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Simulation of Angular Distribution of Gas Bremsstrahlung Depending on the Residual Gas Pressure of Storage Ring

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Abstract

The simulation of gas bremsstrahlung, which generates the interaction of stored electron with residual gas within the storage ring, were carried out to investigate the conditions of the simulation to get sufficient accuracy of the photon intensity and the angular distribution. The dependence of the spectrum and angular distribution on the number of interactions, lower cut-off energy for electron transport, AE and residual gas pressure were discussed and the condition of the simulation for the SPring-8 beamline were also investigated by using EGS4. As the results, the path length of stored electron is required to be less than 10^{-2} g/cm^2 to get the sufficient accuracy of angular distribution instead of the previous recommendation.

1 Introduction

Gas bremsstrahlung, which generates the interaction of stored electron with residual gas within the storage ring, is one of the most important issues of radiation shielding and safety of beamlines, especially for the third generation synchrotron radiation facilities in which many insertion devices are installed. The simulation is normally carried out with the residual gas density corresponding to atmospheric pressure because of the low interaction probability at the operating pressure (less than 133nPa) and the result is linearly scaled to the operating pressure of the storage ring. However, the scaling procedure is not always possible. Since multiple Coulomb scattering and Moller (hard collision of incident electron with atomic electrons) scattering are practically negligible in the storage ring, whereas these scatterings occupy most of the interactions at atmospheric pressure.

In the calculation, in order to suppress Moller scattering in the extremely low-pressure air target below 133nPa (10^{-9}torr), many parameters were employed as indicated in Table 1, and Ferrari et al.[1] recommended to set as 10 MeV and 10 keV for the key parameters of AE (lower cut off energy for electron and threshold energy of Møller scattering to minimize any angular deflection) and AP (lower cut off energy for photon) without multiple Coulomb scattering, respectively. The recommendation is also to set the gas pressure as 10.13 kPa (0.1 atm) for a long straight section over 10 m to eliminate the probability of re-interaction of photons in the target and fulfill the condition of uniformity of the longitudinal distribution of electron interaction in the target. However, it is not sure whether the recommendation can be applied to the third generation synchrotron radiation facility such as SPring-8. The length of straight section of SPring-8 is up to 40 m and stored electron energy is 8GeV so that the verification of the recommendation is required to get sufficient accuracy of photon intensity and emission angle distribution. Using the EGS4 code[2], therefore the simulations of the gas bremsstrahlung production were performed as the functions of the residual gas pressure, the number of the interaction of stored electron with residual gas molecules, and AE.

Table 1 List of Monte Carlo simulations and its parameters for gas bremsstrahlung production.

Author (date)	Organization	code	maximum electron energy	target length	AE (MeV)	AP (MeV)	pressure (atm)	gas material
G.Tromba & A.Rindi[3] (1990)	Sincrotrone Trieste	EGS4	10GeV	1m	1.0	0.01	1.0	air
J.C.Liu[4] (1994)	SLAC	EGS4	10GeV	1m	1.511	0.1	1.0	air
Ferrari et.al [1] (1993)	INFN	FLUKA	1GeV	1,10m	10.0	0.01	1.0, 0.1	air
N.E.Ipe & A.Fasso[5] (1994)	SLAC	FLUKA	7GeV	15m	10.0	0.01	1.0, 0.1	air

2 Calculations

Sensitivity analyses were carried out at

1. the number of interactions,
2. several AE values ranging from 0.521 to 10 MeV under 1.0 and 0.1 atm,
3. several gas pressure values ranging from 1 to 10^{-3} atm under the straight section lengths of 1m, 19m, and 40m, and
4. several stored electron energy, to investigate its dependence on the energy spectrum and the emission angle distribution of the gas bremsstrahlung.

The option of the true angular distribution of the emitted photons[6] is employed in all calculations with double precision. The calculated photon energy spectra and photon emission angle distributions are given in

1. Fig.1 for the number of interactions,
2. Fig.2 and Fig.3 for several AE values ranging from 0.521 to 10 MeV under 1.0 and 0.1 atm,
3. Figs.4 to 9 for several gas pressure values ranging from 1 to 10^{-3} atm under the straight section lengths of 1m, 19m, and 40m, and
4. Fig.10 for several stored electron energy, respectively.

As shown in Fig.1, the gas bremsstrahlung generated within single interactions between the electrons and 0.1205 g/cm^2 air molecules is about 60 % of that generated within multi-interactions. The gas bremsstrahlung is nearly saturated within triple or more interactions. As shown in Figs.2, 3, AE value dependence is apparent on the intensity of gas bremsstrahlung generation, while the energy spectrum and the emission angle distribution are independent of AE values under 0.01205 g/cm^2 (0.1 atm). Figure 4 shows that the energy spectrum is independent of gas pressure under the length of straight section of 1 m, while as shown in Fig.5, although gas pressure dependence is apparent on the emission angle distribution, its dependence becomes less for a gas pressure below 0.01205 g/cm^2 (0.1 atm). However, as shown in Figs. 6, 7, 8, and 9, gas pressure dependence is apparent on both the intensity of energy spectrum and the emission angle distribution under the lengths of straight section of 19 m and 40 m. Moreover, the longer of straight section, the tendency of the dependence is more apparent. The calculation with sufficient accuracy is no longer expected under the gas pressure of 0.1 atm with the AE value of 10 MeV for SPring-8. Figure 10 shows that the emission angle distribution strongly depend on the stored electron energy, especially the extreme directivity is recognized in stored electron energy of 8 GeV.

The effective doses of anterior-posterior irradiation geometry as a function of the radius of the surface of the photon fluence crossing are shown in Fig. 11 with depending on gas pressure with the path length of 16.54m at 40 m from the center of the straight sections, allowing multi interaction of electron. Figure 12 shows the angular distributions of the gas bremsstrahlung as a functions of the number of interactions. As shown in both figures, the effective dose strongly depends on the calculational gas pressure and the effect of the multi interaction is negligible small in angular distribution at the pressure of 0.001 atm.

Figure 13 shows the relations between the angular distributions and electron path length that depends on the gas pressure, indicating the ratio of the emissions within 0.1 mradian to total emissions in the vertical axis. As shown in this figure, the ratio can be on one curve. Moreover, the curve indicates that the ratio is focused to the constant value below the electron path length of 10^{-2} g/cm^2.

3 Conclusions

The simulations of gas bremsstrahlung at SPring-8 beamlines were performed as the functions of the interactions, AE values, and residual gas pressures to get sufficient accuracy of the intensity and angular distribution of the emission. As the results, the simulations under the recommendations of Ferrari et al. have some problems for the conditions of SPring-8 beamlines. The spectrum of gas bremsstrahlung is independent of the gas pressure, however the angular distribution of photon emission depends on the pressure strongly. In order to correct the defect, it is clarified that the path length of stored electron must be set to be less than 10^{-2}g/cm^2. This means that the simulation conditions must be set to be less than 0.1 atm of air in case of the straight section of 1 m and 0.0025 atm for 40 m. Moreover, it is clarified that the simulations of gas bremsstrahlung with sufficient accuracy can be performed under the path length of less than 10^{-2} g/cm^2 without considering the AE (lower cut off energy for electron and threshold energy of Møller scattering to minimize any angular deflection) and the restriction of single interaction of stored electron with residual gas molecules.

References

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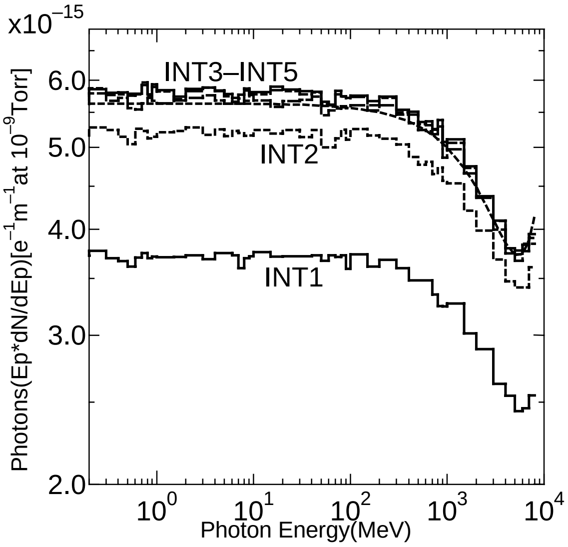

Fig.1 Gas bremsstrahlung spectra depending on the number of the interactions generated by EGS4 resulting from 8 GeV electron and interacting with 0.1205 g/cm^2 air. (INT1; single interactions, INT2; double interactions, INT3,4,5; triple or more interactions.)

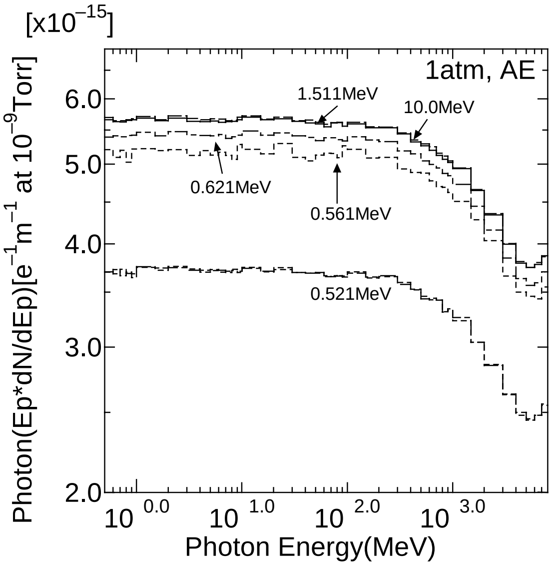

Fig.2 Gas bremsstrahlung spectra depending on lower cut off energy for electron, AE, allowing only single interaction of electron with residual gas of 0.1205 g/cm^2 air.

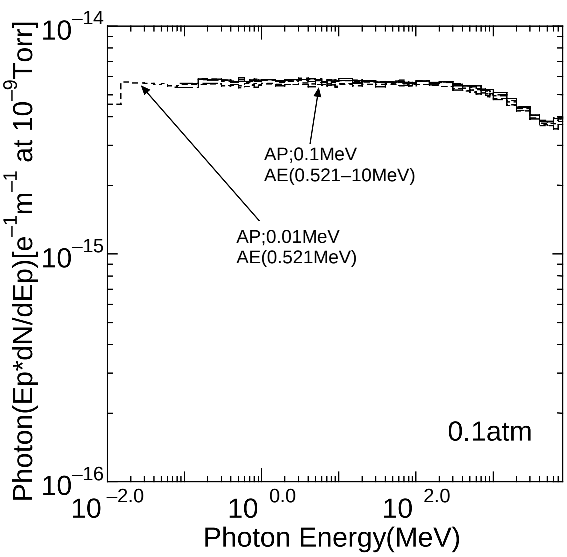

Fig.3 Gas bremsstrahlung spectra depending on lower cut off energy for electron, AE, and lower cut off energy for photon, AP, allowing only single interaction of electron with residual gas of 0.01205 g/cm^2 air.

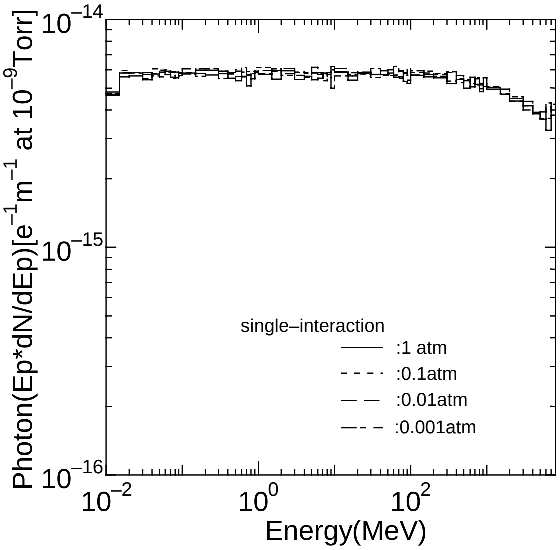

Fig.4 Gas bremsstrahlung spectra depending on gas pressure with the path length of 1 m and AE of 10 MeV, allowing only single interaction of electron.

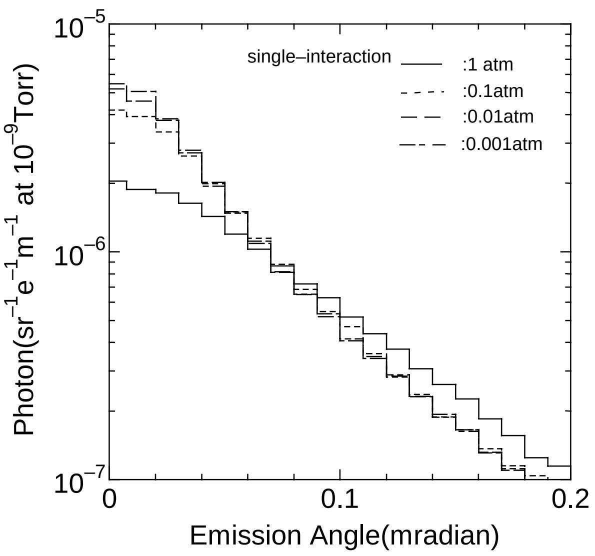

Fig.5 Angular distributions depending on gas pressure with the path length of 1 m and AE of 10 MeV, allowing only single interaction of electron.

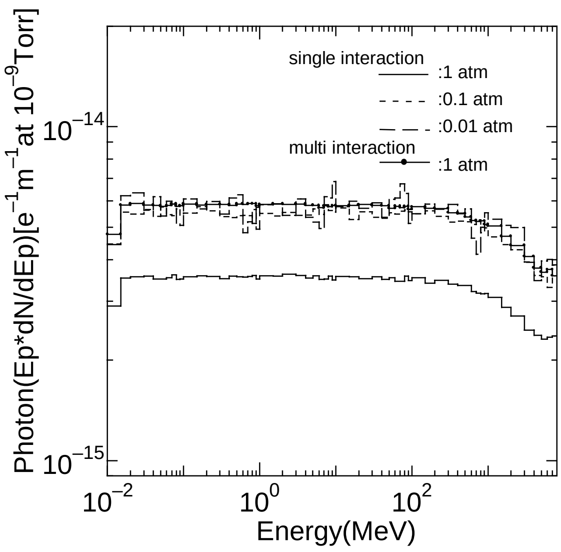

Fig.6 Gas bremsstrahlung spectra depending on gas pressure with the path length of 19 m and AE of 10 MeV, allowing only single interaction of electron and multi interaction.

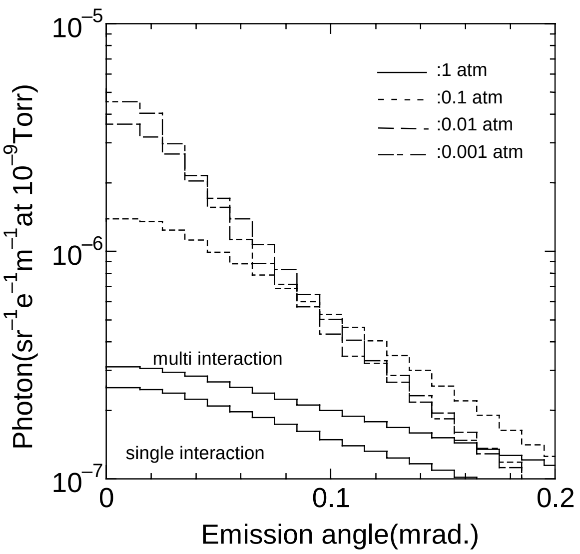

Fig.7 Angular distributions depending on gas pressure with the path length of 19 m and AE of 10 MeV, allowing only single interaction of electron and multi interaction within 1 atm.

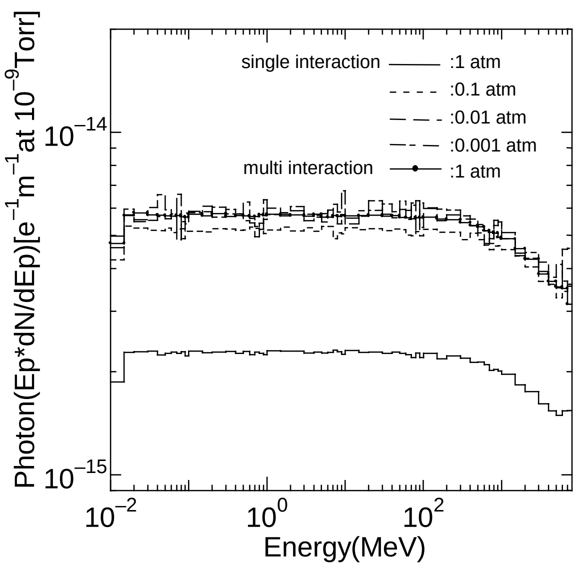

Fig.8 Gas bremsstrahlung spectra depending on gas pressure with the path length of 40 m and AE of 10 MeV, allowing only single interaction of electron and multi interaction.

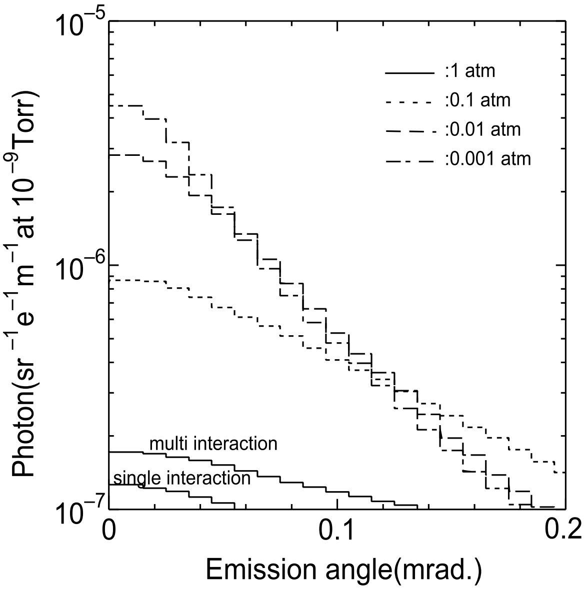

Figure 9: Angular distributions depending on gas pressure with the path length of 40 m and AE of 10 MeV, allowing only single interaction of electron and multi interaction within 1 atm.

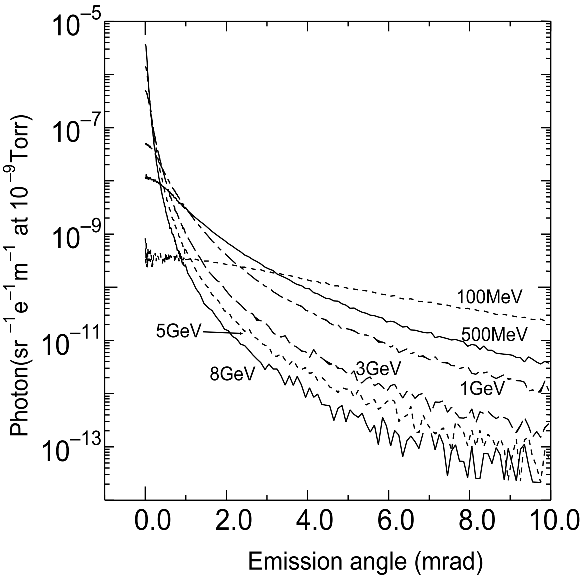

Figure 10: Angular distribution depending on stored electron energy with the path length of 1 m and gas pressure of 0.1 atm, allowing only single interaction of electron.

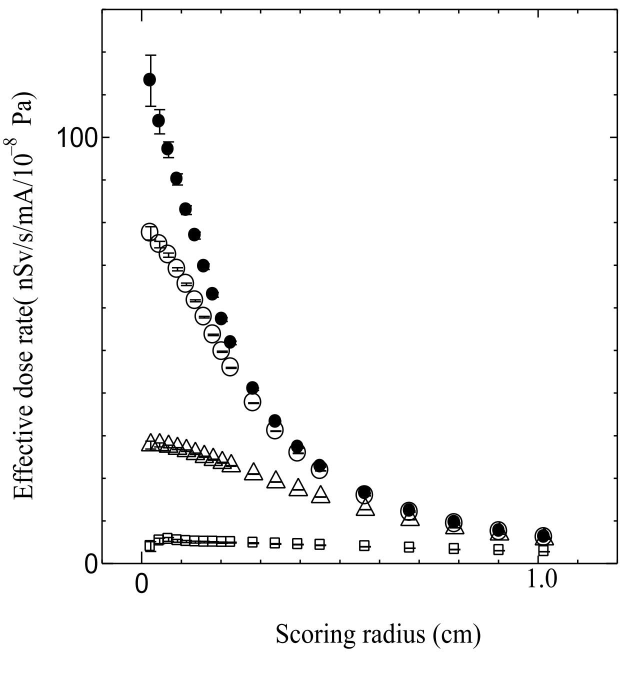

Figure 11: The effective dose distributions as a function of radial scoring area due to gas bremsstrahlung in anterior-posterior irradiation geometry at 40 m from the center of the straight section, allowing multi-interactions and AE of 10 MeV. (The full circles indicate the calculations with the gas pressure of 0.001 atm, open circles; 0.01 atm, open triangle; 0.1 atm, and Open squares; 1 atm)

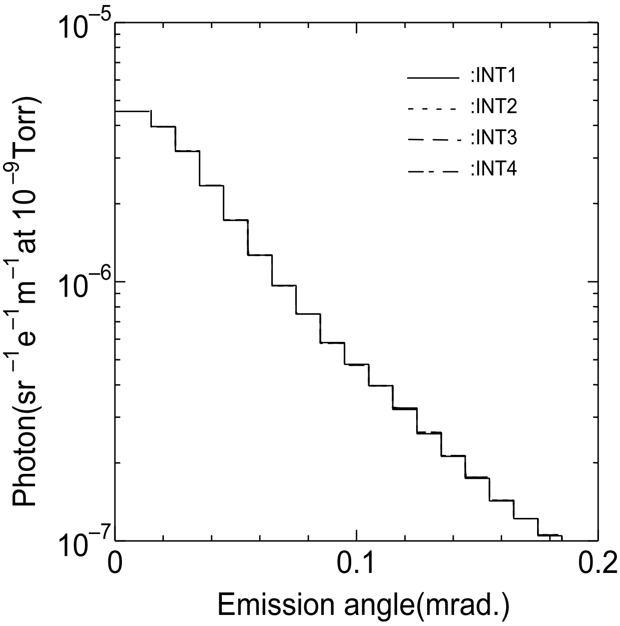

Figure 12: Angular distributions depending on the allowing number of interactions generated by EGS4 resulting from 8 GeV electron and interacting with 0.00482 g/cm^2 air. (INT1: single interactions, INT2; double interactions, INT3,4; triple or more interactions)

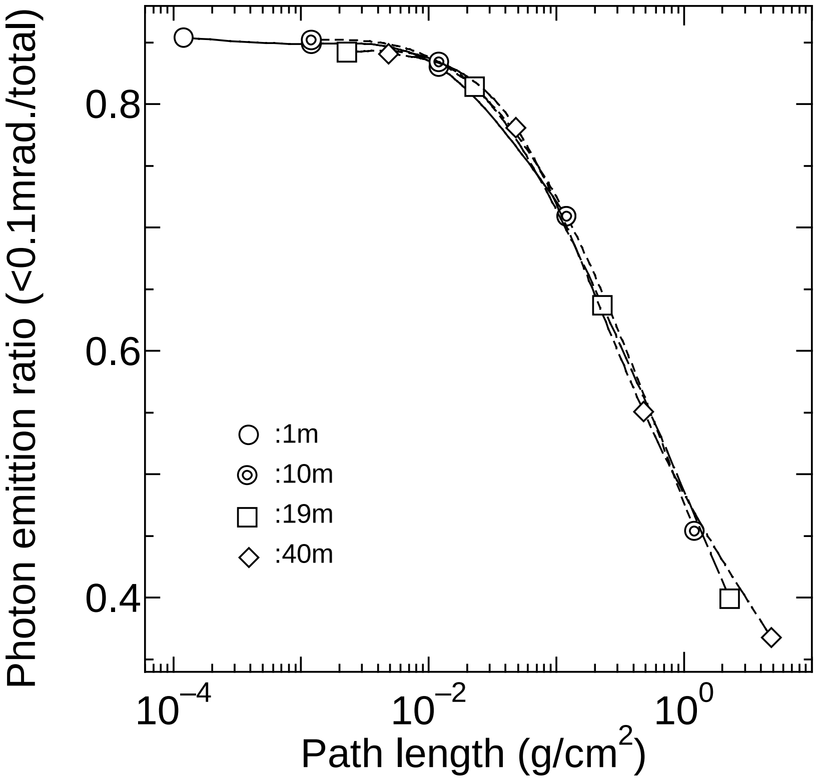

Fig.13 Emission angle dependence of gas bremsstrahlung on electron path length. The vertical axis indicates the ratio of the photons within 0.1 mradian to total photons.