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Absorbed Dose from 7-GeV Bremsstrahlung in a PMMA Phantom

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Electron storage rings generate energetic bremsstrahlung photons through radiative interaction of the particle beam with the residual gas molecules and other components inside the storage ring. At the Advanced Photon Source (APS), where the stored beam energy is 7 GeV, bremsstrahlung generated in the straight sections of the insertion devices comes down through the beamlines. The resulting absorbed dose distributions by this radiation in a 300 mm x 300 mm x 300 mm tissue substitute phantom were measured with LiF:Mg,Ti (TLD-700) thermoluminescent dosimeters. The average normalized absorbed dose, in a cross sectional area of 100 mm^2 at a depth of 150 mm of the PMMA phantom, was measured as 3.3×10^6 mGy h^{-1}W^{-1} for a 7-GeV bremsstrahlung spectrum.

KEYWORDS: Absorbed dose, Bremsstrahlung, PMMA Phantom

I. Introduction

The Advanced Photon Source (APS) consists of a 200-MeV electron linac, a 7-GeV electron booster synchrotron, and a 7-GeV storage ring(1). Bremsstrahlung, the maximum energy of which is equal to the particle beam energy, is produced in the APS storage ring when the circulating particle beam scatters from the storage ring components and/or from the residual gas molecules. The 7-GeV stored electron beam passes through insertion devices (ID), which cause the particles to wiggle or undulate as they pass through the device, producing synchrotron radiation. To accommodate these insertion devices, the storage ring has long straight sections. The total length of the straight paths at the APS is 15.38 m, which includes the 5-m ID straight section and the upstream-downstream sections of the vacuum chamber directly in the line of sight of the synchrotron radiation beamlines. The contribution from each bremsstrahlung interaction in the straight path adds up to produce a narrow mono-directional beam that comes down through the insertion device beamlines along with the synchrotron radiation. This causes a nontrivial radiation safety concern at the insertion device beamlines(2,3).

In one of the ID beamlines (15-ID), simultaneous measurements of the bremsstrahlung absorbed dose rate and the corresponding bremsstrahlung power were conducted. The absorbed dose rate due to bremsstrahlung was measured using a 300 mm x 300 mm x 300 mm polymethyl methacrylate (PMMA) cube phantom. A calorimeter that possesses good resolution and a fast time response(4) with a segmented array of lead glass, positioned inside the first optics enclosure (FOE) of the ID beamlines, was used to measure the corresponding bremsstrahlung spectra and power(2,3). The results of the bremsstrahlung absorbed dose rate measurements normalized to the corresponding bremsstrahlung power are presented in this paper.

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II. Experimental Setup

A schematic of the experimental setup is shown in **Fig. 1**. The PMMA phantom consists of twelve 300 mm x 300 mm x 25 mm slabs. The absorbed dose in the PMMA phantom was measured with LiF thermoluminescent dosimeters (TLD700)(5). Three 5 mm x 5 mm x 1 mm cavities, one in the center of the slab and one each on either side of the center, 5 mm from the edge of the central cavity, were drilled into each of these slabs to hold the TLDs. In one of the slabs, extra cavities were drilled at every 5 mm out to a distance of 15 mm. The TLD dimensions were 3.2 mm x 3.2 mm x 0.9 mm. The TLDs were pre-selected to have responses that differed by less than 10% and were individually calibrated using a ^{137}Cs source. The central cavities were aligned with the bremsstrahlung beam such that the side cavities were alternately parallel and perpendicular to the horizontal plane. During these measurements, the insertion device was kept in a fully open position such that the synchrotron radiation background is a minimum. A 300 mm x 300 mm x 3 mm lead plate was placed in contact with the beam side of the phantom to minimize the residual synchrotron radiation background.

The calorimeter that measured the total bremsstrahlung power is made up of 25 individual lead glass detectors, each 63 mm x 63 mm x 350 mm, stacked into a 5 x 5 array(2,3). A 300 mm x 300 mm x 3 mm lead plate was placed in contact with the beam side of the calorimeter to minimize the residual synchrotron radiation background. The 3-mm lead plate will introduce a systematic correction of less then 2% in the measured bremsstrahlung power(3). The bremsstrahlung beam is aligned along the central detector. Energies of the incident bremsstrahlung photons are measured on an event-per-event basis by a data acquisition system (DAQ) and are stored into a 16K-memory unit for subsequent read out by a computer. Further details of the calorimeter and data acquisition system

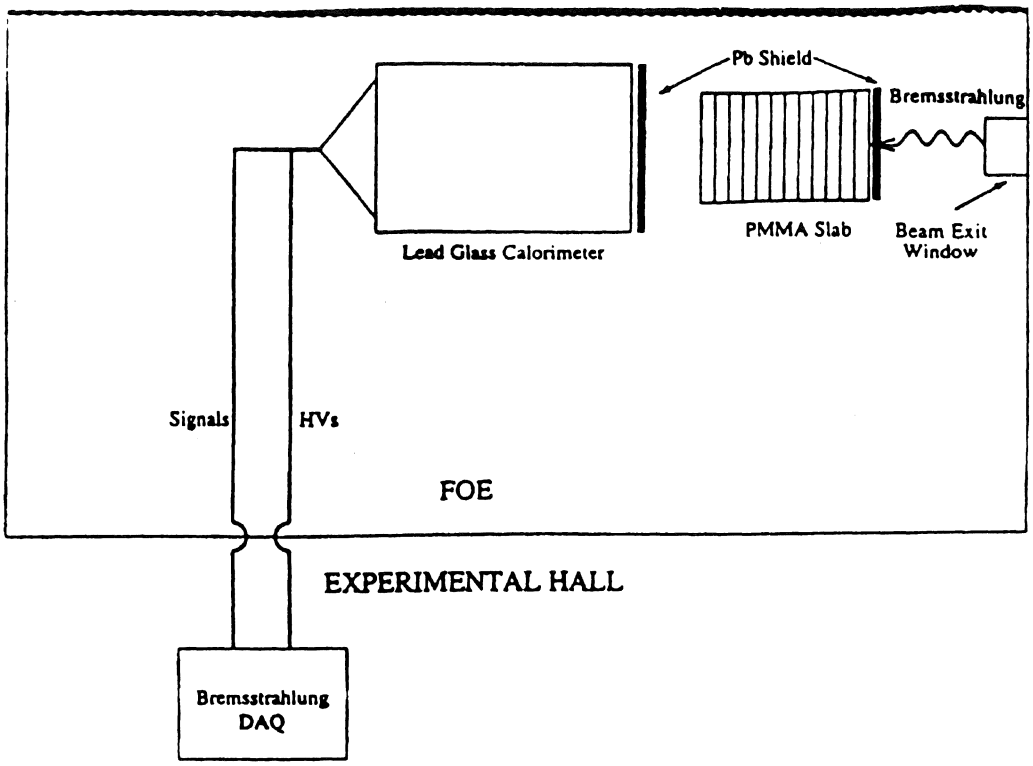

Fig. 1 Schematic diagram of the experimental setup. The PMMA phantom to measure the absorbed dose and the Pb glass calorimeter to measure the bremmstrahlung specturm are shown (not to scale).

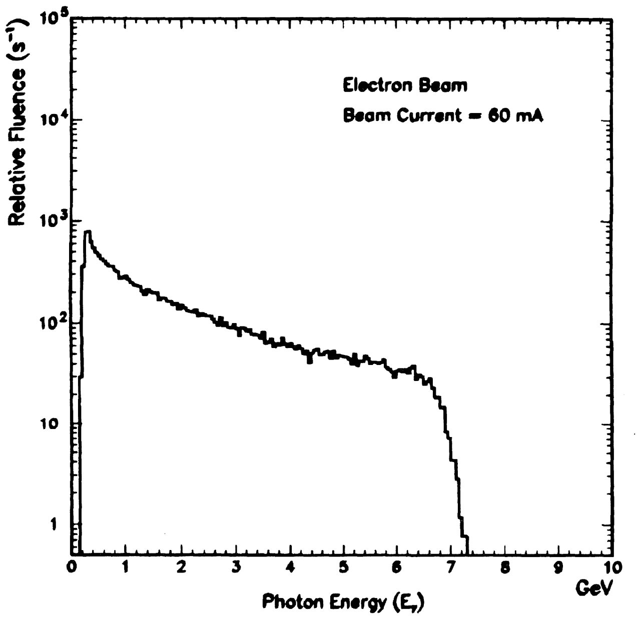

Fig. 2 A typical measured bremsstrahlung spectrum at an insertion device beamline of the APS.

can be found elsewhere[2,3].

III. Data Collection Procedure

The experimental runs for the simultaneous measurements were conducted such that each absorbed dose rate measurement in the PMMA phantom is preceded and followed by a bremsstrahlung power measurement. Once a bremsstrahlung data set was collected, the TLDs were loaded into the PMMA cavities, the centers of which were aligned along the bremsstrahlung beam by taking several images of the beam with a radiation sensitive paper. The phantom was then irradiated for a known time, upon completion of which the TLDs were retrieved from the cavities for analysis. The PMMA cube was then removed from the beam path, and another bremsstrahlung data set was collected. The time elapsed between measurements was kept to a minimum. Because of the long particle beam lifetime (~ 30 h) in the storage ring, the change in the beam current during the measurement interval was small. Thus, the calorimeter and TLD measurements are considered approximately simultaneous. The average power from the two bremsstrahlung data sets was then used to normalize the absorbed dose rate measured in between.

The intensity of the bremsstrahlung is primarily a function of the stored beam current, the composition of the residual gas, and the storage ring pressure. Thus, during the experimental runs at the insertion device beamlines, data were collected to determine the values of the straight section pressure and the chemical composition of the residual gas inside the storage ring. The straight section pressures, as measured by six ion gauges, were written into a data file at two-minute intervals. The residual gas analysis was also conducted at the insertion device straight sections at various beam currents during the experimental runs.

IV. Absorbed Dose Results

The bremsstrahlung energy spectra were measured using the

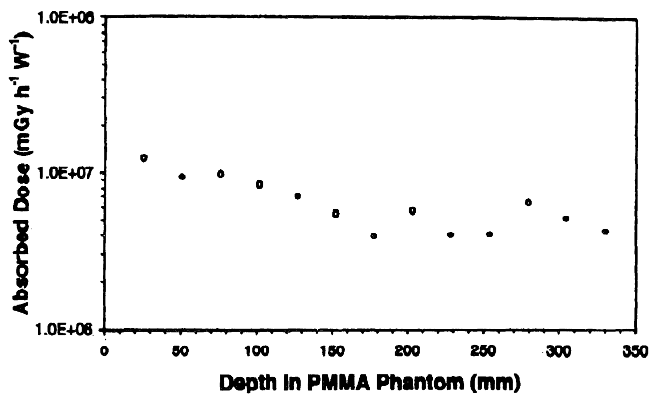

Fig. 3 The measured longitudianal absorbed dose profile along the beam center line in the PMMA phantom.

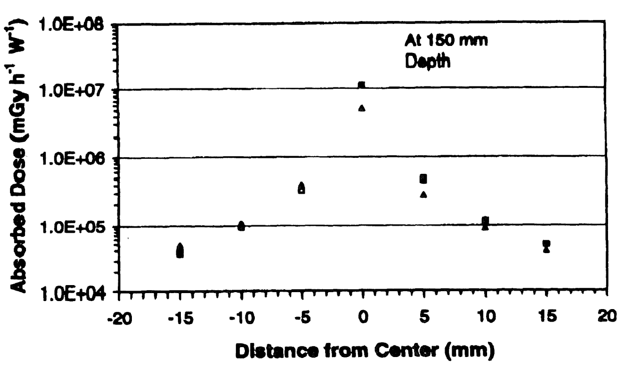

Fig. 4 The measured transverse absorbed dose profile in the PMMA phantom at a depth of 150 mm.

Table 1 Summary of the absorbed dose results, normalized to the corresponding bremsstrahlung power

APS Beamline	Measured Bremsstrahlung Photon Rate (s^{-1})	Measured Bremsstrahlung Power (W)	Absorbed Dose using Rogers Conversion Factors ($mGy\ h^{-1}\ W^{-1}$)	Absorbed Dose in PMMA at 150 mm depth ($mGy\ h^{-1}\ W^{-1}$)
6 ID	1.39×10^4	3.85×10^{-6}	4.42×10^6	-
10 ID	1.98×10^4	5.62×10^{-6}	4.45×10^6	-
11 ID	4.49×10^4	1.36×10^{-5}	4.19×10^6	-
12 ID	3.90×10^4	1.20×10^{-5}	4.18×10^6	-
13 ID	1.48×10^5	4.53×10^{-5}	4.42×10^6	-
15 ID	1.22×10^4	3.45×10^{-6}	4.35×10^6	3.3×10^6

Pb glass calorimeter at six insertion device beamlines for a range of beam currents and vacuum conditions. A typical bremsstrahlung energy spectrum is shown in **Fig. 2**. The total emitted bremsstrahlung power from each beamline was calculated by integrating this spectra from 10 keV to 7 GeV, 10 keV being approximately the lowest energy transmitted through the front-end windows. The absorbed dose rate measurements are normalized to the corresponding bremsstrahlung power and are independent of the rate.

The longitudinal absorbed dose profile in the PMMA phantom, measured by the central TLDs and normalized to the bremsstrahlung power, is given in **Fig. 3**. The data represent the average of five independent measurements at the 15-ID beamline. The profile is relatively flat except for a slight build-up in the first few PMMA layers. This could be due to the residual low-energy synchrotron radiation still present in the beam. The statistical errors in these numbers are less than a few percent. The measured transverse absorbed dose distribution from three independent measurements at the depth of 150 mm of the PMMA is given in **Fig. 4**. The results show that the absorbed dose is an order of magnitude smaller, even at a distance of 5 mm from the beam. **Table 1** (last column) gives the normalized absorbed dose, in a cross-sectional area of 100 mm^2, at a depth of 150 mm of the phantom. The dose becomes negligible beyond a distance of a few centimeters from the beam central line, which shows that the major portion of the dose is within a few millimeters of the beam.

V. Analysis of the Results

The bremsstrahlung spectrum, measured by the lead glass calorimeter, can be directly converted into absorbed dose rate by the available fluence-to-dose conversion factors. This can then be compared with the measured absorbed dose rate in the slab phantom. Rogers[(6)] has previously calculated fluence-to-dose equivalent conversion factors as a function of depth, for broad parallel beams of mono-energetic electrons, positrons, and photons incident on a 300-mm-thick slab of ICRU four-element tissue. The maximum dose equivalent (MADE) technique was implemented, by using the maximum fluence-to-dose factors in the 300-mm-thick slab, to convert the measured 7-GeV fluence spectra into the absorbed dose rate. In this case the dose equivalent rate given by Rogers factors is identical to the absorbed dose rate, as a quality factor of 1 was used for all the calculations. The measured bremsstrahlung spectra were converted into their respective energy fluence spectra by dividing them by a cross- sectional area of 100 mm^2. The energy fluence spectra were then converted into the corresponding absorbed dose rate spectra using the fluence-to-dose conversion factors. The maximum absorbed dose from each of the six separate beamlines, normalized to the bremsstrahlung power, was calculated by summing the events under the corresponding absorbed dose rate spectra along the entire energy range. The results of this analysis are given in Table 1 (column 4). The conservative nature of the MADE technique is further enhanced because the fluence-to-dose-equivalent conversion factors, calculated by Rogers, are for broad beams only.

The results in column 4 of Table 1 show the general agreement between the measurements and the calculations for all of the beamlines involved. The fitted result of the absorbed dose calculated from Rogers broad beam conversion factors is $4.4\pm0.1 \times 10^6$ mGy $h^{-1}W^{-1}$. The normalized absorbed dose measured in the PMMA phantom in this experiment is 3.3×10^6 mGy $h^{-1}W^{-1}$ (column 5, Table 1), which provides a value lower by a factor of 1.3 than the one obtained from the broad beam conversion factors. Such a factor is consistent with the ratios expected due to buildup in a broad beam case[7].

Comparison with the absolute measurements of dose rates from other facilities is difficult because of normalization. The absorbed dose rate is not only a function of stored beam current and the storage ring pressure but also of parameters like straight section length, location of the measurement, residual gas composition in the storage ring and the stored beam energy. Therefore, for a given spectrum, the absorbed dose rate normalized to the total emitted bremsstrahlung power seems to be the relevant quantity with which meaningful comparisons can be made. However, not many measurements normalized to this unit are available. But absorbed dose rate results normalized to the beam current and storage ring pressure are available from other facilities for broad comparisons[8,9,10]. These results ranged from 8.8×10^{-3} mGy $h^{-1}mA^{-1}nT^{-1}$ to 2×10^{-2} mGy $h^{-1}mA^{-1}nT^{-1}$. These can be compared with the present measurement of 2.3×10^{-2} mGy $h^{-1}mA^{-1}nT^{-1}$ at the 15-ID beamline of the APS. Corresponding total bremsstrahlung power in each of the previous results is not available for dose normalization. Preliminary analysis of similar measurements conducted at the European Synchrotron Radiation Facility[11] shows the normalized absorbed dose value of 3.6×10^6 mGy $h^{-1}W^{-1}$ for the 6-GeV bremsstrahlung spectrum. This agrees with the present measurement of 3.3×10^6 mGy h^{-1} W^{-1} for the 7-GeV bremsstrahlung spectrum at the APS.

VI. Summary and Conclusions

The normalized absorbed dose, in a cross-sectional area of 100 mm^2 and at a depth of 150 mm of the PMMA cube phantom, was measured as 3.3×10^6 mGy $h^{-1}W^{-1}$ for a 7-GeV bremsstrahlung spectrum. The bremsstrahlung spectrum measured by the lead glass calorimeter was also converted to the absorbed dose by the known fluence-to-dose conversion factors and normalized for comparison. The measured dose rates were also compared with results from other facilities that are normalized to beam current and storage ring pressure. It is observed that the absorbed dose, normalized to the total emitted bremsstrahlung power, seems to be the relevant quantity with which to make comparisons for a given spectrum.

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