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Monte-Carlo simulation of bremsstrahlung induced dose depending on source matrix

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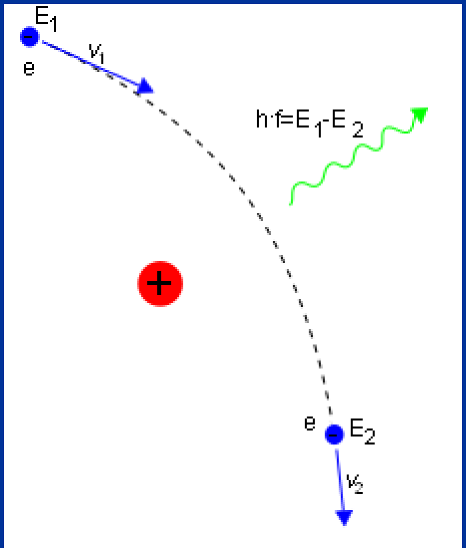
-The radiation protection from external irradiation due to presence of pure beta emitters is simplified in comparison to the corresponding technical requirements for shielding of radioactive sources which emit, in addition, gamma radiation.

-This is caused by relatively strong absorption (i.e. short range) of electrons in different materials

- However, specific attention should be devoted to the bremsstrahlung radiation induced in source encapsulation (matrix), especially for emitters with relatively high beta-endpoint energy (1 MeV order of magnitude).



Electromagnetic radiation produced by the deceleration of electron when deflected by an atomic nucleus

-In present work, the bremsstrahlung spectra, produced in various materials by the following beta emitters Sr-90(together with its daughter Y-90), P-32, Bi-210 were investigated, applying Monte-Carlo simulations using GEANT-4 software (Version 4.9.5.) In this simulations is supposed that point radioactive source is surrounded by cylindrically shaped matrix made from different materials : Pb, Cu, Al, glass, and plastic

-In the case of Sr-90(Y-90) placed within cylindrical lead and aluminum matrices, the variation of dimensions of these matrices was performed

-The absorbed dose rates arising from bremsstrahlung radiation were calculated for situation where encapsulated point source is placed at distance of 30 mm from the surface of water cylinder with mass of 75 kg (which roughly represents a human body)

-Initial parameters for simulations : dimensions of cylindrical matrix containing point source

(These dimensions are chosen to be nearly equal to the range of most energetic electrons from beta decay in certain matrix (thus drastically minimizing probability that some electrons can escape from matrix) , but simultaneously, without taking too thick layer of matrix, minimizing in a such way the effects of self-absorption for bremsstrahlung)

- Maximal and average energies of electrons for analyzed beta emitters:

Sr-90 $E_{\beta max} \approx$ 546.2 keV , $\langle E\beta \rangle$ = 196 keV

Y-90 $E_{\beta max} \approx$ 2281.5 keV , $\langle E\beta \rangle$ = 934 keV

P-32 $E_{\beta max} \approx$ 1710.3 keV , $\langle E\beta \rangle$ = 695 keV

Bi-210 $E_{\beta max} \approx$ 1161.5 keV , $\langle E\beta \rangle$ = 389 keV

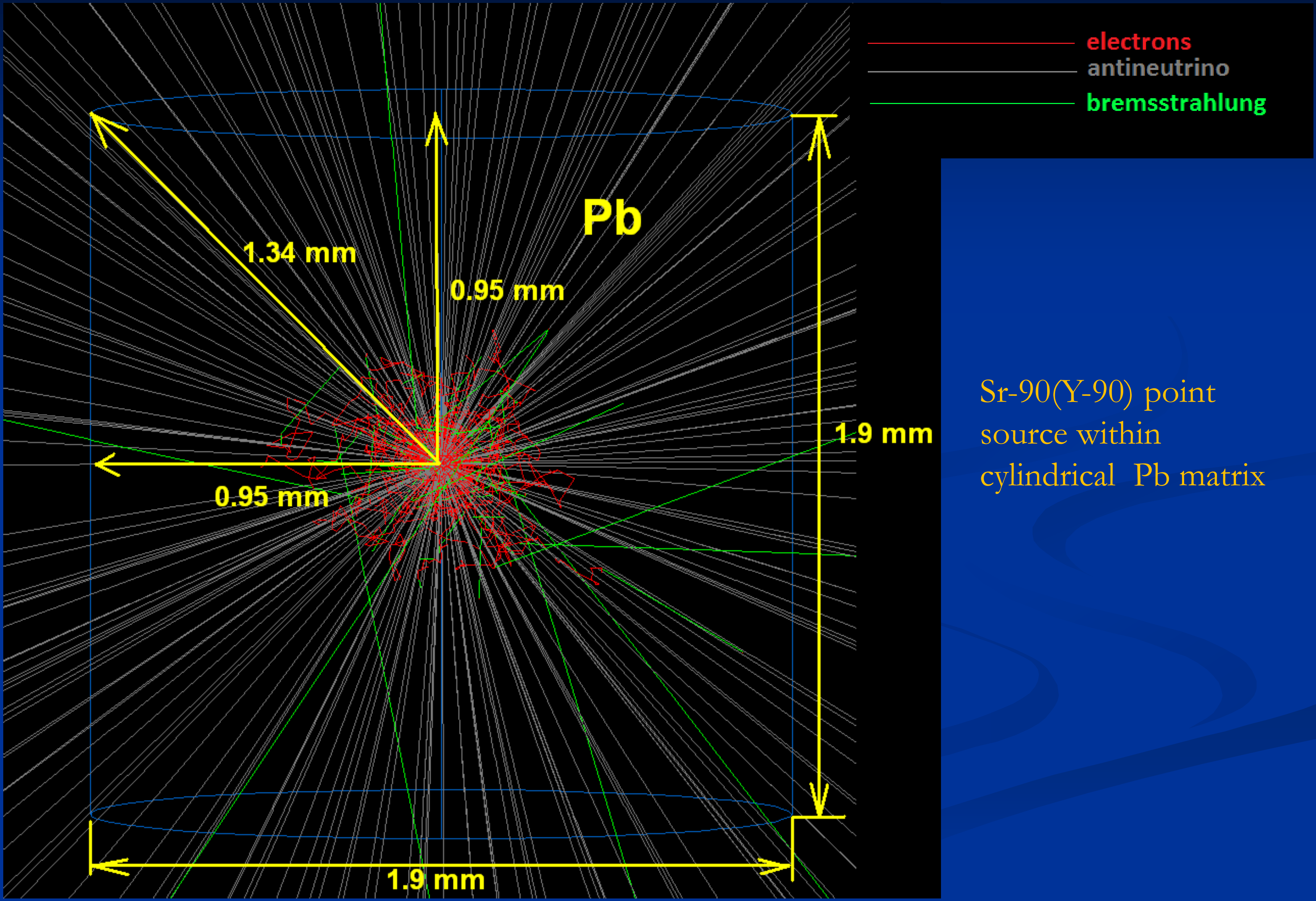
The maximum range, *R*max [g/cm^2] , of a beta particle can be computed from an empirical formula given by Katz and Penfold (L. Katz and A.S. Penfold, *Rev. Mod. Phys.*, 24 (1952), p. 28.)

$$R_{\max}\,[\mathrm{g/cm^2}] = \begin{cases} 0.412\, E_\beta^{1.265-0.0954\ln(E_\beta)} & 0.01 \le E_\beta \le 2.5\,\mathrm{MeV} \\ 0.530\, E_\beta - 0.106 & E_\beta > 2.5\,\mathrm{MeV} \end{cases}$$

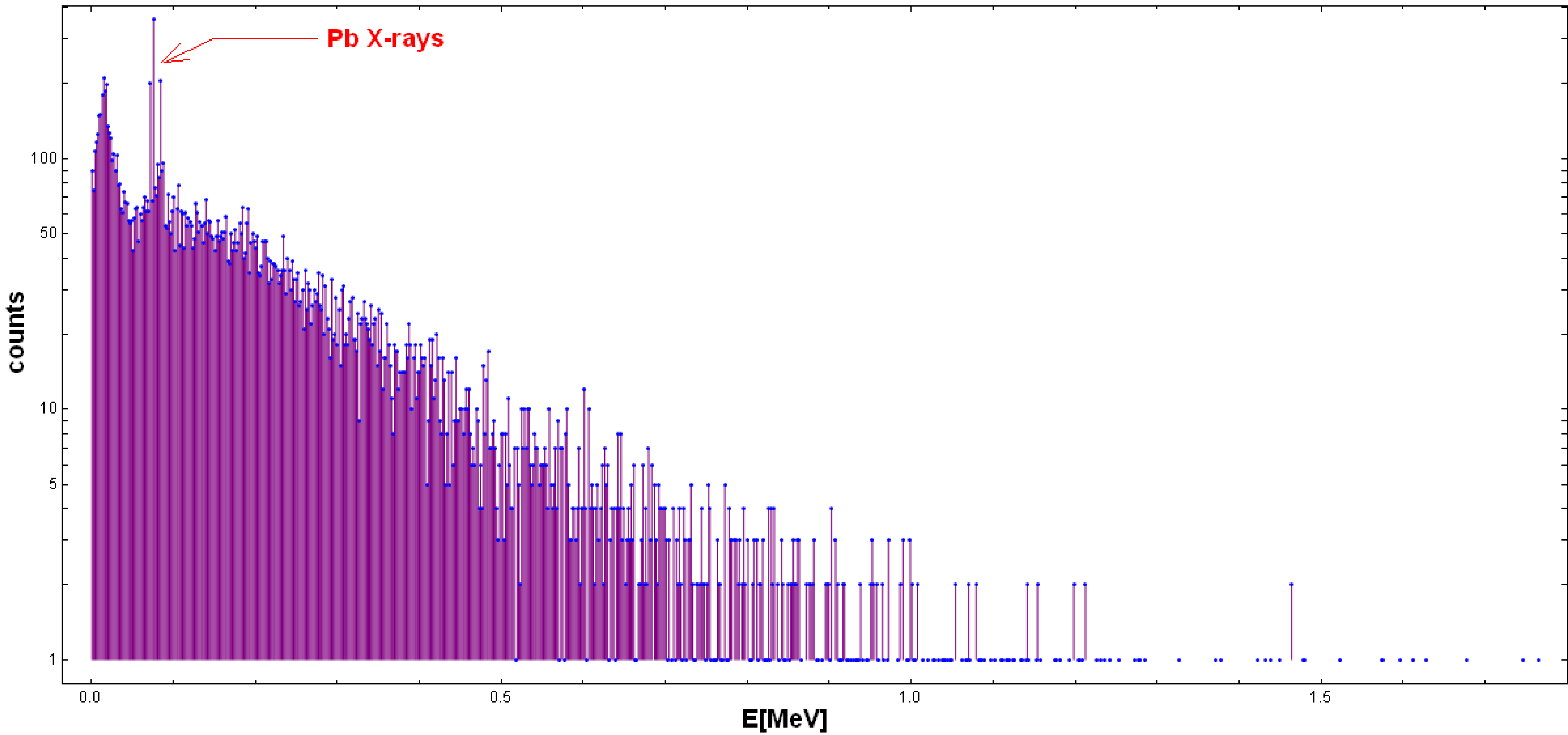
where E_β is the maximum beta energy in MeV.

If matrix is Pb ($\varrho = 11.34\ \mathrm{g \cdot cm^{-3}}$) $\Rightarrow$ Rmax' = Rmax/ϱ = 0.96 mm

According to previous calculation, we started from this matrix geometry:



Sr-90(Y-90) point source within cylindrical Pb matrix



Spectrum of deposited energies of bremsstrahlung events in water cylinder

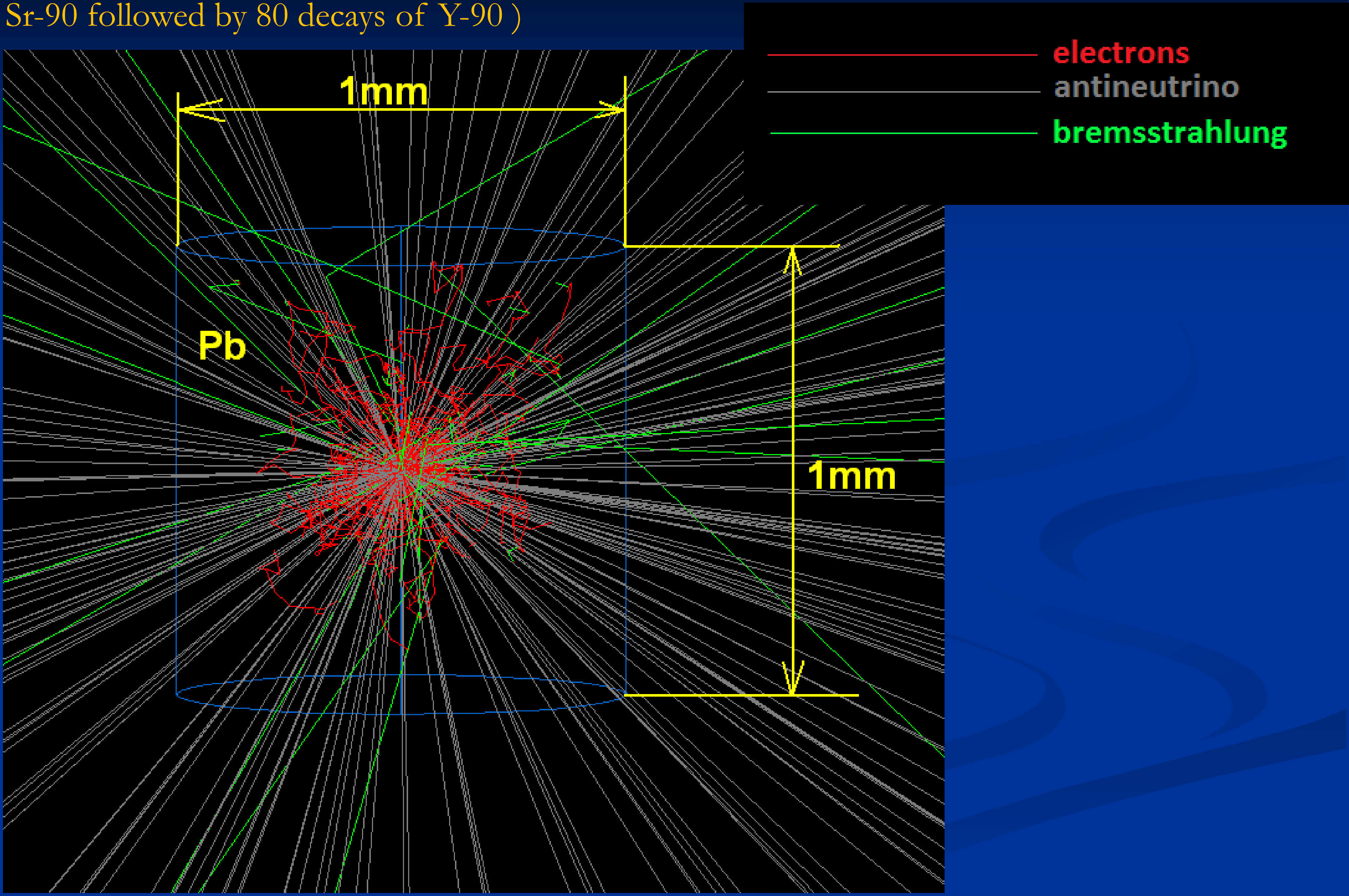
By integration of this spectrum, the following data were obtained:

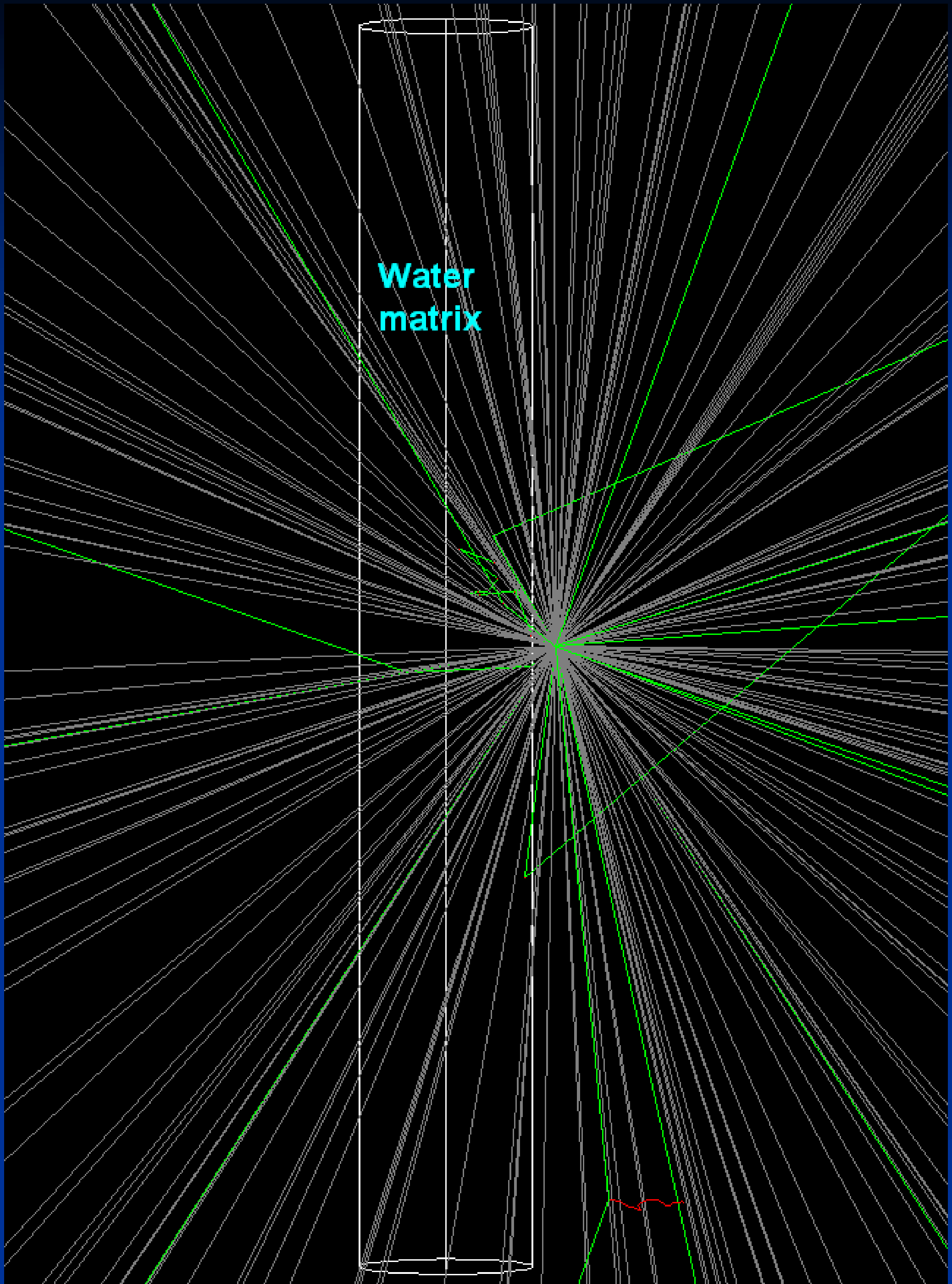
- The total number of counts : 12713

-The total deposited energy : ΔE_{bremss} = 2399 MeV

Then, we decreased the dimensions of Pb matrix

Sr-90(Y-90) point source within cylindrical Pb matrix (100 decays of Sr-90 followed by 80 decays of Y-90)





Parameters of water cylinder representing the human body

Height: 1.7 m

Diameter:0.237 m

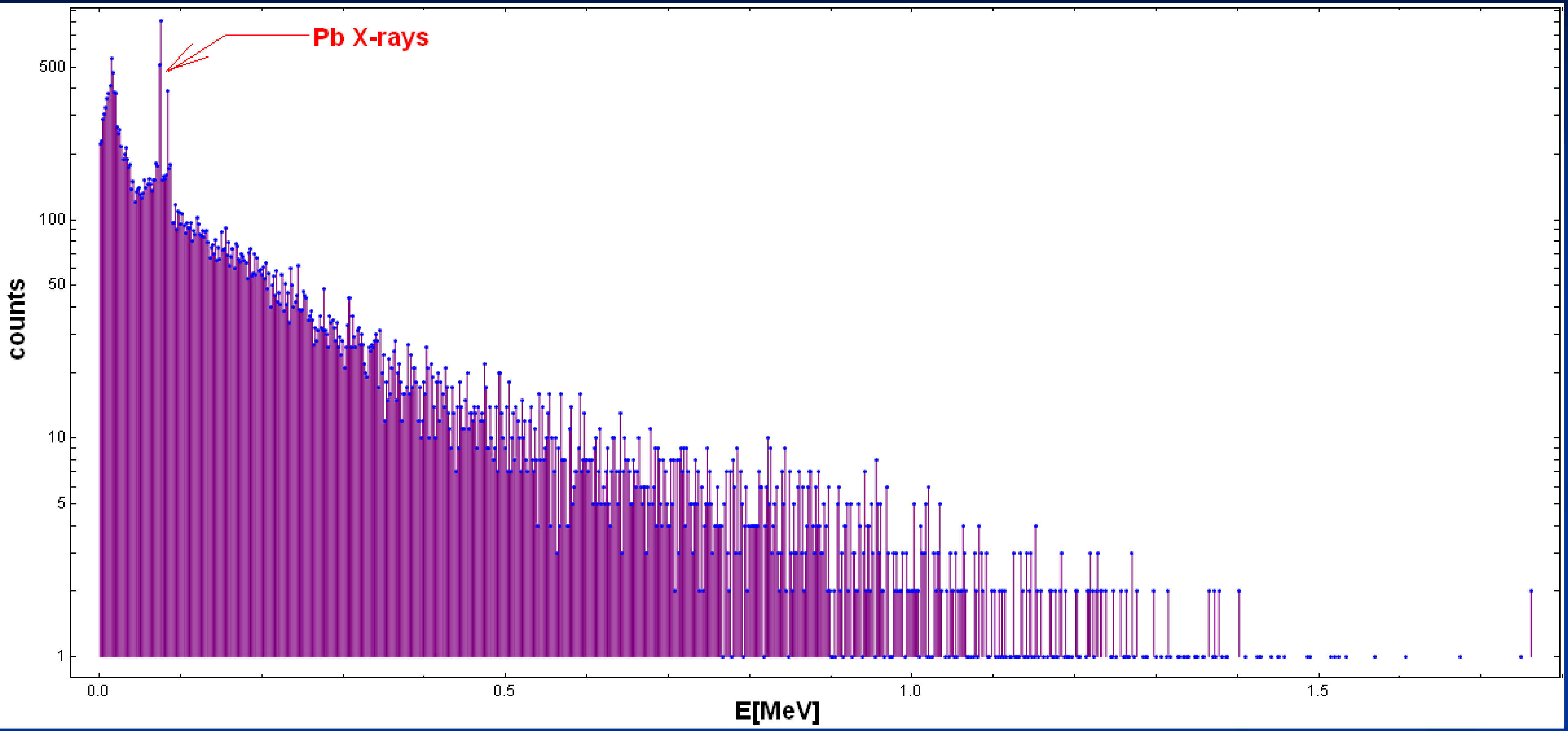
Density: 1000 kg/m3 (water)

Mass: 75 kg

- Number of initially generated decays in each simulation: N=500 000

- In the case of Sr-90, this number of decays was followed by about 400 000 decays of its daughter, Y-90

Pb matrix (dimensions of cylinder: h= 1 mm , d= 1 mm)



Spectrum of deposited energies of bremsstrahlung events in water cylinder

- The total number of counts : 23078

-The total deposited energy : ΔE_{bremss}= 3990 MeV

Calculation of dose rate from bremsstrahlung radiation for given activity of Sr-90

The absorbed dose in water cylinder for N=500 000 decays of Sr-90 (followed by 400 000 decays of Y-90) from bremsstrahlung radiation is:

$$D = \frac{\Delta E_{bremss}}{\Delta m}$$

, where

ΔE_{bremss}=3990 MeV=6.392 x 10^{-10}J, Δm=75 kg (having in mind the penetration ability of bremsstrahlung photons with above distribution, the absorbed dose is calculated taking into account the total mass of water cylinder)

From these numerical values we found: D = 8.52 x 10^{-12} Gy

If activity of Sr-90 source is A= 10 µCi = 370 000 Bq, then the time required for N=500 000 decays of Sr-90 is t = N/A= 500 000/370 000 s^{-1}= 1.35 s.

(in our simulation the 500 000 decays of Sr-90 is followed by 400 000 decays of Y-90, so this corresponds to situation where the activity of Y-90 reached 80% of Sr-90 activity)

Dose rate caused by bremsstrahlung radiation for this case:

D' = D/t = 8.52 x 10^{-12} Gy/1.35 s = 6.31 x 10^{-12} Gy/s = 2.27 x 10^{-8} Gy/h = 0.023 µGy/h

The absorbed dose rates for different activities of Sr-90 source (Sr-90 point source is at 30 mm from surface of water cylinder , placed within 1 mm x 1mm lead cylinder)

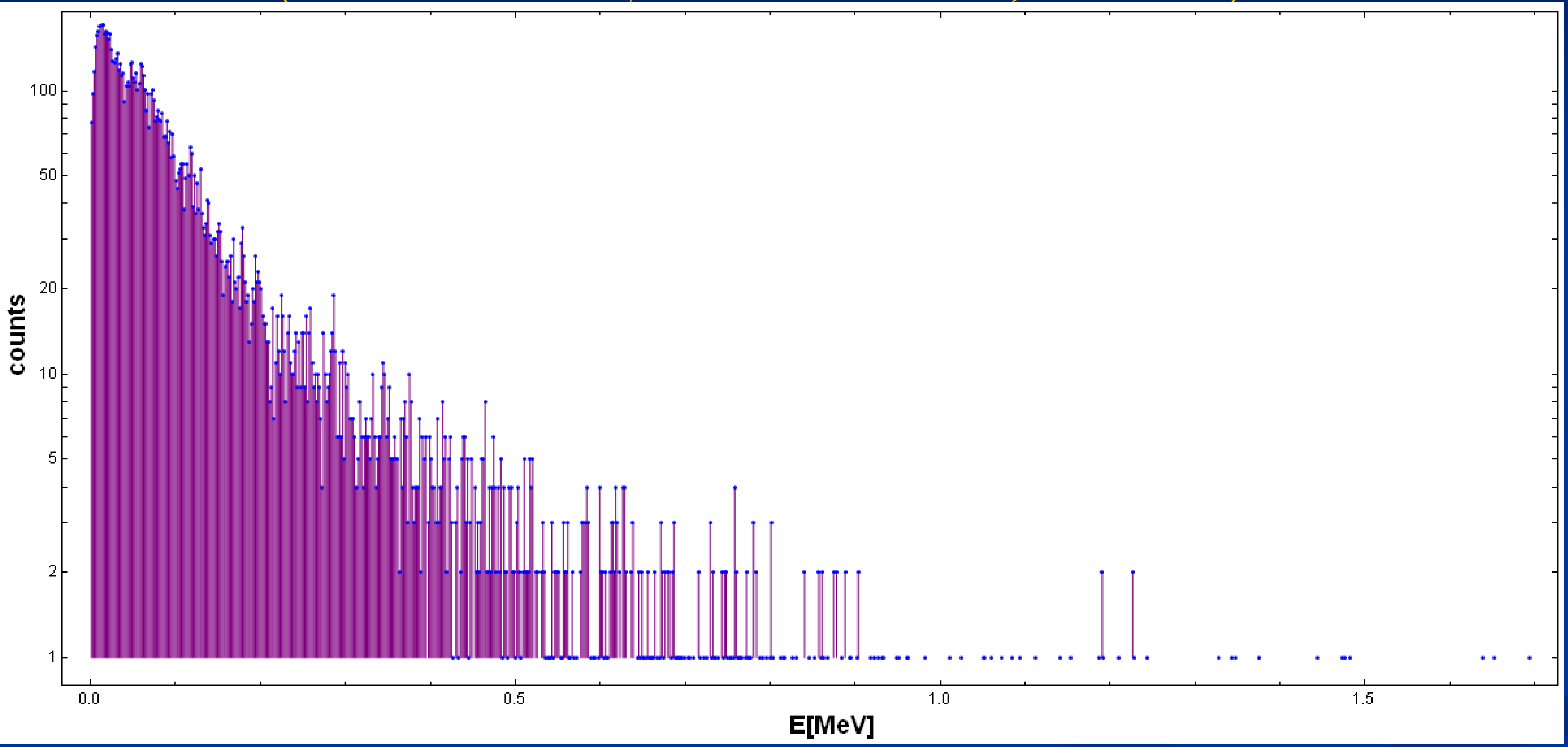
(Activity of Y-90 is 80% of Sr-90 activity)

Sr-90 activity [mCi]	Bremsstrahlung dose rate [μGy/h]
0.01	0.023
0.1	0.23
1	2.3
10	23
100	230

Other matrices (Cu, Al, glass, polyethylene) with Sr-90 point source

(The dimensions of cylindrically shaped matrices were increased in comparison with Pb matrix, due to increasing of range of electrons)

Cu matrix (dimensions of cylinder: h= 2 mm , d= 2mm)

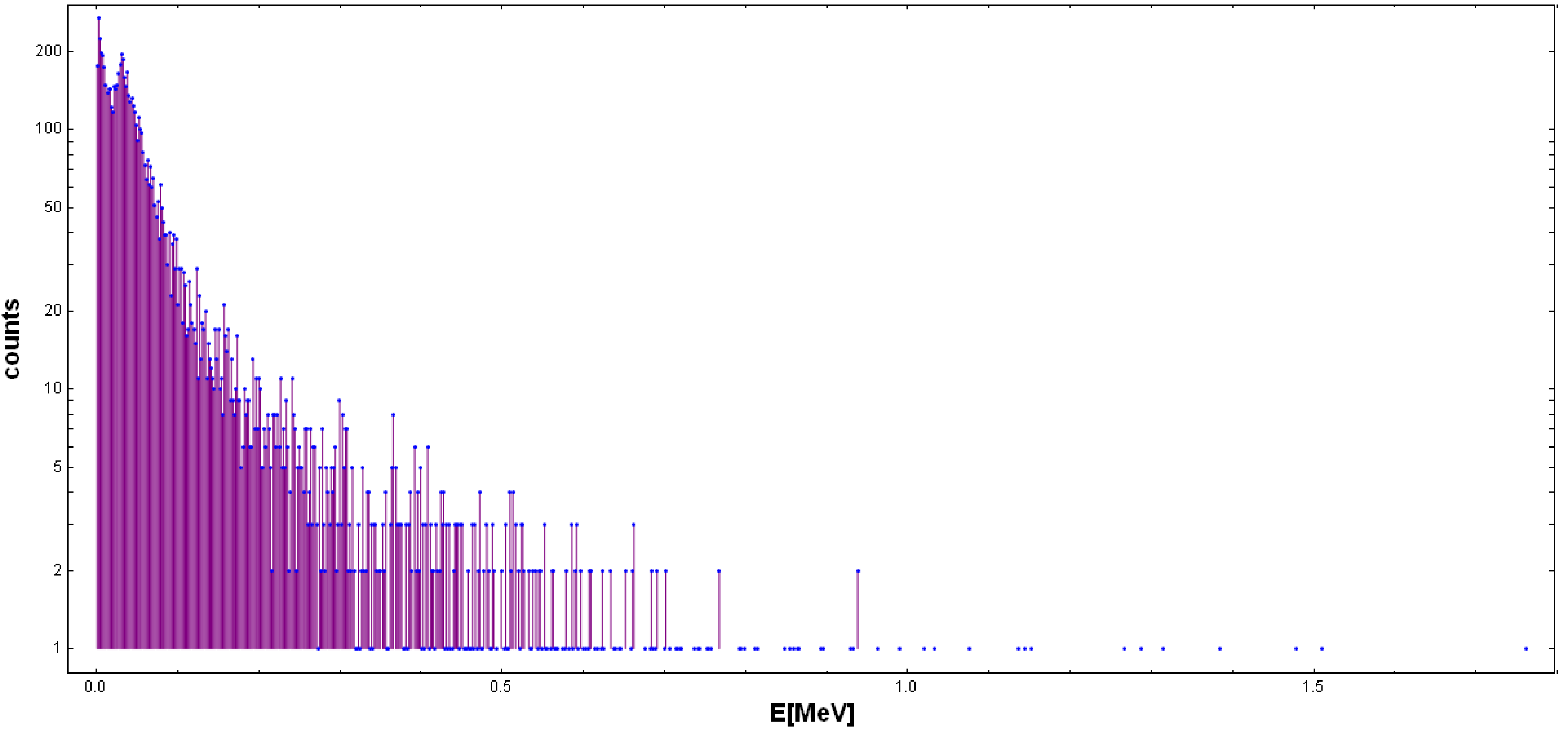


Spectrum of deposited energies of bremsstrahlung radiation

- The total number of counts : 9890

-Total deposited energy: 1157 MeV ⇒ Dose rate = 6.67 μGy/h for 10 mCi source

Al matrix (dimensions of cylinder: h= 7 mm , d= 7 mm)



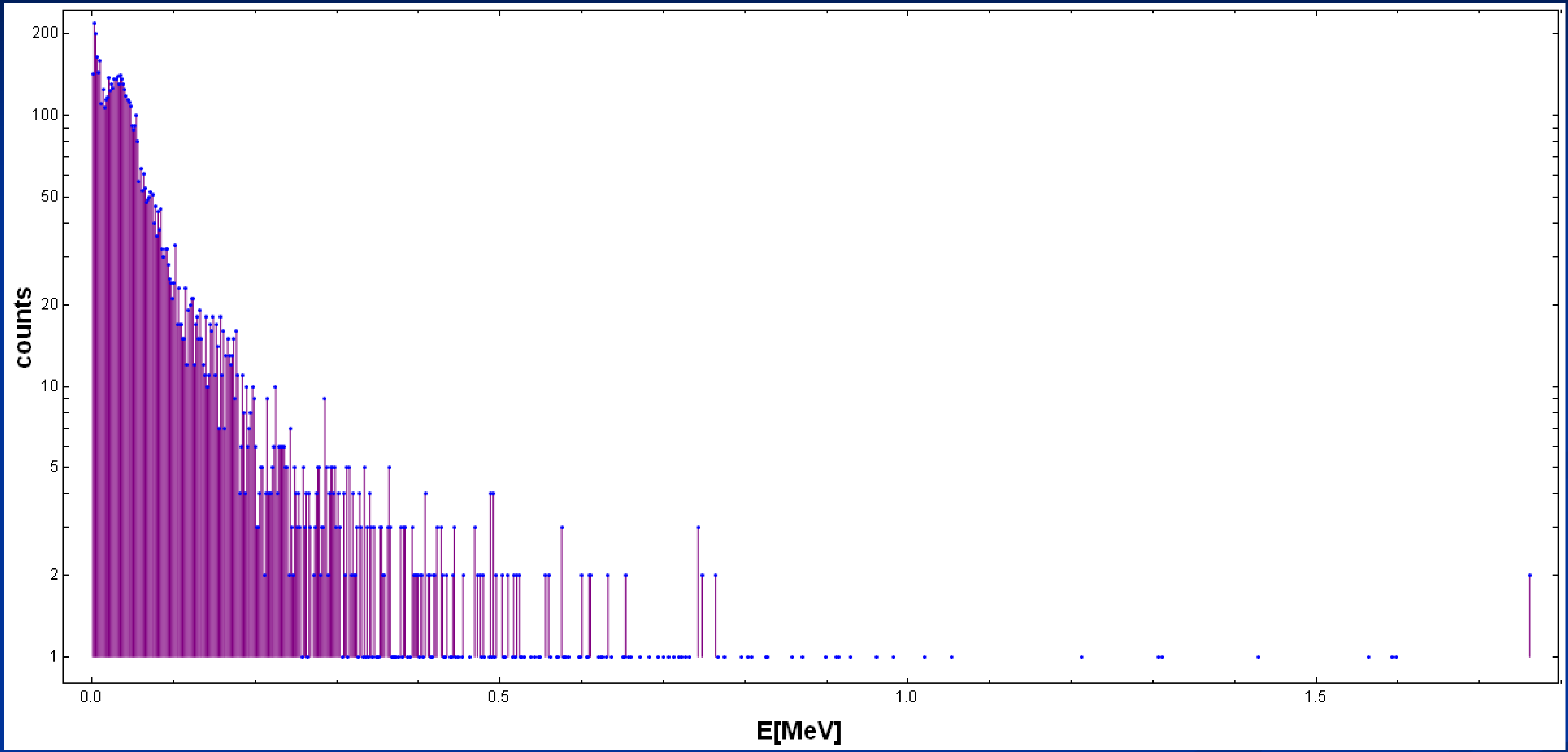
Spectrum of deposited energies of bremsstrahlung radiation

- The total number of counts :7583

Total deposited energy: 616 MeV ⇒ Dose rate = 3.55 μGy/h for 10 mCi source

Glass matrix (dimensions of cylinder: h= 8 mm , d= 8 mm)

("Glass", Al 0.53% - Si 34.82% - Mg 0.6%- Ca 7.15% - Na 9.65%-K 0.415%-
O 46.835%, 2.5*g/cm3)

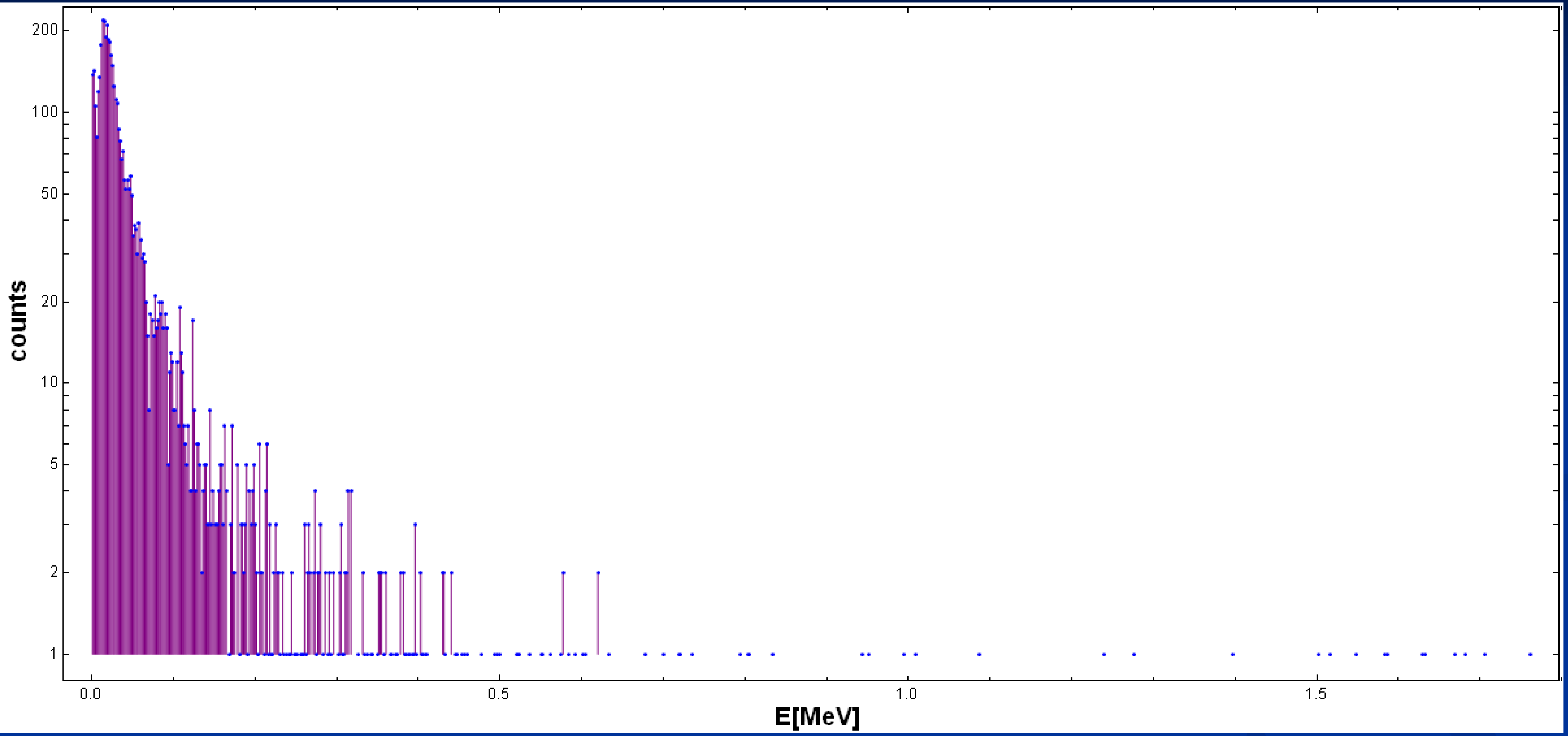


Spectrum of deposited energies of bremsstrahlung radiation

- The total number of counts : 6437

Total deposited energy: 499 MeV ⇒ Dose rate = 2.88 μGy/h for 10 mCi source

Polyethylene matrix (dimensions of cylinder: h= 20 mm , d= 20 mm)

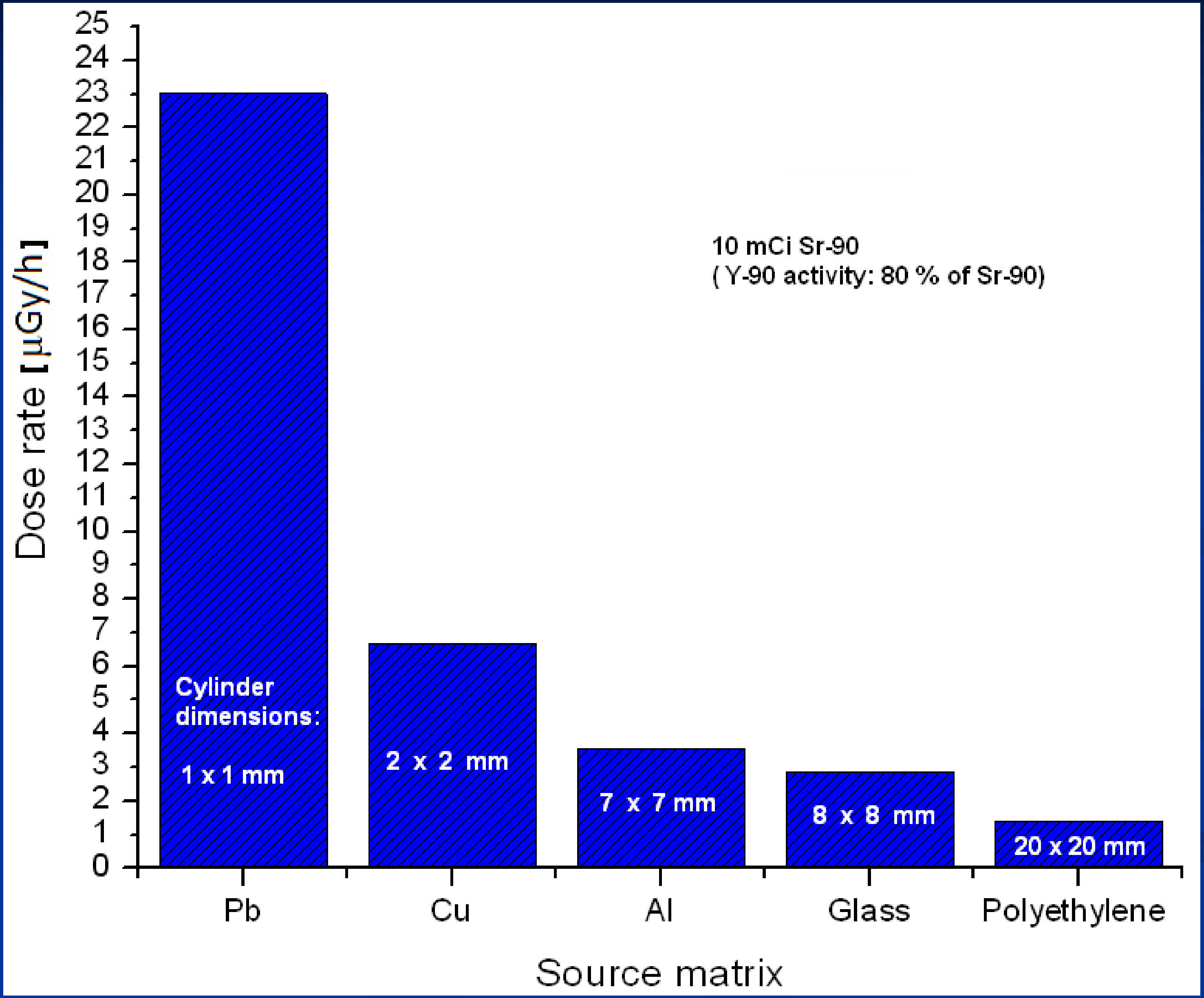


Spectrum of deposited energies of bremsstrahlung radiation

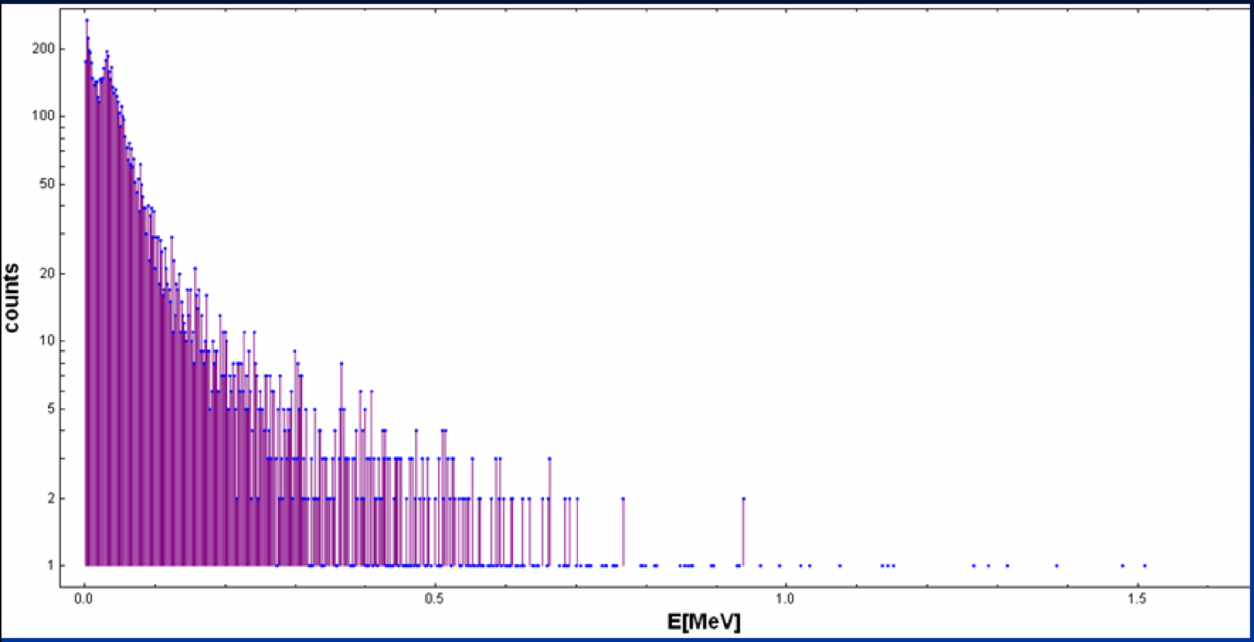
- The total number of counts : 4472

Total deposited energy: 245 MeV ⇒ Dose rate = 1.41 μGy/h for 10 mCi source

Comparison of results for Sr-90(Y-90) in different matrices

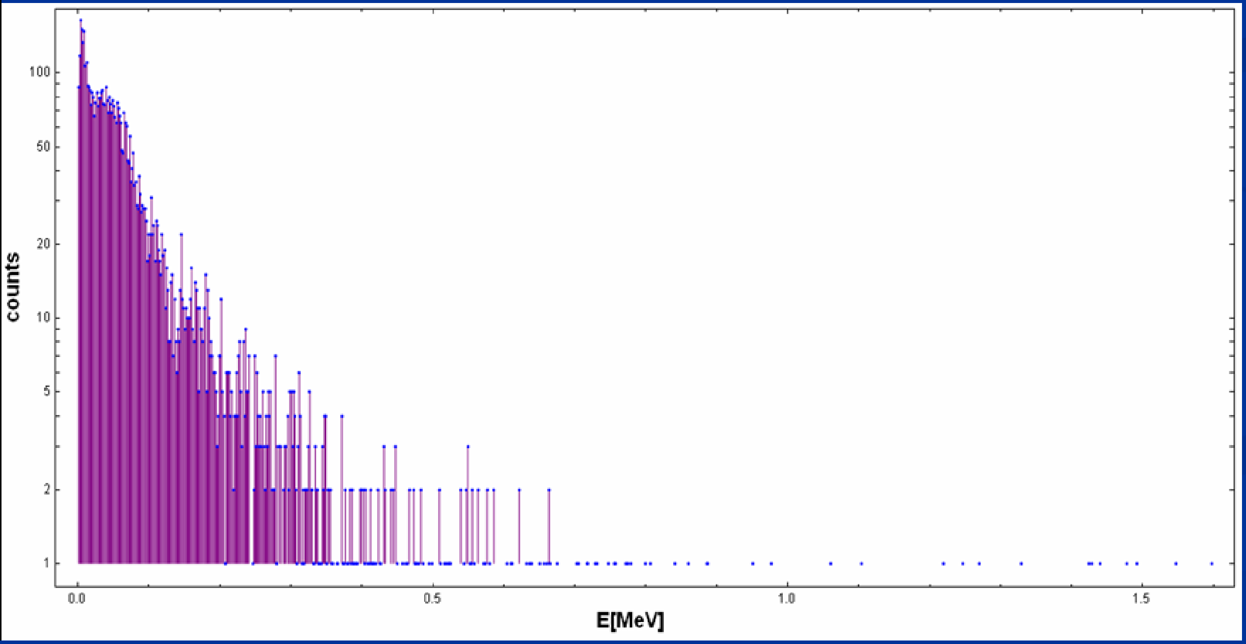


Increase of dimensions of Al cylindrical matrix (Sr-90 point source inside)



Al matrix (dimensions of cylinder: h= 7 mm , d= 7 mm)

Total deposited energy: 616 MeV
⇒ Dose rate = 3.55 μGy/h for 10 mCi source

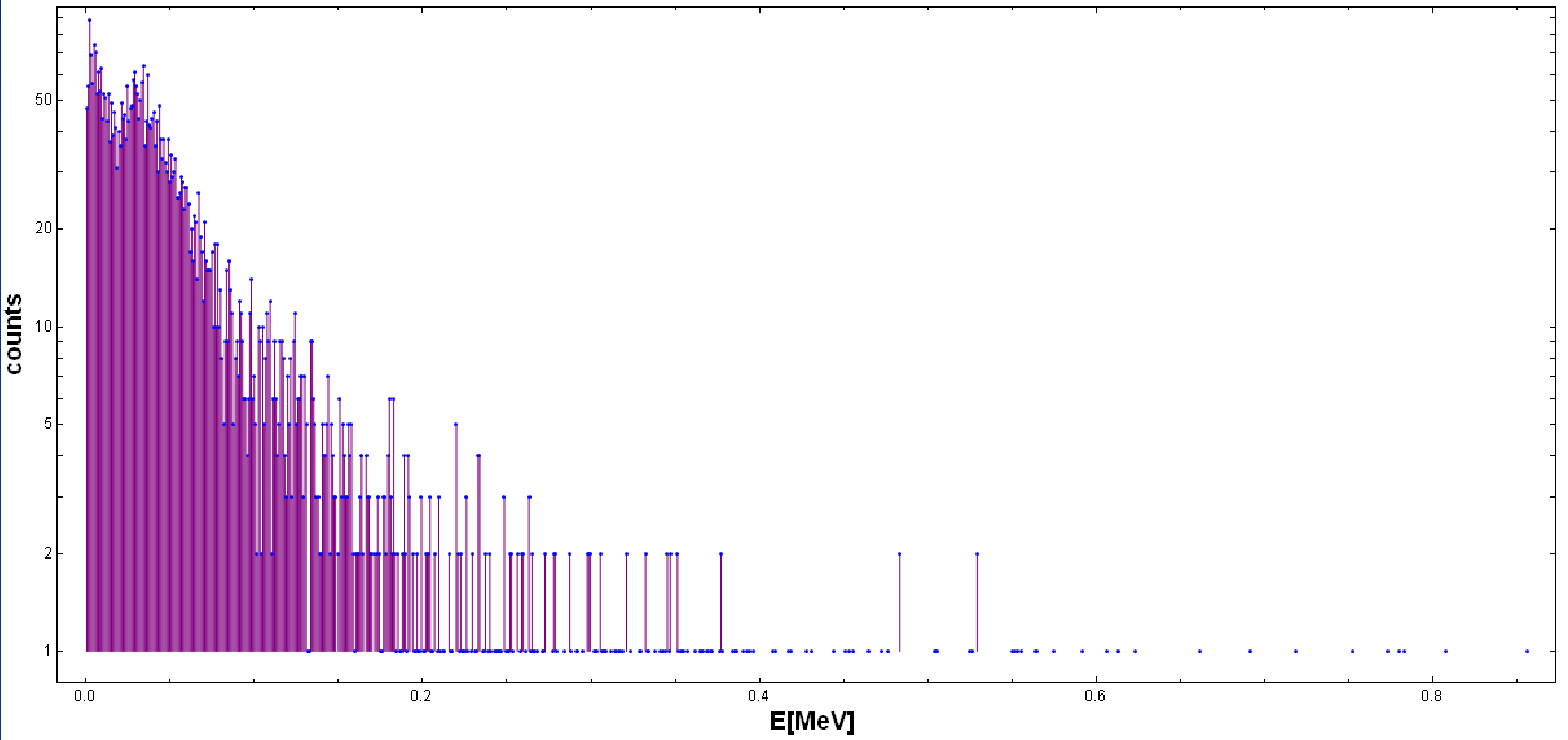


Al matrix (dimensions of cylinder: h= 20 mm , d= 20 mm)

Total deposited energy: 447 MeV
⇒ Dose rate = 2.57 μGy/h for 10 mCi source

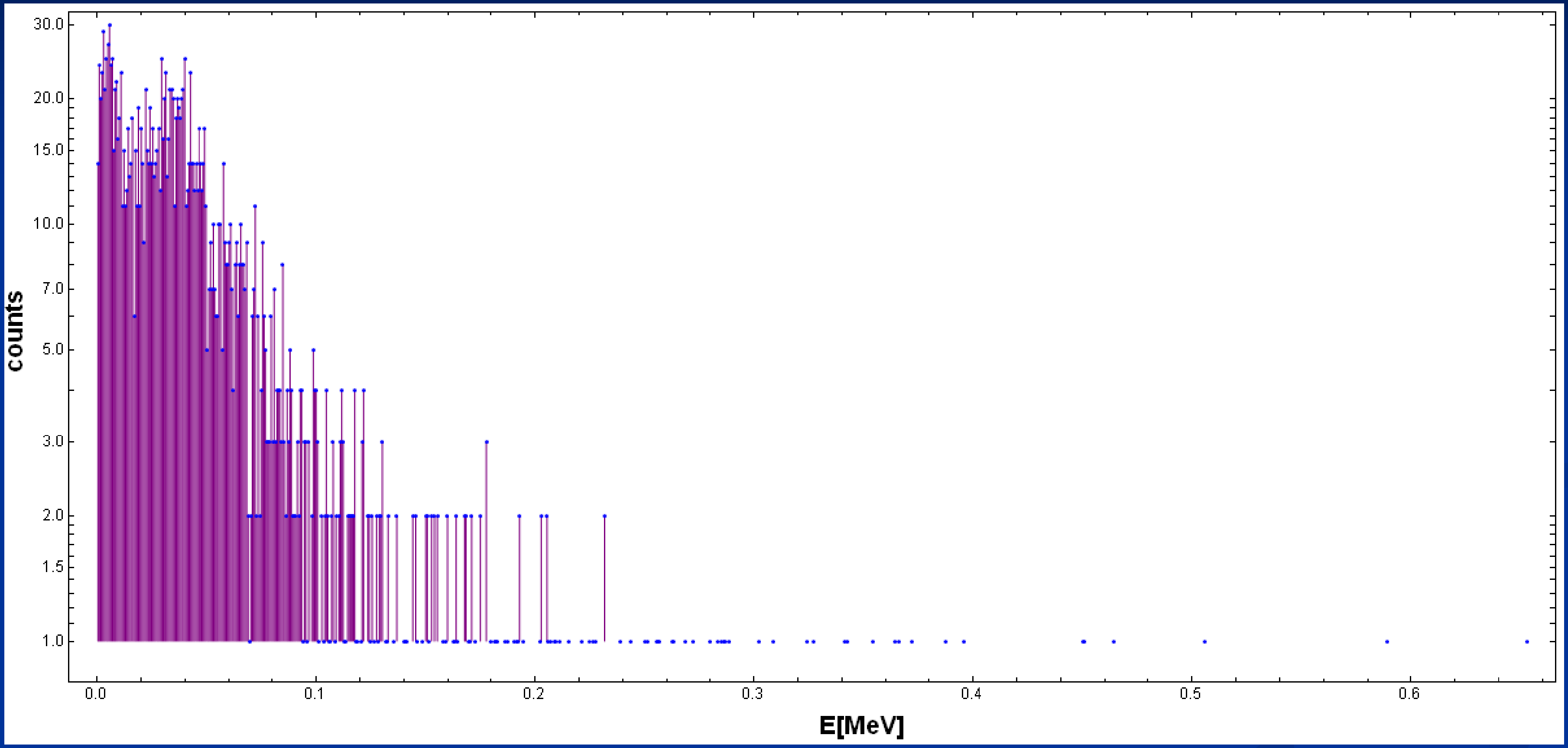
Different sources within the same cylindrical matrix (aluminum, dimensions : 7 mm x 7 mm)

P-32



- The total number of counts : 4382
- Total deposited energy: 265 MeV ⇒ Dose rate = 1.53 μGy/h for 10 mCi source

Bi-210



- The total number of counts : 1898

Total deposited energy: 94 MeV ⇒ Dose rate = 0.54 μGy/h for 10 mCi source

- Relative uncertainties of these simulations are related to the statistics of registered bremsstrahlung events in water matrix, and these uncertainties are in the range 1.3 – 4.5 %, at 95% confidence level.

Conclusions

- Real energy distributions of emitted beta particles (not just average, or highest energy) are included in simulation processes

-Production of bremsstrahlung as well as self-absorption of this radiation in certain matrix are taken into account by simulation

-The small increase in dimensions of Pb matrix leads to significant decrease in bremsstrahlung dose rate (in our simulated cases (1mm x 1mm of Pb and 1.9 mm x 1.9 mm of Pb with Sr-90(Y-90)) the decrease was about 40%)

-For aluminum matrix, this effect is much smaller (simulations: 7 mm x 7 mm of Al and 20 mm x 20 mm of Al ⇒ the decrease was ≈ 27 %)

- Bremsstrahlung dose rate for given activity of Sr-90(Y-90) source decreases for more than 16 times when Pb matrix is applied in comparison with polyethylene matrix

- Since that energy distribution of electrons (endpoint and average energy) from beta decay is important for bremsstrahlung production , the bremsstrahlung dose rate from Sr-90(Y-90) in the same matrix (i.e aluminum) is 2.3 times higher than dose rate from P-32, and 6.5 times higher than dose rate from Bi-210