



## **Tutorial: Xenos for X-ray source design**

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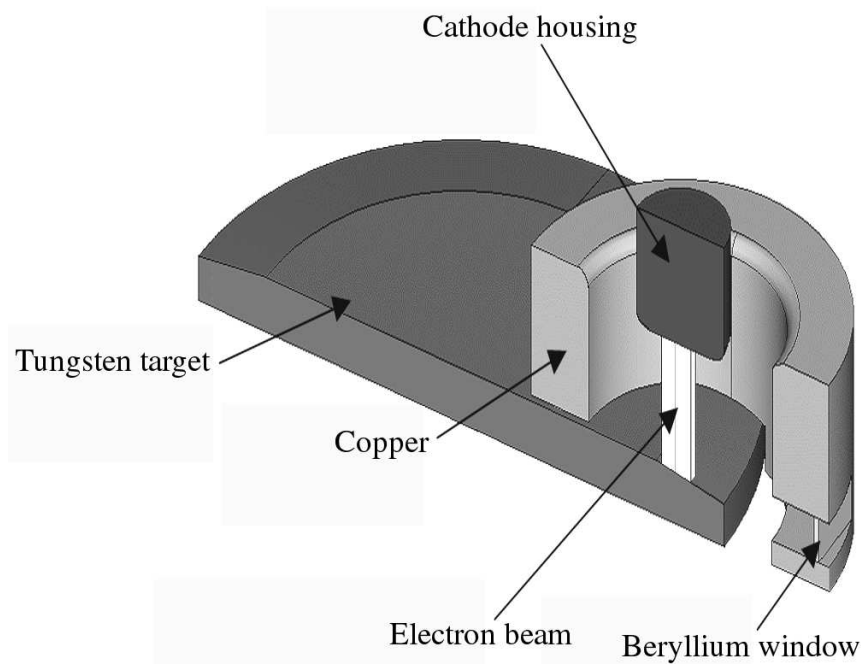


Figure 1: Rotating target X-ray source

## 1 Introduction

This tutorial demonstrates **Xenos** setup techniques to characterize a high-power, rotating-target X-ray source. Figure 1 shows the geometry. The 140 keV electron beam carried 500 mA current. The spot size on the target was about  $1.5 \times 10.0$  mm. Information was required in two areas:

- The power flux on the beryllium window from backscattered electrons.
- The X-ray flux and spectrum exiting the window.

My goal was to obtain useful and accurate numerical information with the shortest possible setup and run times.

My first activity was to analyze the system and requirements to determine the most direct procedure to generate the information. I divided the work into five tasks:

- **Task 1. Two-dimensional backscatter calculation**

I set up a two-dimensional planar calculation with 140 keV electrons incident from a void on a tungsten target at  $90^\circ$  and  $83^\circ$ . The second value of incidence angle corresponds to the inclined target of Fig. 1. The goals were to document the characteristics of the backscattered electrons and to provide a benchmark for the three-dimensional calculations.

- **Task 2. Electric field calculations**

The electric field distribution determines how backscattered electrons find their way to the window. I performed a **HiPhi** field calculation in two stages for good resolution and short run time: 1) a global solution that covered the full gun region shown in Fig. 1 and 2) a local, high-resolution solution centered on the target and window. The second solution used values from the first solution to set boundary values of electrostatic potential.

- **Task 3. Three-dimensional electron backscatter distribution**

A large set of model electrons is required for the three-dimensional transport calculation of Task 4. My strategy was to employ **GenDist** to create model electrons that represented the beam incident on the target. Using this as input, I performed a **GamBet** backscatter calculation in a mesh local to the target surface and captured the resulting backscattered electrons in a filtered source file.

- **Task 4. Backscattered electron flux on the X-ray window**

I combined the microscopic field solution from Task 2 with the backscattered electron distribution from Task 3 in an **OmniTrak** run to trace particle orbits. I then used **GenDist** to filter the resulting particle file to include only electrons incident on the window.

- **Task 5. X-rays transmitted through the beryllium window**

I created a **GamBet** simulation with the following inputs: the microscopic mesh from Task 2 to define the geometry and the input electron distribution created for Task 3. The run employed a bremsstrahlung forcing factor of 100.0. I then used **GenDist** to filter the resulting distribution, including only photons emerging from the window.

## 2 Two-dimensional backscatter calculation

The range of 140 keV electrons in tungsten is about 26  $\mu\text{m}$ . To resolve dose, I picked an element size of 2.0  $\mu\text{m}$  along the propagation direction. I started 50,000 model electrons in a pencil beam moving along the line shown in Fig. 2. The figure also shows the relative dose distribution, the trajectories of selected electrons in the material and the distribution of backscattered electrons. I defined backscattered electrons as primary particles that left the solution-volume boundaries in the void region. At 90dg incidence, a fraction 49.82% of the electrons were backscattered with an average kinetic energy 110.33 keV. At 83°, the ratio was 49.99% with average energy 110.43 keV. The average direction angle of electrons shown in Fig. 2 was -174.6° relative to the  $x$  axis. Figure 3 shows the energy distribution.

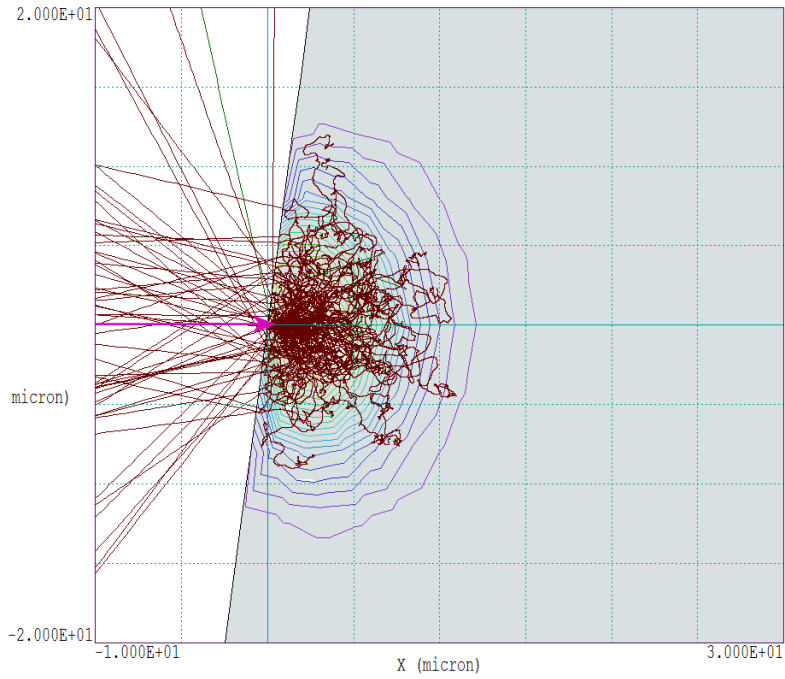


Figure 2: Electrons with 140 keV energy incident on a tungsten target at  $83^\circ$ . Relative dose distribution and selected electron trajectories.

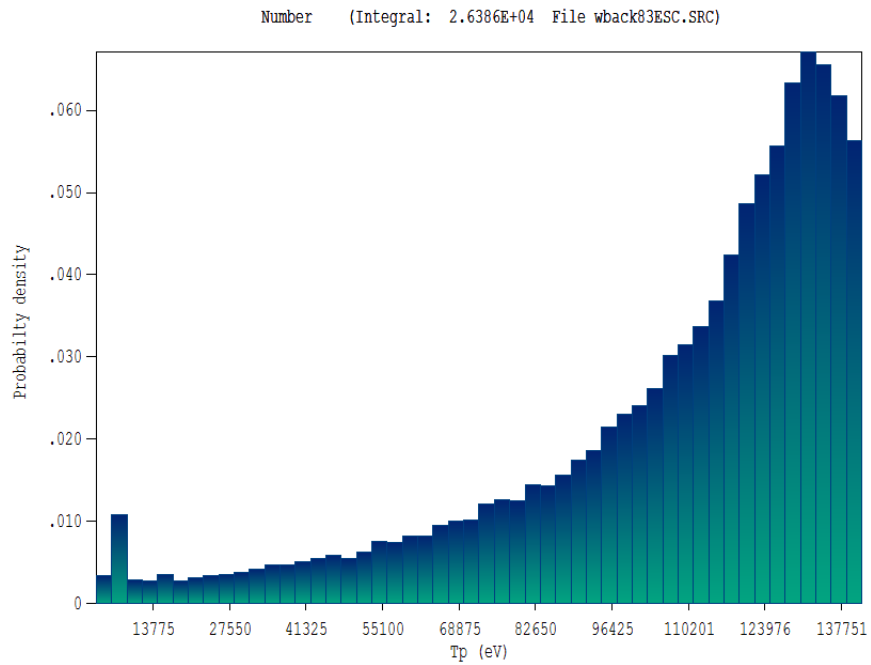


Figure 3: Kinetic-energy distribution of backscattered electrons, 140 keV beam incident on a tungsten target at  $83^\circ$ .

### 3 Electric field calculations

Meshes were required for the electrical field solution as well as the Monte Carlo simulations. Many **MetaMesh** user are tempted to utilize the STL import capabilities for any assembly, leaving critical decisions to the code. This approach often leads to non-optimal meshes. There are several reasons why I decided to work directly from drawings of the system using the native geometric models of **Geometer/MetaMesh**:

- It provided an opportunity for a careful analysis of dimensions to decide on good element sizes.
- I identified critical planes to set in the foundation mesh to facilitate accurate representations with minimal fitting.
- I determined that the entire assembly could be represented with the simple *Box* and *Turning* models.
- With regard to future work, it is much easier to make small dimension changes when the geometry is determined by parametric models.

In the end, the mesh generation process for all examples used in this study took about three hours.

The first step was to create a mesh covering the region of significant electric fields. Figure 4 is a three-dimensional view of the assembly parts from the  $-z$  direction. The figure shows the cathode (blue), the rotating target (orange), the housing (violet) and the X-ray extraction slot (green). The 2.0 mm beryllium window is not visible. Note that the outer radius of the housing was larger than the actual part to fill out the solution volume. The change had no effect on the internal electric fields. The incident electron beam moved in the  $+z$  direction while X-ray extraction through the window was in the  $+x$  direction. The grid in the figure shows the solution volume boundaries that I choose, omitting regions of zero electric field.

One feature of interest in the **MetaMesh** file is the extraction slot, specified by the entry:

```
PART
  Region: Slot
  Name: Slot
  Type: Box
  Fab: 75.00 50.00 15.00
  Shift: 67.00 0.00 0.00
  Surface Region Ground
  Coat Ground Ground
END
```

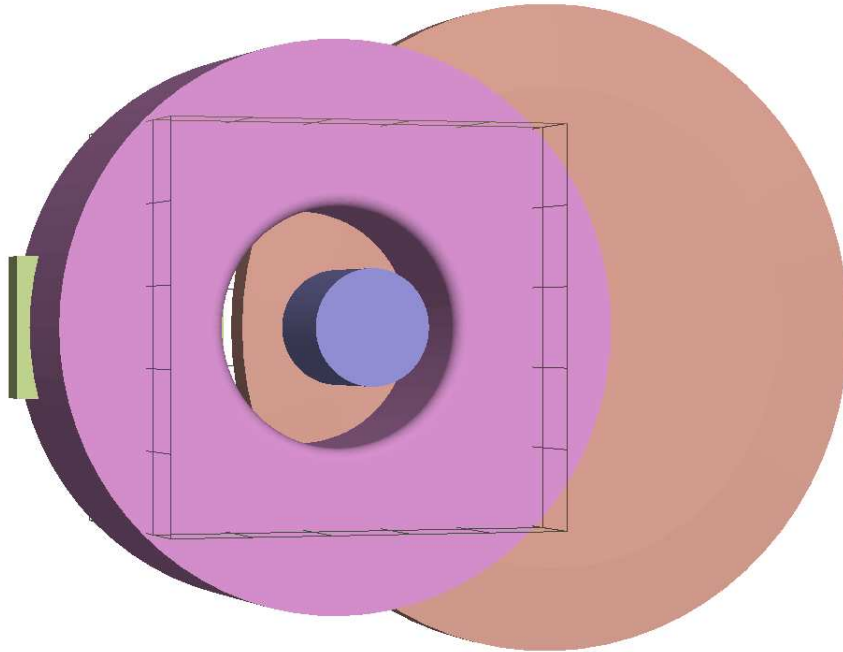


Figure 4: **Geometer** view of the parts of the assembly showing the boundaries of the volume for the global solution.

Note that I assigned a unique region designation to the slot even though it had the properties of vacuum. This was a precaution to avoid ambiguities and distorted elements when fitting the surface of the housing. The *Coat* command ensured that nodes shared between the slot and housing had the fixed-potential designation of the housing. Figure 5 shows the resulting mesh in the plane  $y = 0.0$ . The choices of element size and resolution boundaries gave a good representation of all parts with a moderate number of elements (1,108,800). I assigned the fixed-potential condition ( $\phi = 0.0$  V) to all boundaries except *ZUp*. The electric-field solution took about 90 seconds.

The second electrostatic solution covered only the volume accessible to backscattered electrons. The lower boundary in  $z$  extended to -30 mm, giving sufficient space for reflection of backscattered electrons. The upper boundary in  $x$  was the output surface of the window. It was easy to construct the mesh. I simply pasted designations of the parts that were in the local volume and relied on **MetaMesh** to do the clipping.

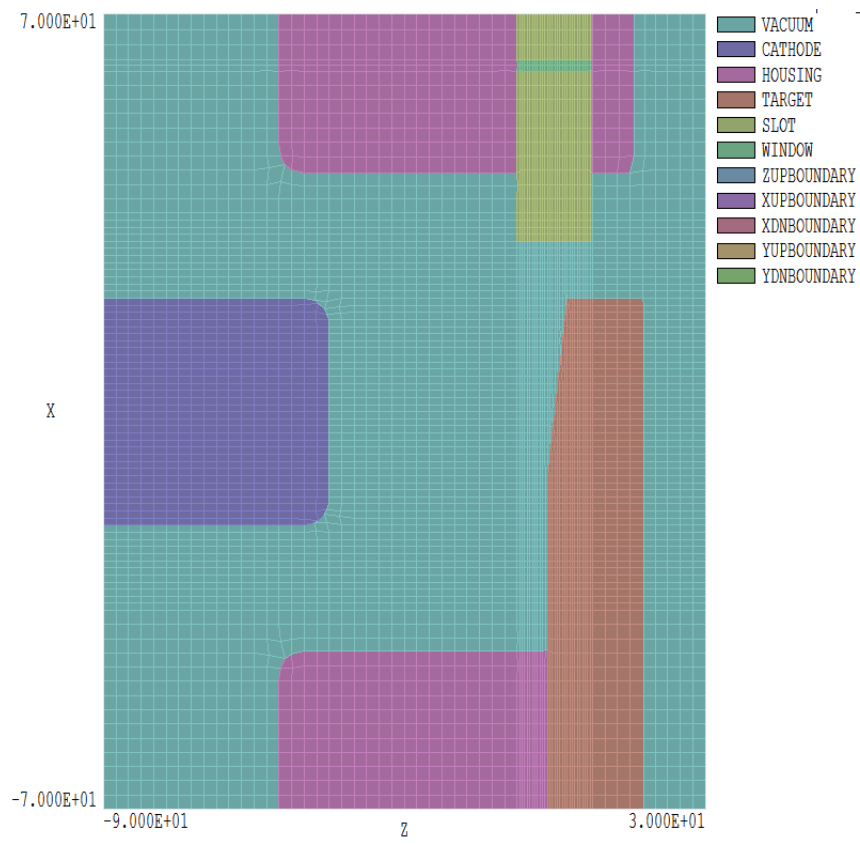


Figure 5: View of the mesh for the global electric-field solution in the plane  $y = 0.0$ .

## 4 Electron backscatter distribution

A three-dimensional distribution of backscattered electrons was required for orbit tracking in **OmniTrak** (Sect. 5). I created a mesh localized at the inclined surface of the target (Fig. 6) which I used as the geometry file for a **GamBet** simulation. In contrast to the calculation of Sect. 2, I needed an input electron distribution to represent a finite-dimension beam. As input to **GenDist**, I created the following file:

```
FileType = SRC
Particle = E-
Energy = 1.4000E+05
Current = 5.0000E-01
Def(Rect) = 5.0000E+00 7.5000E-01 100 25
Shift = 0.000 0.000 -1.499
Distribution = Uniform
EndFile
```

The information represents an electron beam with current 0.5 A and kinetic energy 140 keV. The beam moves in  $z$  with full width 10.0 mm in  $x$  and 1.5 mm in  $y$ . The **GenDist** output file `INPUTBEAM.SRC` contained 2500 model electrons distributed uniformly over the beam cross section. The **GamBet** input file contained the entry  $NpMult = 10.0$ , giving 25,000 incident model electrons. I used **GenDist** to filter the escape file from the run to include only electrons. I saved the 12,232 backscattered model electrons to the file `BSCATTELECTRONS.PRT`. The backscatter fraction determined from this calculation was 48.15%. Figure 6 shows a projection of selected orbits along with mesh element boundaries and the dose in the target surface. Note that because the boundary of the solution volume in Fig. 6 did not correspond exactly to the target surface, the kinetic energy of the backscattered electrons was slightly high in the subsequent orbit calculation. The effect on the orbits and window loading was small.

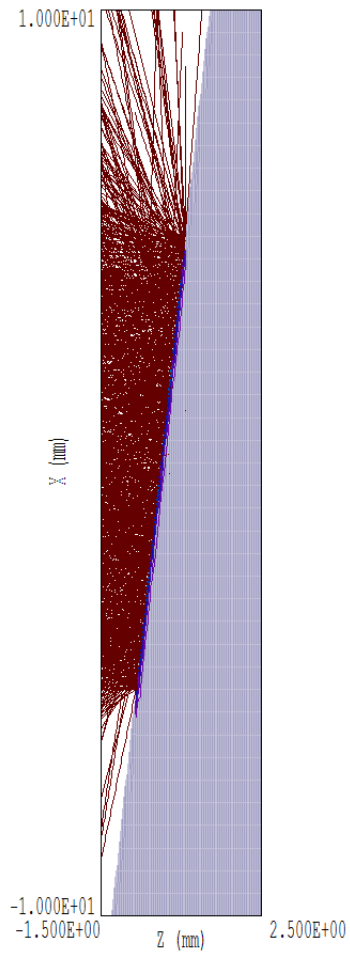


Figure 6: Electron backscatter distribution for the three-dimensional calculations. Orbit projections and view of mesh in the plane  $y = 0.0$  mm.

## 5 Electron orbits and window loading

At this point, I had sufficient information to determine power loading on the output window. The orbit calculations were controlled by the file `WINDOW.OIN` with the following content:

```
FIELDS
  EFIELD3D: Detail.HOU
  DUNIT:   1.0000E+03
  MAXCYCLE: 500
  RESTARGET: 5.0000E-07
END
PARTICLES TRACK
  PFILE: BScattElectrons
END
DIAGNOSTICS
  PARTFILE: Window
END
ENDFILE
```

The run used the electric field solution from Task 2 and the backscattered electron distribution from Task 3. Figure 7 shows selected electron orbits projected to the plane  $y = 0.0$  mm along with some equipotential lines.

I loaded the output file `WINDOW.PRT` into **GenDist** and applied a filter that passed only electrons that hit the window:  $x > 59.9$  mm,  $-25.0$  mm  $\leq y \leq 25.0$  mm and  $-7.5$  mm  $\leq z \leq 7.5$  mm. Of the initial 25,000 model electrons in 70 kW beam, a total of 107 electrons with an average energy of 106.1 keV hit the window. The positions of electron hitting the window surface are shown on the top of Fig. 8. The total electron current at the window was 2.14 mA giving a deposited power of 227 W. The electron distribution was fairly uniform in  $y$ . The bottom section of the figure shows the distribution in  $z$ . The power density had an approximately linear variation concentrated near the top edge. The result reflects shielding of the window by the target (Fig. 7).

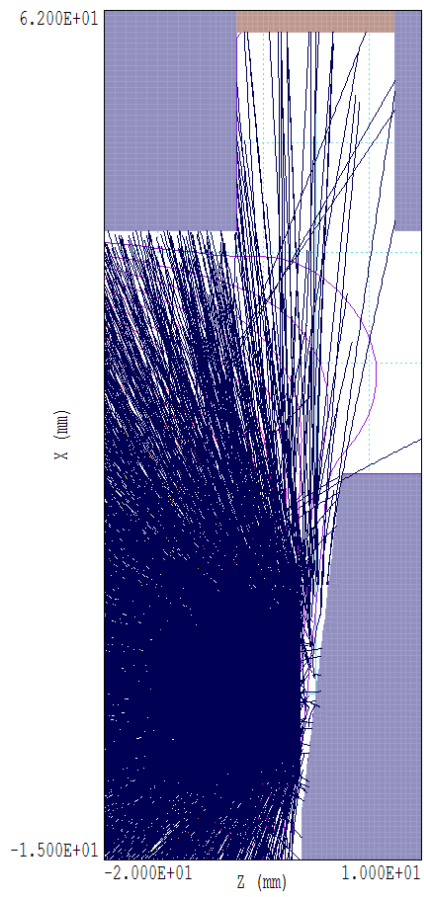


Figure 7: Orbits of selected backscattered electrons.

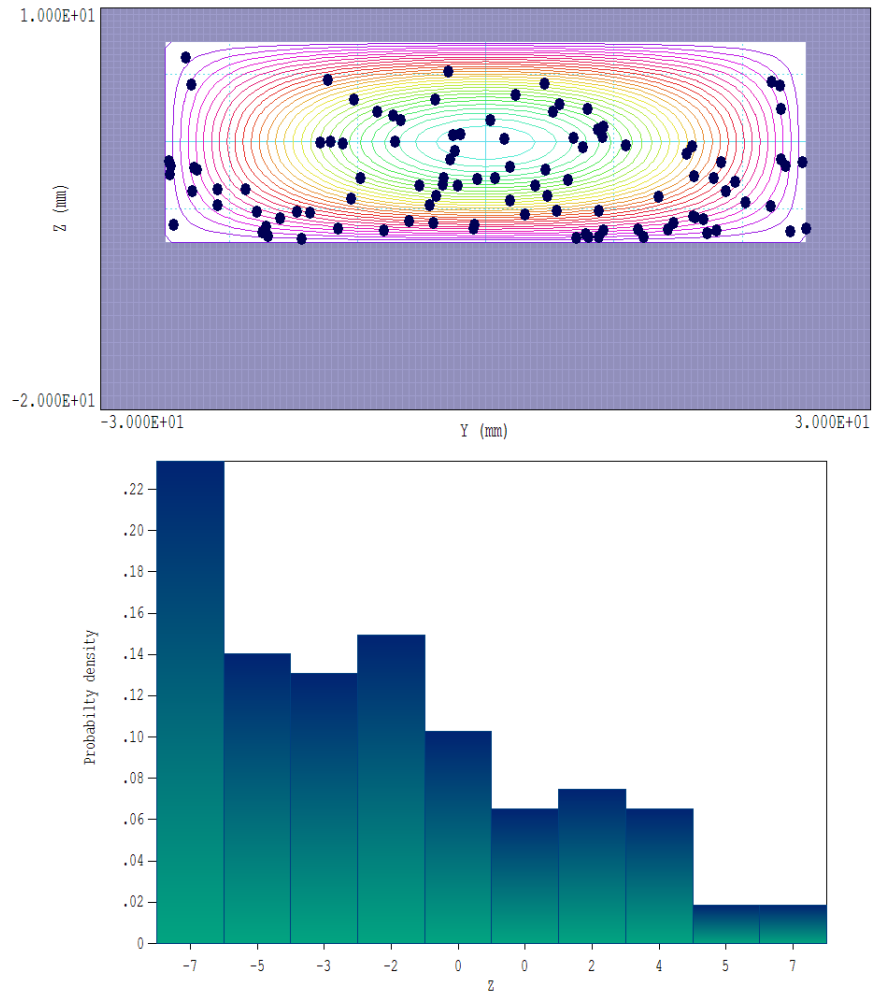


Figure 8: Backscattered electrons incident on the vacuum side of the output window. Top: Orbit intersections with the window. Bottom: Distribution of electrons on the window as a function of height ( $z$ ).

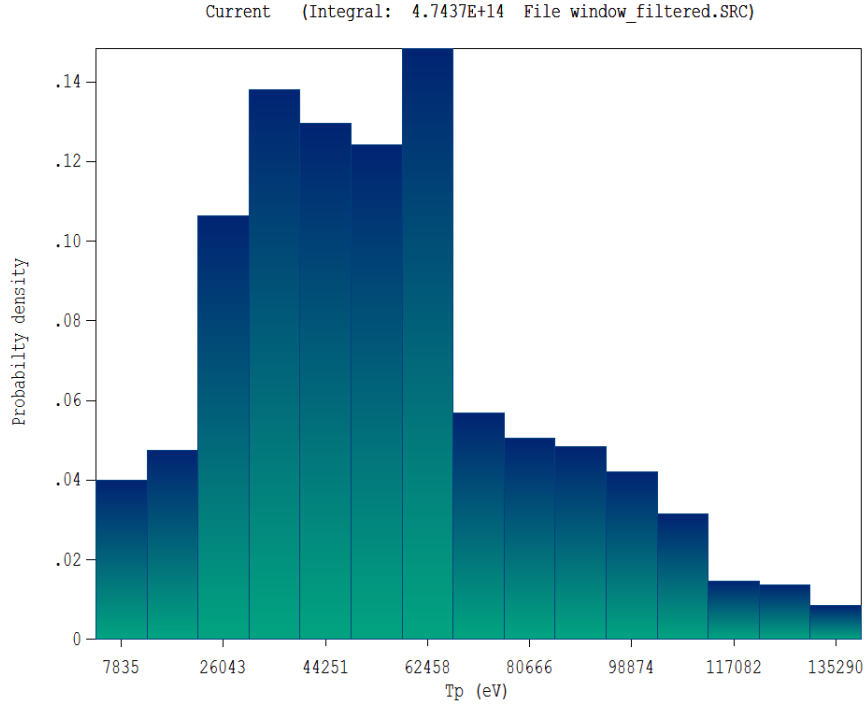


Figure 9: Energy distribution of photons emerging from the window.

## 6 Extracted X-ray flux and spectrum

The final calculation addressed the X-ray flux emerging from the window. The geometry mesh file for **GamBet** was similar to that used for the local electric field solution in Sect. 3. I used file `INPUTBEAM.SRC` (described in Sect. 4) to define the incident beam electrons. To improve statistics, I used the value  $NpMult = 25$  and a bremsstrahlung forcing factor of 100.0.

The escape file contained all electrons and photons that left the solution volume. I loaded this file into **GenDist** and removed the electrons. The resulting filtered escape file contained 68938 photons with an average kinetic energy of 41.68 keV. The total photon flux was  $4.191 \times 10^{16}$  photons/s. The total power flux of X-rays was 279.5 W, giving a yield of 0.40%. The NIST EStar site gave the maximum total yield as 1.39%. The **GamBet** result is reasonable considering the contributions of absorption in the target and housing. Applying the window filter discussed in the previous section, I found that 950 model photons with an average energy of 55.97 keV exited the beryllium window. The flux of  $4.744 \times 10^{14}$  photons/s corresponded to 4.25 W for a power yield of 0.006%. Finally, Fig. 9 shows the energy distribution of photons passing through the window.