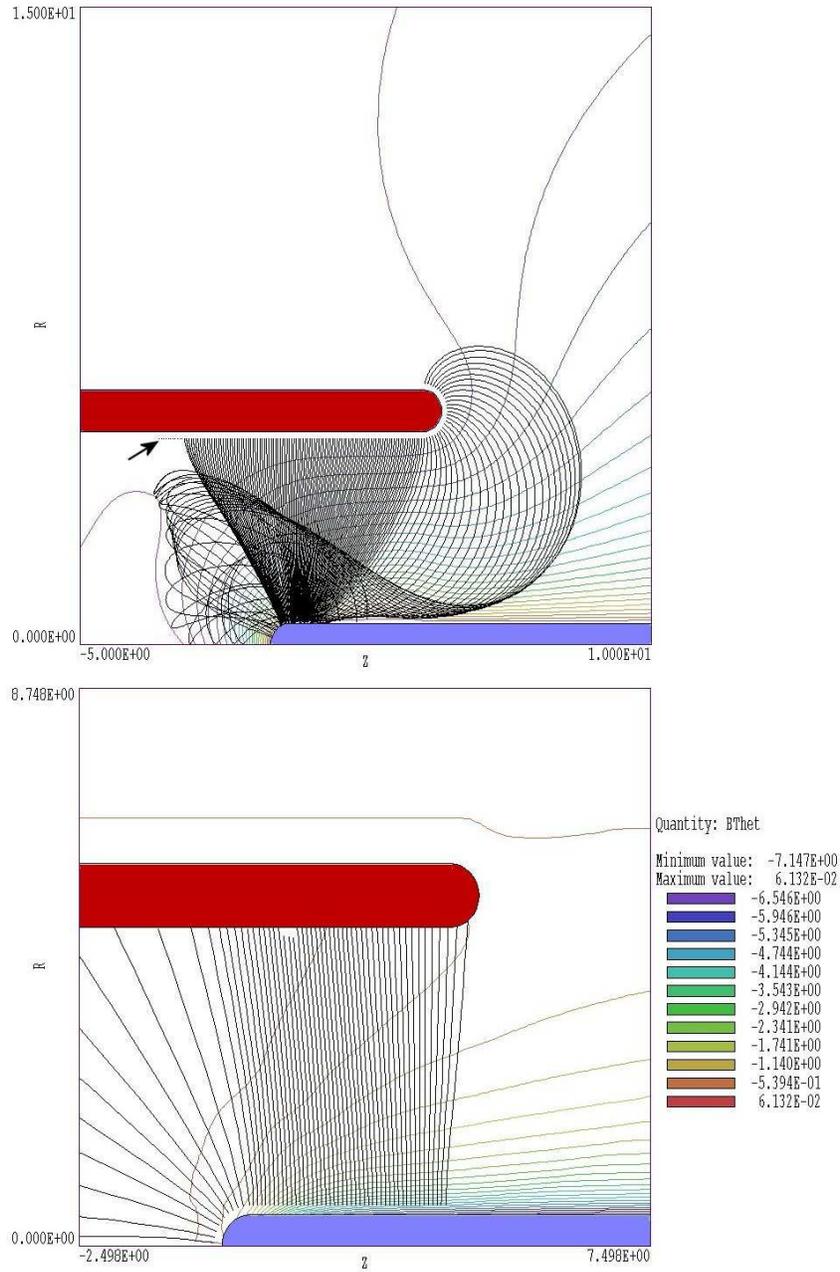


Figure 12: Nested-cylinder diode, 1.2 MV, dimensions in mm. Top: selected electron orbits and lines of constant electrostatic potential. Bottom: Lines of constant  $B_\theta$  and selected ion orbits.

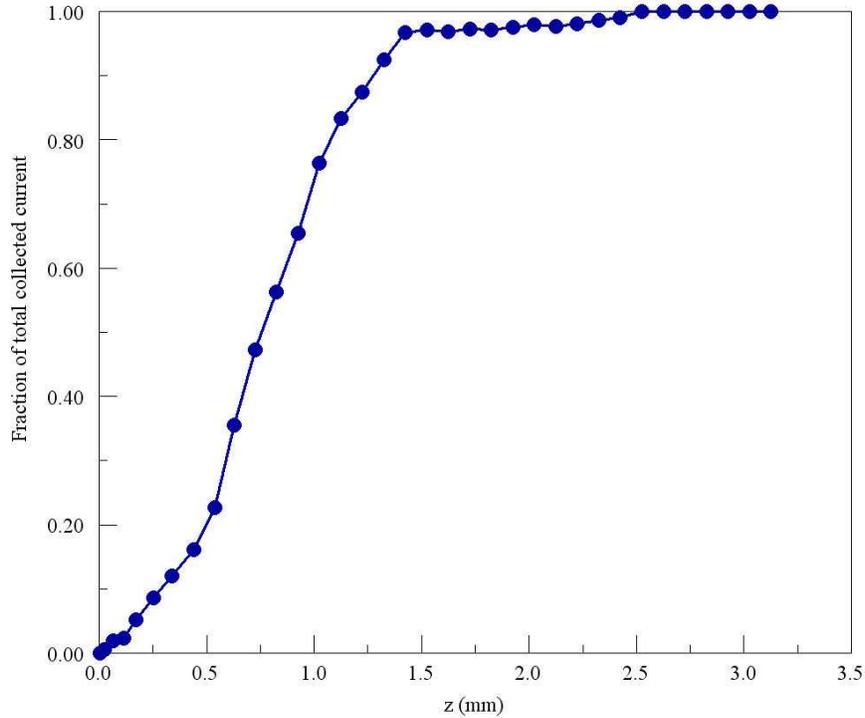


Figure 13: Total electron current collected on the target as a function of distance from the tip

electron current (18.44 kA) is deposited within 1.0 mm of the anode tip.

The file `PINCHDIODE.PRT` created by **Trak** contains the final parameters of all particles, including ions and electrons that stagnate near the cathode. For the **GamBet** run, the distribution must be filtered to include only electrons that strike the target. In **VTrak**, load the file with the `FILE/LOAD DISTRIBUTION FILE` command and transfer to the distribution menu. Set up a filter that passes only electrons by setting the maximum mass to 0.9 AMU. Set the maximum kinetic energy to 1.0 MeV to admit only electrons that reach the anode. Save the filtered distribution as `PINCHDIODEE.PRT`.

The next step is to create a geometry file for **GamBet**. We use a simplified version of the geometry of Fig. 12 that contains only features relevant to the Monte Carlo calculation. Run **Mesh** with `PINCHDIODEX.MIN` to create `PINCHDIODEX.MOU`. Figure 14 shows the geometry mesh. It contains a portion of the tungsten anode surrounded by a spherical void of radius 15.0

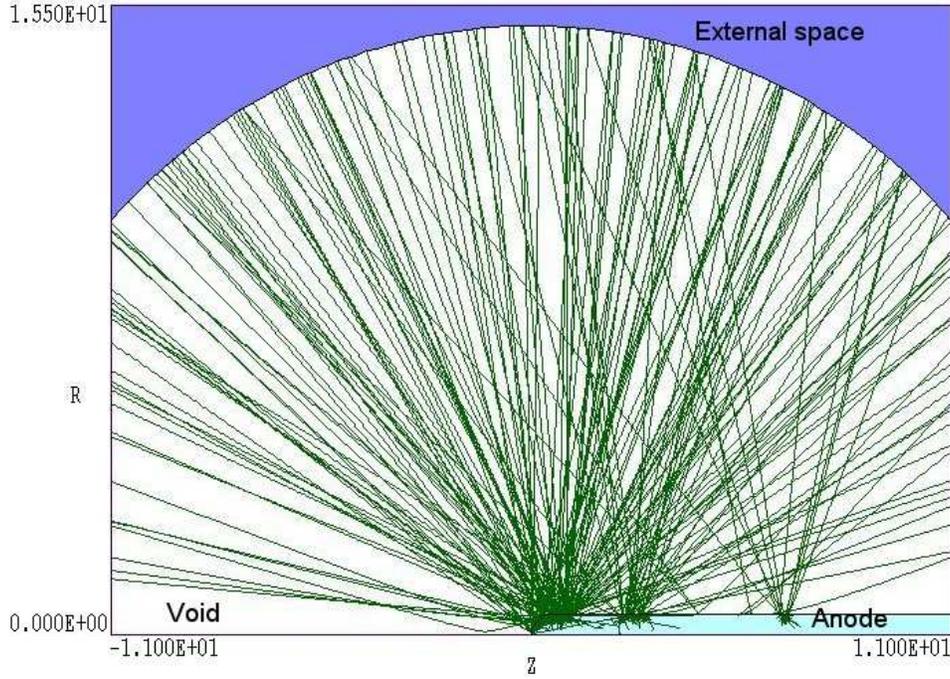


Figure 14: View of a section of the GFile geometry for the **GamBet** simulation showing selected photon trajectories

mm centered at the anode tip. The thin aluminum cathode has been omitted because it has a negligible effect on photon transport. The void region is large enough to track the orbits of backscattered electrons emerging from the target. In the field-free tungsten region electrons interact with the material producing bremsstrahlung photons. There are no material interactions in the void region. Here, backscattered electrons are reflected by the radial electric field and drift away from the tip under the influence of the toroidal magnetic field. Photons travel through the void unimpeded to the boundary where their properties are recorded in the escape file. Note that **GamBet** stops photon orbits exactly at the boundary, even though the mean-free path from the last interaction may be substantially larger than the void radius. Precise termination at the spherical boundary makes it possible to back-project the orbits to determine the effective spot size of the X-ray source.

Table 5 shows the contents of the **GamBet** script PINCHDIODEX.GIN. In response to the *GFILE2D* command, the program loads the geometry mesh of Fig.14 and applies cylindrical weighting. The *EFILE2D* command

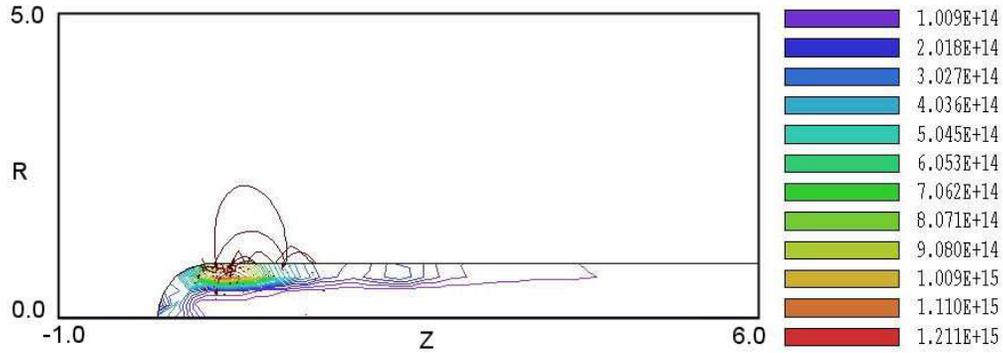


Figure 15: Dose-rate deposition profile in the target in units of Gy/s.

loads the electric field file created with the **Trak** *EDUMP* command. The *RELMODE* calculation includes data for the toroidal magnetic field. The *SFILE* command loads the electron source file derived from the **Trak** particle file output. **GamBet** generates 50 showers for each incident particle. To speed the calculation, electrons and photons below a cutoff value of 50 keV are absorbed *in situ*. Lower energy photons would be absorbed in the vacuum chamber walls surrounding the diode and would not contribute to the available dose. A bremsstrahlung forcing factor of 200 is used to improve statistics.

Figure 15 shows contours of electron energy deposition in the tungsten anode. The plot emphasizes the unique capability of **GamBet** to score interactions using elements as sub-zones. The energy-deposition profile is consistent with Fig. 13. The plot also shows drift orbits of backscattered electrons, which move away from the tip in the combined electric and magnetic fields. Figure 16 shows the angular distribution of photons in the escape file. The top (direct output from **GBView2**) shows the distribution as a function of polar angle relative to the  $z$  axis of the diode. The bottom graph plots a derived quantity, the relative flux per unit solid angle. The photon flux is almost uniform over most of the sphere. It drops to zero at  $0^\circ$  and  $180^\circ$  because of absorption in the rod target. The general decrease at small forward angles reflects the angular distribution of electrons striking the tip.

The *DISTRIBUTION TRANSFORMATIONS* command of **GBView2** was used back-project the photon distribution recorded in the escape file *PINCHDIODE.SRC*. In this case the distribution was filtered to include only photons exiting at the radius of the spherical void. The photons positions

Table 10: **GamBet** control script PINCHDIODEX.GIN

```
* Regions
*      1  VOID
*      2  TARGET
GEOMETRY
  DUnit 1000.0
  GFile2D PINCHDIODEX.MOU Cylin
  EFile2D PINCHDIODEP.EOU BTheta
END
COMPOSITION
  Material W
  Region(1) = Void
  Region(2) = 1
END
SOURCE
  SFile PINCHDIODEE
  NPMult = 50
END
PROCESS
  EAbs Electron 5.0E4
  EAbs Photon 5.0E4
  EAbs Positron 5.0E4
  C1 0.20
  C2 0.20
  Wc 10000.0
  Wcr 10000.0
  EMax 1.4E6
  DsMax(1) = 0.02
  DsMax(2) = 0.05
  StepMax = 20000
  PlotOn 200
  Force Brems 200.0
END
ENDFILE
```

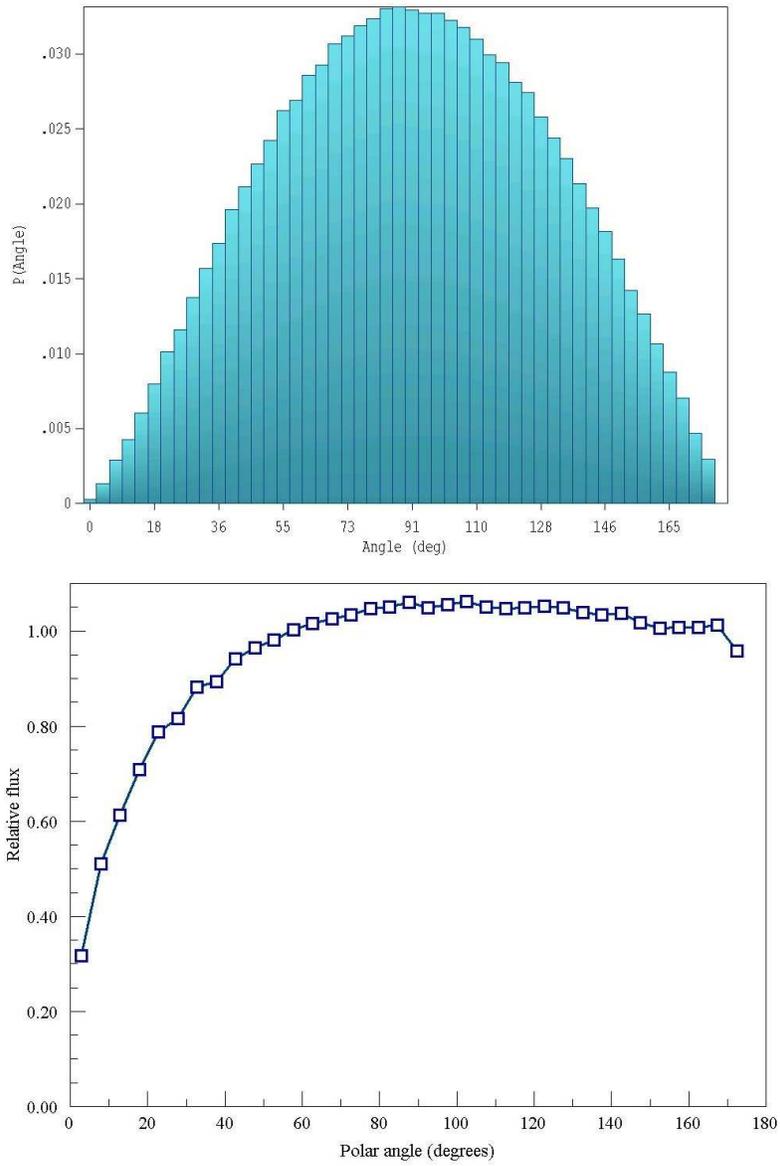


Figure 16: Relative fraction of escape photons (top) and flux per unit solid angle (bottom) as a function of polar angle.

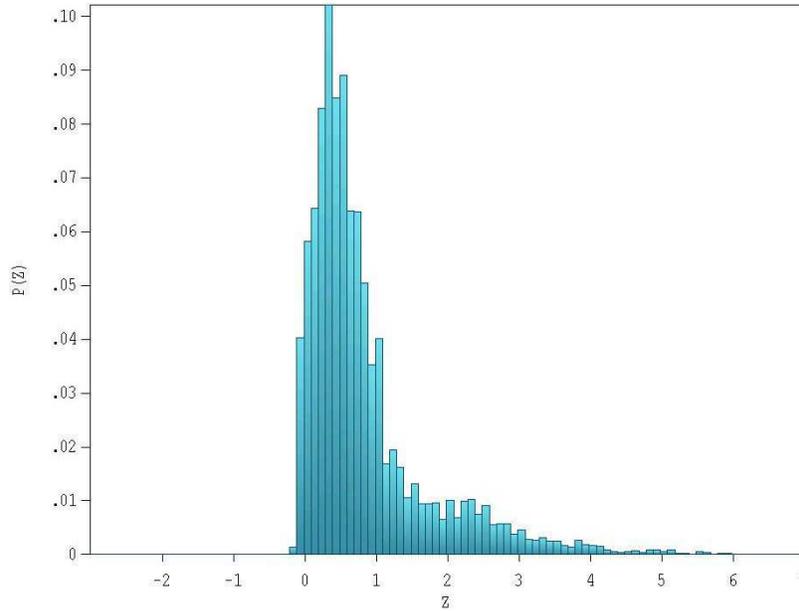


Figure 17: X-ray source size – axial distribution of photon starting positions

were moved back a distance 15.0 mm to determine the approximate positions of origin. The data were saved in a new **SRC** file and used in **GBView2** to create the plot of Fig. 16. The figure shows that the effective source size is less than 1 mm in the axial direction. We can also use the escape file to determine the radiation conversion efficiency. The statistics window displayed when **PINCHDIODE.SRC** is loaded shows that the file contains 618,836 photons with an average energy of 237.3 keV. The file **PINCHDOPDEE.PRT** contains 429 electrons with average energy equal to 1.17 MeV. We must also factor in the effects of the bremsstrahlung forcing factor of 200 and the multiplication factor of 40. The photon conversion efficiency is therefore:

$$\frac{618836 \times 0.2373}{200 \times 40} \frac{1}{429 \times 1.17} = 3.7\%.$$

The ideal conversion efficiency with no target absorption listed on the NIST EStar site is 6.7%.

Another quantity of interest is the radiation dose produced at points removed from the diode. We could use information in the escape file to make an analytic estimate, but the calculation is quite complex. It is easier to apply **Gambet** directly. To perform the calculation, we create an alternate

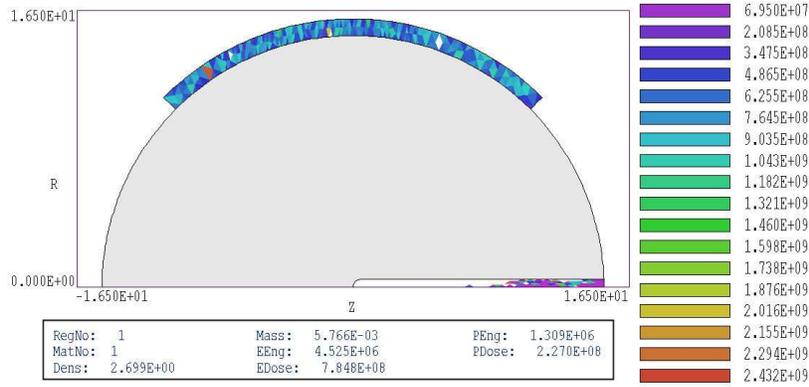


Figure 18: Alternate geometry for calculating available dose from the source. Element plot with adjusted limits shows the dose rate in the aluminum shell. The results of a region calculation is shown in the box at the bottom.

solution geometry with an aluminum shell outside the void as shown in Fig. 18 and determine the average dose in the shell. The figure is then adjusted for the beam pulselength and extrapolated to the desired radius. The input files for the calculation are PINCHDIODED.MIN and PINCHDIODED.GIN. The **GamBet** run generates the dose file PINCHDIODED.G2D which is loaded into **GBView2**. Figure 18 shows an element plot of the dose rate from energy deposition by secondary electrons generated by the photons. The data is statistically noisy, so we use the *DOSE ANALYSIS/REGION PROPERTIES* command to calculate an area-weighted average over the aluminum shell. The results (shown in the box at the bottom of the figure) are  $7.848 \times 10^8$  Gy/s for secondary electron processes and  $2.270 \times 10^8$  Gy/s for direct photon processes. The total dose rate is  $1.012 \times 10^9$  Gy/s. If we had a 15 ns beam pulse, the dose at a distance of 100 cm would be

$$(1.012 \times 10^9) (15.0 \times 10^{-9}) (1.55/100)^2 = 3.416 \times 10^{-3} \text{ Gy}$$

or 314.6 mrad.