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DESIGN STUDY OF GAS BREMSSTRAHLUNG BEAM STOP FOR BEAMLINES AT THE CANADIAN LIGHT SOURCE

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Abstract

Gas bremsstrahlung beam stops, which will be used for the beamlines of the Canadian Light Source (CLS) are examined in detail. These beam stops are made from either lead or tungsten of rectangular shape. A simulation of the showers due to the gas bremsstrahlung impinging on the beam stop is carried out. Estimates of the dose rate are made for various sizes of beam stops. The dose rate from the photoneutrons via the giant resonance photonuclear reaction which takes place inside the lead or tungsten stop is also obtained. Taking two radiations into account the proper dimension of the beam stop of each material is determined.

1 Introduction

High energy electrons interacting with the residual gas molecules in the vacuum chamber produce the gas bremsstrahlung. When the gas bremsstrahlung radiation is emitted in the straight section of the storage ring, the highly forward peaked radiation travels along the beamline. This presents a serious radiation problem, as the entire section is in the line of sight. It is thus imperative to prevent such radiations from entering the first optics enclosure (FOE) or the experimental hutch. We accomplish this by placing the beam stops at the suitable places along the CLS beamlines.

In the previous design reports [1] [2], the shielding requirement was set at 5 μSv/hr. However, since we realize that safety regulations are likely to increase, the shielding criterion employed in this communication is a total dose rate of 2.5 μSv/hr. This is the same design limit adopted at APS [3].

When the gas bremsstrahlung photons strike the beam stop, the electron-gamma cascade shower ensues. The EGS4 code [4] is used to simulate the showers in the beam stop. Also studied is the dose rate due to the neutrons produced inside the beam stop by the gas bremsstrahlung via the giant dipole resonance photo-nuclear reaction. The aim of this report is to determine the dimension of the beam stop for which the total dose rate is below 2.5 μSv/hr. This may also be found useful in designing the collimators or beam shutters for the CLS beamlines.

One of the CLS beamline components is the monochromater aperture and the bremsstrahlung stop made of tungsten. The tungsten block with aperture acts as a mono-beam pass and at the same time acts as a bremsstrahlung beam stop in the beam path. This component is placed in the first optics enclosure(FOE) or in the white beam station. As an application, the offset, i.e., the distance between the mono-beam line and the bremsstrahlung ray is examined.

2 Geometry and Parameters

In this section the general method to assess the dose rate is described when the gas bremsstrahlung strikes the beam stop with transverse dimensions of $A * B\ cm^2$ and the thickness of $C\ cm$. The EGS4 Monte Carlo code [4] calculates the energy deposition in water which we place around the beam stop. The geometry considered is depicted in Fig.1. The numbers in Fig.1 indicate regions of interest. For example the gas bremsstrahung impinges at the center of Region 14, the beam entrance region from which we take the origin of coordinates; the Z axis is the propagation direction of the gas bremsstrahlung. Directly behind Region 14 is Region 39, which is expected to have the highest dose rate. In the following, the volume of the Region 39 is taken as $4 * 4 * 2\ cm^3$ with water thickness of 2 cm throughout this work. The EGS4 simulations are performed to calculate the energy deposition in Regions 38, 39 and 44. From a shielding point of view, the radiation through the upper, lower and side areas of the beam stop may not present any problem to workers because of the side walls and the roof or other materials that moderate the radiation. Nevertheless, the radiation exists and it might be of some interest to estimate the radiation levels through these areas. It is useful to assess the energy deposition as a function of a variable C along the Z axis. Here we consider an equally spaced segment. For example if C is 28 cm long, the energy deposition in a segment from 0 to 4 cm or from 4 to 8 cm etc. may be obtained. In this case there are 7 segments in total. If the beam stop is 18 cm long, we may consider 9 segments, each 2 cm long.

The EGS4 results are expressed in terms of energy per unit mass per photon. Since we are interested in the dose rate, the EGS4 results must be multiplied by the number of photons produced per unit time in the straight section of the beamline. Hence the number of photons produced depends on, for example, the energy and current of circulating electrons, the gas pressure in the storage ring and the length of the straight section. A detailed account may be found in Appendix. Let N_γ denote the number of photons per unit time. The salient parameters used to obtain N_γ are as follows;

- the electron energy is 2.9 GeV.
- the stored current is 500 mA.
- the gas pressure in the storage ring is 133 nPa (10^{-9} torr).
- the length of straight section is 7.626 m.
- the effective charge Z of the residual gas is 8.1.
- the temperature is taken to be 20°C.

With these parameters, N_γ takes a value 8.1773×10^8 [photons/hr]. The dose rate is then obtained by multiplying N_γ by the energy deposition/photon from the EGS4 simulatuion.

A choice of the effective charge Z=8.1 may require some further explanation. The values used in the literature are 4.6 [5], 7.23 [6], 7.8, 10.0 both from [7] and 8.1 [8]. The number of photons produced is proportional to the Bethe-Heitler bremsstrahlung cross section which contains a factor Z(Z+1). Hence larger Z values result in higher dose rates. In other words the choice of a larger Z value results in a conservative approach to the design of the beam stop. It should be mentioned that in [8], Z is obtained by fitting the observed spectrum and checked at two beamlines of SPring-8.

3 Gas Bremsstrahlung Dose Rate and Beam Stop

The beam stop under consideration is a lead or tungsten block, A cm wide, B cm high and C cm thick, denoted by (A,B,C). Several values of A, B and C are examined for each material. As mentioned in the previous section the dose rates in Regions 39, 44 and 38 are studied. The results are shown in Table 1 , Table 2, Table 3, Table 4, Table 5 and Table 6 for a lead block. The dose rates for the upper, lower and lateral sides vary with a distance along the Z axis so that only the maximum value is shown in the Table. The bracketed range indicates where the maximum value occurs. For a tungsten block the results are given in Table 7, Table 8, Table 9, Table 10 and Table 11. The percent error quoted in the Table depends on the number of the incident particles used in the simulation, called the number of histories. It takes more time to complete a simulation with a larger value of histories. In Table 5, for instance, 1.4×10^6 histories were examined to give the result with 13.98 % statistical error but the execution time was 67 hours on a DELL GX240 machine. Similarly for a tungsten stop in Table 9, 2.2×10^6 histories took almost 102 hours to finish with 9.89 % error.

If only the radiation through the back of the beam stop is considered, the minimum length required to attenuate the gas bremsstrahlung is 26 cm for a lead stop and 16 cm for a tungsten stop. To be a stand-alone beam stop, the dimension must be at least (A,B,C)= (30, 30, 28) for a lead stop and (20, 20, 16) for a tungsten stop. The contribution from neutrons, of course, must be added when finalizing the size of the beam stop. In the next section we look at the radiation from neutrons.

4 Neutron Yield and Dose Rate

The neutrons are generated inside the beam stop by the gas bremsstrahlung. As was done in Section 2 the neutron yield is evaluated as a function of a variable C along the Z axis.

The neutron yield Y from the giant resonance neutron (GRN) reaction is expressed as [9] [10]

$$Y = N_0 \frac{\rho}{A} \int_{k_{th}}^{k_{max}} \frac{dl}{dk} \sigma(k) dk \tag{1}$$

$$\sigma(k) = \frac{\sigma_m}{1 + \frac{(k^2 - k_m^2)^2}{k^2 \Gamma^2}} \tag{2}$$

where N_0 is the Avogadro's constant. ρ and A are the density and mass number of the beam stop, respectively. For the tungsten stop Eq.(2) is replaced by the sum

$$\sigma(k) = \sum_{i=1}^{2} \frac{\sigma_{m_i}}{1 + \frac{(k^2 - k_{m_i}^2)^2}{k^2 \Gamma_i^2}} \tag{3}$$

owing to the deformed spheroidal nucleus. The integration limit k_{th} is the reaction threshold energy, 7.37 MeV and 7.41 MeV for lead and tungsten, respectively. k_{max} is the energy of the upper limit of the giant resonance photoneutron reaction. It is assumed to be 40 MeV. The differential track length is denoted by $\frac{dl}{dk}$ (cm/MeV), which may be obtained by the EGS4 code. $\sigma(k)$ is the Lorentz line shape giant resonance cross section. The peak cross section σ_m, the resonance energy k_m, and the full width at half maximum(FWHM) Γ are taken from [10]. They are for a lead stop

- $\sigma_m = 639 \times 10^{-27} cm^2$
- $k_m = 13.43$ MeV
- $\Gamma = 4.07$ MeV

and for a tungsten stop

- $\sigma_{m_1} = 211 \times 10^{-27} cm^2$
- $\sigma_{m_2} = 334 \times 10^{-27} cm^2$
- $k_{m_1} = 12.59$ MeV
- $k_{m_2} = 14.88$ MeV
- $\Gamma_1 = 2.29$ MeV
- $\Gamma_2 = 5.18$ MeV

We note that the peak cross section for lead is about twice that of tungsten with a similar FWHM. The neutron yield and therefore the dose rate due to GRN from lead is expected to be higher than that from tungsten.

In the evaluation of Y, the integration is replaced by the summation over the photon energy between k_{th} and k_{max} with the photon energy bin width of 5 MeV. Hence in the EGS4 code, $\frac{dl}{dk}$ is sorted into the appropriate energy bin (seven energy bins altogether) for each segment. The equivalent dose D_N is expressed as

$$D_N = C_N \times \frac{Y}{4\pi r^2} \tag{4}$$

where C_N is the conversion factor of 3.18 $\times 10^{-10} Sv \cdot cm^2$ [6] and r is the distance between the stop and the detection point. We note here that in the giant photoneutron production, isotropic distribution is assumed, and the beam stop is regarded as a point source. Under these conditions the dose rates are evaluated at one meter away from the source. The results are shown in Table 12. As seen from Table 12 the dose rates show no difference for the same material, 1.14 μSv/hr for a lead stop and 0.535 μSv/hr for a tungsten stop. This indicates that the neutrons are produced near the beam entrance region and the size of the beam stop has little effect once dose rate reaches the plateau.

5 Mono-Beam Aperture and Beam Stop

The mono-beam aperture and beam stop is placed in FOE or in the white beam station. The dimension of the tungsten block is (A,B,C)=(20,20,19). The aperture is taken to be 6 cm in the horizontal(X), 1.6 cm in the vertical(Y) and 19 cm in the longitudinal(Z) direction. The schematic diagram is shown in Fig.2. Let (XI,YI) denote the coordinate where the incident bremsstrahlung strikes the tungsten block. We are interested in the energy deposition in Region 39 when the incident beam is on the Y axis, e.g.,(XI,YI)=(0,-2.0) in units of cm. The geometry used in the simulation is depicted in Fig.3. Note that the Region 14 is the vacuum region and that the area of Region 39 (also 14) is 6 * 1.6 cm^2, not 4 * 4 cm^2 as was previously described in Section 2.

The maximum dose rate is, as mentioned before, set to be 2.5 μSv/hr. Following the example of [3], we assume a 10 % occupancy in FOE or in the white beam station, hence the dose rate of 25 μSv/hr is permissible in this area. With a given shape and size of the beam aperture and stop unit, the dose rate in Region 39 is estimated as a function of the incident beam position YI. The results are shown in Table 13. From this the offset is found to be 2.0 cm in order for the dose rate to be under 25 μSv/hr. It is, however, cautioned that the offset value obtained is for the aperture size (6 cm x 1.6 cm) only. The dose rate, hence, must be assessd case by case for specific aperture sizes.

6 Conclusion

The gas bremsstrahlung beam stops are studied for the CLS beamlines. They are made of lead or tungsten of rectangular shape. Using the EGS4 code the dose rates are calculated for various sizes of stops. Also studied is the radiation from neutrons generated by the gas bremsstrahlung inside the beam stop. It is the sum of the bremsstrahlung and neutron dose rate which must be below the guide line 2.5 μSv/hr.

From the present study of the gas bremsstrahlung beam stops the following recommendations are made for the CLS beamlines;

- a lead stop of (A, B, C) = (30, 30, 28), i.e., 30 cm wide, 30 cm high and 28 cm thick lead block.

- a tungsten stop of (A, B, C) = (20, 20, 18), i.e., 20 cm wide, 20 cm high and 18 cm thick tungsten block

If the radiation from the side of the lead block is considered serious, the local shielding to suppress the neutrons is required. This may be accomplished by placing a 5 cm thick high density polyethylene around the lead block.

The dose rates behind the beam aperture-stop are investigated. Assuming a tungsten block (A,B,C) = (20,20,19) with an aperture 6 cm * 1.6 cm, the offset is determined to be 2.0 cm. This value is inherent to the apeture size and the dimension of the block considered in this report.

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A Bremsstrahlung Production Rate

The gas bremsstrahlung production rate per unit stored current is of the form[7];

$$I = 6.25 \times 10^{15}\ S\ \frac{6.02 \times 10^{23}}{2.24 \times 10^4} \frac{p}{1.01 \times 10^5} \frac{273}{T} \times L_e \tag{5}$$

where
I = photon production rate above k_{min} MeV per unit store current (photons/mA/sec)
S = bremsstrahlung cross section (cm^2)
p = residual gas pressure in vacuum chambers (Pa)
T = temperature (K) and
L_e = electron path length (cm).

S is expressed in a form;

$$S = \int_{k_{min}}^{E_0 - 0.511} \sigma(E_0, k) dk \tag{6}$$

and $\sigma(E_0, k)$ is a Schiff 3BS(e) formula in [11];

$$\begin{aligned}\sigma(E_0, k) = 2\alpha r_e^2 Z(Z+1)\frac{dk}{k}\Bigg[&\left(1 + \left(\frac{E}{E_0}\right)^2 - \frac{2E}{3E_0}\right)\left(\ln M(0) + 1 - \frac{2}{b}\ tan^{-1}b\right) \\ &+\frac{E}{E_0}\left(\frac{2}{b^2}\ln(1+b^2) + \frac{4(2-b^2)}{3b^3}\ tan^{-1}b - \frac{8}{3b^2} + \frac{2}{9}\right)\Bigg]\end{aligned} \tag{7}$$

where

$$b = \frac{2E_0 E Z^{1/3}}{111k}$$

$$\frac{1}{M(0)} = \left(\frac{k}{2E_0 E}\right)^2 + \left(\frac{Z^{1/3}}{111}\right)^2$$

We note here that in 3BS(e) formula, all energies in σ_0 are in units of the electron rest mass energy $m_e c^2 = 0.511$ MeV. The various constants are defined below;

E_0 = incident electron total energy
k = bremsstrahlung photon energy
E = $E_0 - k$, post bremsstrahlung electron energy
α = the fine structure constant $\approx \frac{1}{137}$
r_e = classical electron radius = 2.82 fm
Z = the atomic number of residual gas in vacuum chambers
k_{min} = the minimum photon energy considered. In this report the minimum photon energy is taken to be 100 MeV.

Using Eqs.(A.1), (A.2) and (A.3), the photon production rates are obtained and the results are summarized below for several electron total energies;

- 283 photons/sec for 1 GeV.
- 390 ptotons/sec for 2 GeV.
- 425 photons/sec for 2.5 GeV.
- 448 ptotons/sec for 2.9 GeV.

assuming that

- the gas pressure in the storage ring is $1. \times 10^{-6}$ Pa.
- the electron path length is 1 meter.
- the stored current is 1 mA.
- Z, the atomic number of the residual gas, is taken to be 8.1.
- T, the temperature, is 20°C.

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Table 1: Dose Rate for Lead Stop (A,B,C) = (20,20,18)

Regions	Dose Rate (μSv/hr)	$\pm$ % error
39	34.29	3.34
44	8.41	3.48
38	4.22	7.01
Upper	31.07 (6-8cm)	3.33
Lower	30.52 (6-8cm)	3.42
Side	34.03 (6-8cm)	3.30

Table 2: Dose Rate for Lead Stop (A,B,C) = (24, 24, 24)

Regions	Dose Rate (μSv/hr)	$\pm$ % error
39	2.47	8.36
44	0.18	11.06
38	0.20	15.03
Upper	8.85 (4-8cm)	3.83
Lower	8.52 (4-8cm)	3.77
Side	10.04 (4-8cm)	3.80

Table 3: Dose Rate for Lead Stop (A,B,C) = (24, 24, 28)

Regions	Dose Rate (μSv/hr)	$\pm$ % error
39	0.57	21.76
44	0.05	41.76
38	0.03	22.01
Upper	8.50 (4-8cm)	5.23
Lower	8.73 (4-8cm)	4.14
Side	9.21 (4-8cm)	3.69

Table 4: Dose Rate for Lead Stop (A,B,C) = (26, 26, 28)

Regions	Dose Rate (μSv/hr)	$\pm$ % error
39	0.43	10.26
44	0.03	23.83
38	0.04	18.10
Upper	4.70 (4-8cm)	4.02
Lower	4.58 (4-8cm)	3.39
Side	5.07 (4-8cm)	3.66

Table 5: Dose Rate for Lead Stop (A,B,C) = (30,30,28)

Regions	Dose Rate (μSv/hr)	$\pm$ % error
39	0.29	13.98
44	0.03	29.61
38	0.03	14.23
Upper	1.50 (4-8cm)	6.05
Lower	1.43 (4-8cm)	3.73
Side	1.61 (4-8cm)	4.34

Table 6: Dose Rate for Lead Stop (A,B,C) = (34,34,28)

Regions	Dose Rate (μSv/hr)	$\pm$ % error
39	0.20	15.36
44	0.02	24.69
38	0.02	16.68
Upper	0.43 (4-8cm)	6.30
Lower	0.51 (4-8cm)	8.27
Side	0.48 (4-8cm)	5.29

Table 7: Dose Rate for Tungsten Stop (A,B,C) = (20,20,14)

Regions	Dose Rate (μSv/hr)	$\pm$ % error
39	3.95	4.35
44	0.70	7.25
38	0.52	8.30
Upper	1.63 (4-6cm)	6.87
Lower	1.69 (2-4cm)	5.70
Side	1.99 (2-4cm)	5.54

Table 8: Dose Rate for Tungsten Stop (A,B,C) = (20,20,16)

Regions	Dose Rate (μSv/hr)	$\pm$ % error
39	0.92	11.70
44	0.14	10.09
38	0.11	11.07
Upper	1.66 (4-6cm)	6.64
Lower	1.52 (2-4cm)	6.19
Side	1.99 (4-6cm)	6.36

Table 9: Dose Rate for Tungsten Stop (A,B,C) = (20,20,18)

Regions	Dose Rate (μSv/hr)	$\pm$ % error
39	0.18	9.89
44	0.05	15.47
38	0.03	16.04
Upper	1.49 (2-4cm)	5.10
Lower	1.50 (2-4cm)	4.37
Side	1.79 (2-4cm)	5.65

Table 10: Dose Rate for Tungsten Stop (A,B,C) = (20,20,20)

Regions	Dose Rate (μSv/hr)	$\pm$ % error
39	0.09	16.64
44	0.01	33.16
38	0.01	45.57
Upper	1.51 (4-8cm)	4.52
Lower	1.46 (4-8cm)	4.53
Side	1.74 (2-4cm)	7.54

Table 11: Dose Rate for Tungsten Stop (A,B,C) = (22,22,18)

Regions	Dose Rate (μSv/hr)	$\pm$ % error
39	0.19	17.83
44	0.03	16.03
38	0.01	19.57
Upper	0.63 (4-6cm)	6.12
Lower	0.72 (4-6cm)	9.62
Side	0.73 (2-4cm)	7.10

Table 12: Dose Rate due to Neutron Production

Beam stop	Dose Rate (μSv/hr)
PB (24,24,24)	1.14
PB (24,24,28)	1.14
PB (30,30,28)	1.14
W (20,20,16)	0.535
W (20,20,18)	0.535

Table 13: Dose Rate in Region 39 for Different Entrance Positions

Entrance Position(XI,YI)	Dose Rate (μSv/hr)	% error
(0,−1.6)	61.77	4.78
(0,−1.7)	46.04	6.04
(0,−1.8)	33.62	5.38
(0,−1.9)	25.15	6.48
(0,−2.0)	17.43	5.32
(0,−2.1)	14.78	6.41

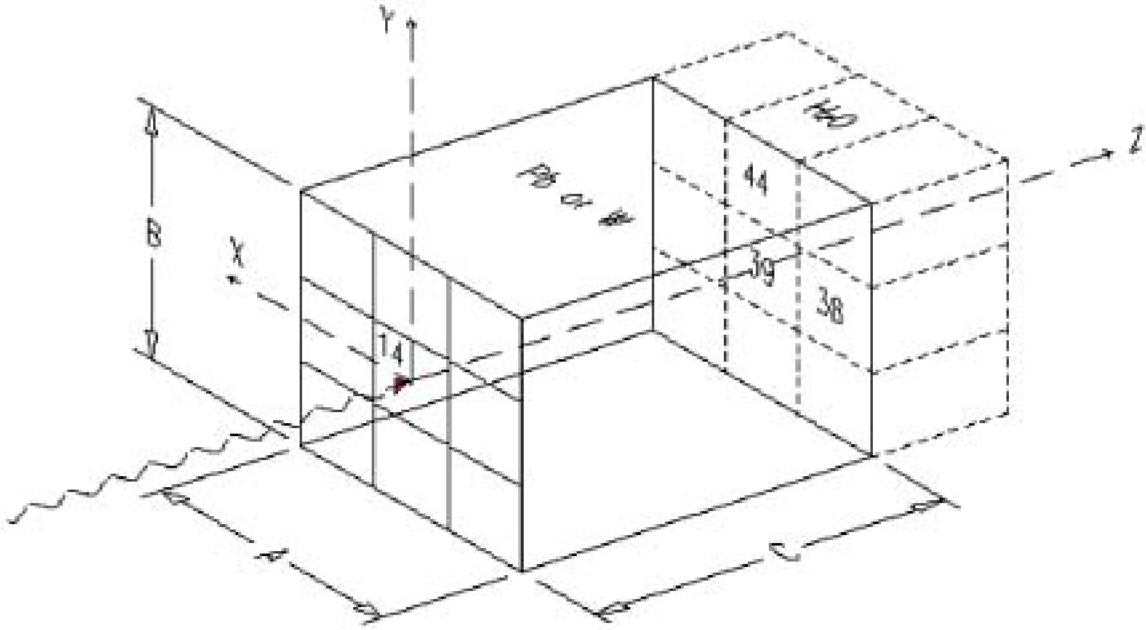

Figure 1: Geometry of beam stop. Numbers refer to the regions used in EGS4 simulation. Water in upper, lower and side areas is not shown for clarity.

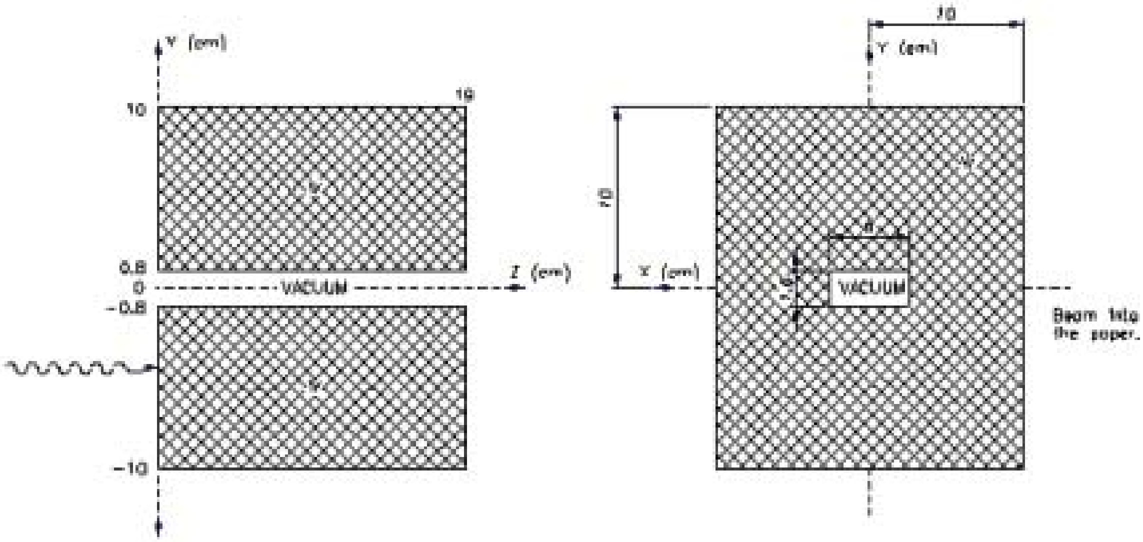

Figure 2: Schematic view of the mono-beam aperature and bremsstrahlung stop.

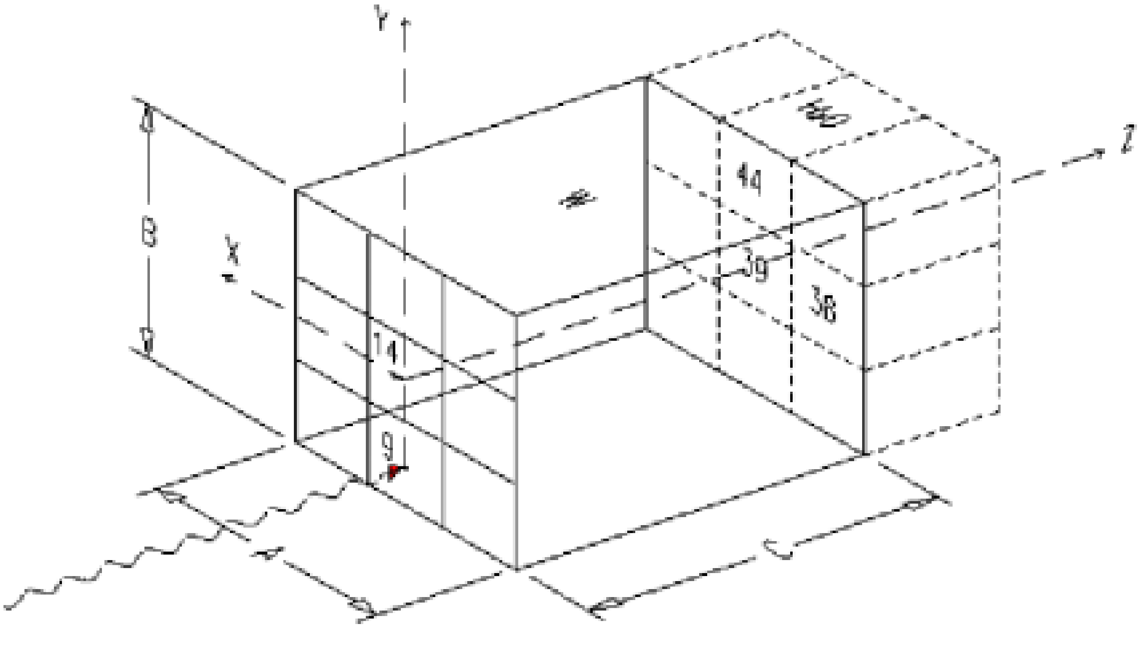

Figure 3: Geometry of the mono-beam aperture and bremsstrahlung stop.