Benchmarking MCNP Low-Energy Bremsstrahlung Modeling for Electronic Brachytherapy Simulations

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ABSTRACT

Purpose: Electronic brachytherapy (EBT) sources have been used clinically for over a decade; however, dosimetric characterization methods using measurements or calculations are not well-established. Monte Carlo methods for simulating electron transport, and subsequently photon production, have not been benchmarked to the same degree as photon-emitting HDR ^{192}Ir or LDR ^{125}I brachytherapy sources.

Materials & Methods: Towards better understanding the capabilities of MCNP5 to simulate radiation transport for the Xoft Axxent™ HDR X-ray Source, this study presents a comparison of calculated MCNP5 results obtained using coupled electron:photon transport with measured bremsstrahlung spectra from the literature. Given the electron energy and target material, MCNP5 bremsstrahlung modeling accounts for photon energy, angle, and probability based on the cross-sections and angular distributions from NIST (Seltzer and Berger, 1985). The Axxent™ EBT source currently operates at 50 kV with electrons bombarding a ~ 1 μm thick high/low Z target. Pertinent high/low Z comparisons for thin targets, defined as materials thin enough to produce negligible electron absorption in the target, were available from Motz and Placious (1958) using 50 kV on 5.2 nm Au and 63 nm Al, from Dyson (1959) using 10 kV on 25 nm Au, and from Doffin and Kuhlenkampff (1957) using 34 kV on 25 nm Al.

Results: Comparisons of calculations and experimental data indicate that the bremsstrahlung angular peak, relativistically shifted forward, agreed within a few degrees with measurements in the literature. However, the overall simulated distribution exhibited angularly invariant regions in the forward direction, attributed to MCNP low-energy physics simplifications of the NIST dataset. Given that the brachytherapy target is ~ 50 times thicker, with resultant smearing of the energy/angular distributions, the practical impact of this effect is under investigation.

Conflict of Interest: This research was supported in part by Xoft, Inc.

PROJECT BACKGROUND

- The Xoft Axxent™ Electronic Brachytherapy System, including the x-ray source, are FDA approved. Clinical implementation requires acquisition of measured and calculated brachytherapy dosimetry data; this study aims to validate the methodology for acquiring calculated data.
- Calculated dose rate distributions were obtained with a generalized radiation transport code (MCNP5) with explicit characterization of every source component. The source is a miniature x-ray tube. Following electron impingement on a high-Z (tungsten) anode, photons are created via the bremsstrahlung process. For an operating voltage of 50 kV, the maximum photon energy is 50 keV. These x-rays are emitted with a quasi-isotropic spatial distribution for *in vivo* radiation therapy applications.
- This study analyzed the MCNP5 bremsstrahlung process in a theoretical framework to confirm proper operation of the MCNP radiation transport code. Emitted photon energy fluence and angular distributions were assessed for a variety of target materials, target thicknesses, and electron impingement energies.

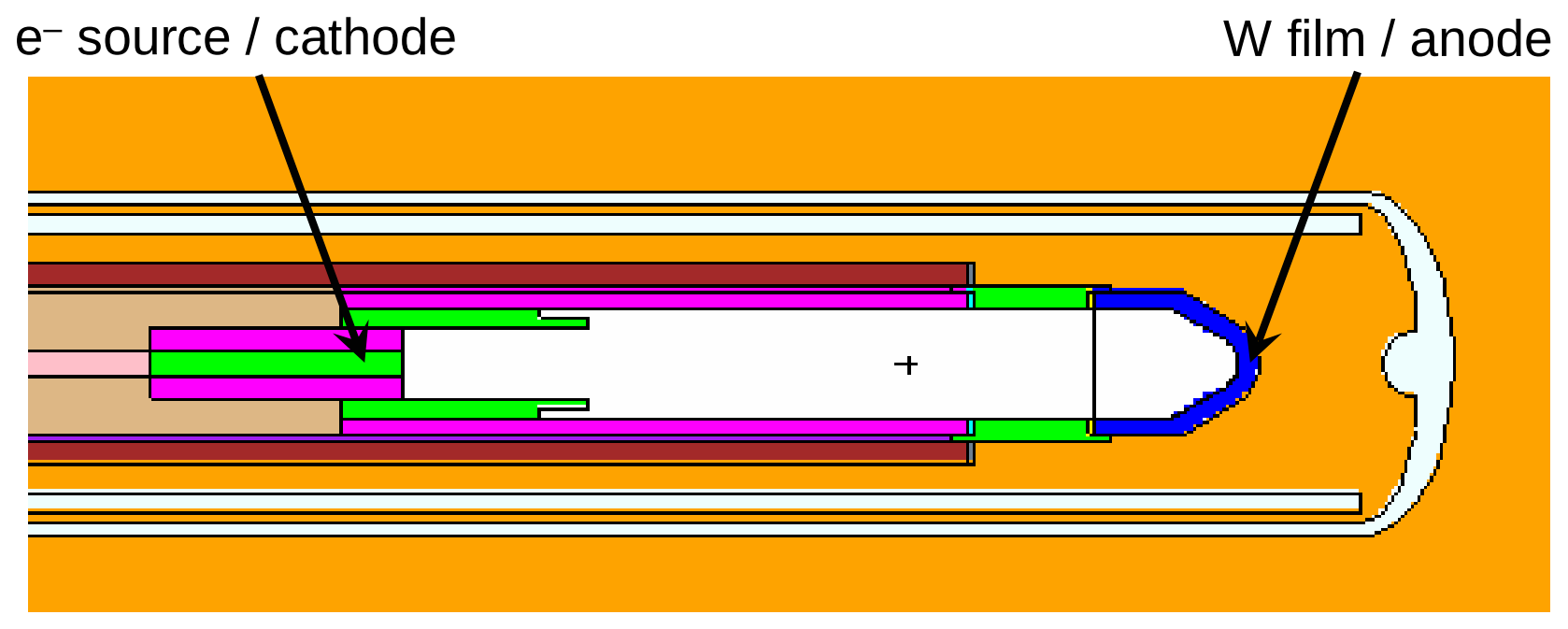


Figure 1. Cross-sectional view of the Axxent™ x-ray source showing cathode and anode positions.

METHODS

PURPOSE

The purpose of this study was to demonstrate the reasonableness of using MCNP5 for this application through comparisons of simple computational studies with similarly simple published measurements. Since the comparison showed results were in good agreement, and since there is a wealth of published data benchmarking the MCNP code for this type of application, a rigorous benchmarking of MCNP5 for low-energy bremsstrahlung production was not performed.

LITERATURE REVIEW

Published studies of measurements and calculations were considered for comparison. These publications covered a range of materials and energies complementary for comparison with MCNP5 modeling of the Axxent™ source.

- Motz and Placious examined the bremsstrahlung differential cross-section for impingement of 50 keV electrons as a function of photon energy. Using a scintillation spectrometer, photon energy fluence was measured as a function of photon emission angle (typically 10° increments). To minimize competing physical effects such as absorption from determination of the measured differential bremsstrahlung photon production, thin film targets were prepared. These targets were gold (Z = 79) and aluminum (Z = 13) at 10 μg/cm^2 and 17 μg/cm^2, respectively. Using the mass density to convert to actual effective thickness, values of 5.2 nm and 63 nm, respectively were obtained. Because the gold target atomic number (Z) was more similar to the Axxent™ target (Z_W = 74), only comparisons to the measured gold differential bremsstrahlung photon production results were performed.
- Motz and Placious prepared a thorough review of bremsstrahlung theory and related formulae. Parameters used in the formulae were based on extensive measurements for arbitrary electron impingement energy, target Z, and emission angle. Agreement between measured and theoretical results for high-Z and T < 100 keV was within 10%, which was much less than measured uncertainties.
- In the development of radiation transport codes, Berger and Seltzer examined bremsstrahlung and photo-neutron production from thick tantalum (Z = 73) and tungsten (Z = 74) targets over a wide range of electron impingement energies (10 keV $\leq$ T $\leq$ 100 MeV). For our study of the Axxent™ EBT source, only results pertinent to tungsten were of interest. For W targets thicker than 70 μm, target self-absorption effects become pronounced. Thick-target simulations are a greater challenge to model accurately due to multiple-electron scattering. While the Axxent™ W anode film is about 1 mm in diameter and no more than 2 μm thick, oblique electron impingement and scattering will increase the effective path lengths traversed by the electrons and bremsstrahlung photons. Since Berger and Seltzer obtained good agreement between calculated and measured bremsstrahlung production for a wide range of electron impingement energies and for thick targets, the theory and formulae used in subsequent radiation transport codes were considered rigorously validated.
- A review was performed of modern medical applications using MCNP to simulate bremsstrahlung photon production in environments comparable to the Axxent™ EBT source geometry. DeMarco, et al. examined bremsstrahlung photon production from thick targets such as Pb using MCNP over a wide range of photon emission angles. While the electron impingement energy (T = 15 MeV) is much higher than that for the Axxent™ (T = 0.05 MeV), DeMarco, et al. obtained agreement within 7% in their study, and considered the MCNP code validated for their purposes.
- Even more appropriate for comparison with our application, Mercier, et al. examined bremsstrahlung photon production for 20 $\leq$ T $\leq$ 150 keV on tungsten using MCNP. Excellent agreement over all energy ranges was obtained with measured spectra (i.e., errors of 1%, 3%, and 5% at 150, 50, and 30 keV, respectively). Differences were approximately equal to measurement uncertainties (5%) while calculated statistical errors were approximately 1%. As version 4 of MCNP was revised to account for non-unity values of the scaled energy loss ratio, η, current MCNP versions (e.g., MCNP5 using the MCPLIB04 library) now account for the energy- and Z-dependence of η. This is important since $\eta < 0.05$ for electron impingement energies < 100 keV.
- In the most recent comparable study, Ay, et al., various empirical, semi-empirical, and Monte Carlo models were compared as to the shape of tungsten-anode bremsstrahlung photon spectra at an emission angle of 12.5°. Based on comparisons between measured and simulated transmission, MCNP produced the most accurate results (2.0% mean and 2.7% maximum difference) for T = 80 kV. Differences obtained using EGS4, empirical approaches, or semi-empirical approaches were from 5% to over 15%. While there was a significant difference between calculated and measured characteristic K-edge x-rays on molybdenum targets (Z = 42) at T $\leq$ 30 keV, differences between measured and calculated photon transmission and absorbed breast dose for mammography applications using a tungsten target were always less than 5% and typically less than 2%. Based on these published results, the MCNP code appears well-benchmarked for the Axxent™ EBT application of 40 $\leq$ T $\leq$ 50 keV on thin W targets..

BACKGROUND

In comparison to ^{125}I or ^{192}Ir, characterization of dose rate distributions from electronic brachytherapy (EBT) sources are subject to the additional challenge of unforeseen photon energy spectra. When simulating photon energy spectra and resultant dose rate distributions, Monte Carlo investigators first generate electrons which bombard the x-ray anode and subsequently create photons via bremsstrahlung. These modeling techniques for this endeavor are largely unexplored.

The Xoft Axxent™ model S700 electronic brachytherapy source is a miniature x-ray tube. The operating voltage may range from 20 - 60 kV; this study focussed on 50 kV, and examined impingement energy (T) of 50 keV electrons on the anode target. The tungsten target (Z = 74) is of variable thickness (0.5 to 2.0 μm). Electrons impinge the target over a range of angles (0° to 90°) normal to the target surface.

MCNP SIMULATION METHODS

- It would be a circular argument to use measured results of the Xoft Axxent™ transmission curves or 2-D polar anisotropy function as a means to validate the Monte Carlo simulations of the Axxent™ radiation dose distributions since data used in the calculation model was somewhat dependent on measured results. Therefore, the applicability of MCNP5 (X-5 Monte Carlo Team 2003) was tested through comparisons of simple calculated studies with similarly simple published measurements.
- The three studies used for this comparison were Motz and Placious, using 50 kV on 5.2 nm Au and 63 nm Al; Dyson, using 10 kV on 25 nm Au; and Doffin and Kuhlenkampff, using 34 kV on 25 nm Al.
- While less directly applicable to Axxent™ simulations, Dyson reported on the angular dependence of bremsstrahlung photons from 8, 10, and 12 kV electron beams impinging on a 1 μm thick gold (Z = 79) target. The target used in the measurements was considered "thick" based on electron self-absorption, and corrections were applied to ameliorate this effect. Consequently, a 1 nm Au target was used in our study to test MCNP bremsstrahlung photon production without having to correct for self-absorption effects. The bremsstrahlung photon angular distribution was determined using T = 10 keV and 1° angular resolution. To match the historical coordinate system, 0° corresponded to photon production along the direction of incident electrons while 90° corresponded to photon production normal to the incident electron beam. Both the measurement and computational geometries were cylindrically-symmetric about the 0° axis. Bremsstrahlung photon production was normalized to the 90° production rate. Results were evaluated based on the angle of maximum photon production and the value at that angle. Since results were presented only graphically by Dyson, his figures required magnification and hand measurements to quantitatively determine the peak production rate and angle of maximum photon production.
- Least relevant from a Z-perspective but salient from an energy-perspective is the comparison to Doffin and Kuhlenkampff's results for T = 34 keV on a 25 nm Al target using an MCNP simulation methodology identical to Dyson's comparison.
- In all cases, the MCNP ESTEP parameter, and the electron range in the target, were monitored to assure adequate sampling for improved radiation transport accuracy. Typically, 20+ electron substeps were simulated within nanometer thick targets. Thus the relativistic, dipolar angular dependence exhibited lobes oriented laterally towards 90°.

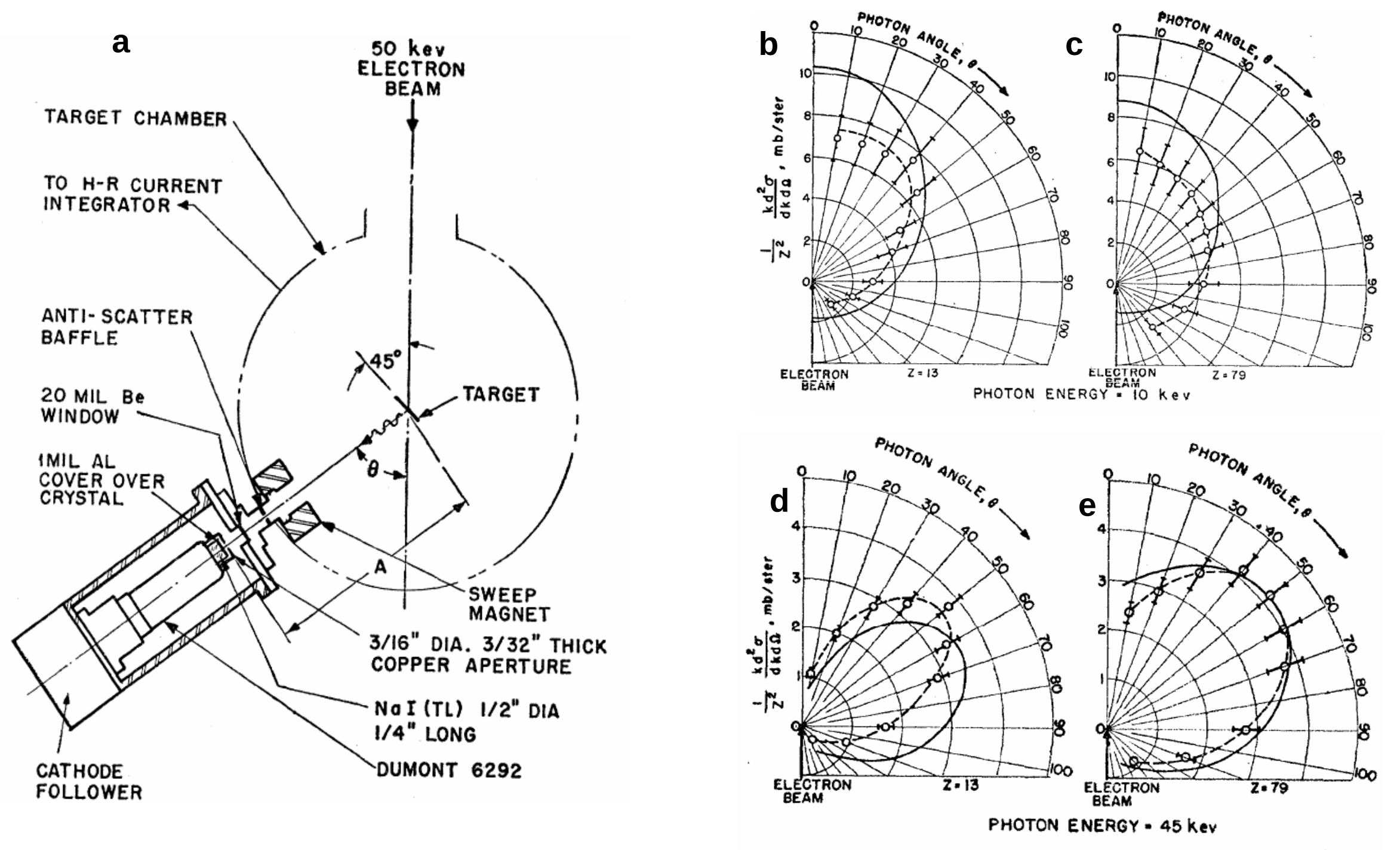


Figure 2a. Bremsstrahlung photon measurement geometry from Motz and Placious.

Figures 2b-e. Measured bremsstrahlung photon production in Au and Al at T = 10 and T = 45 keV.

RESULTS

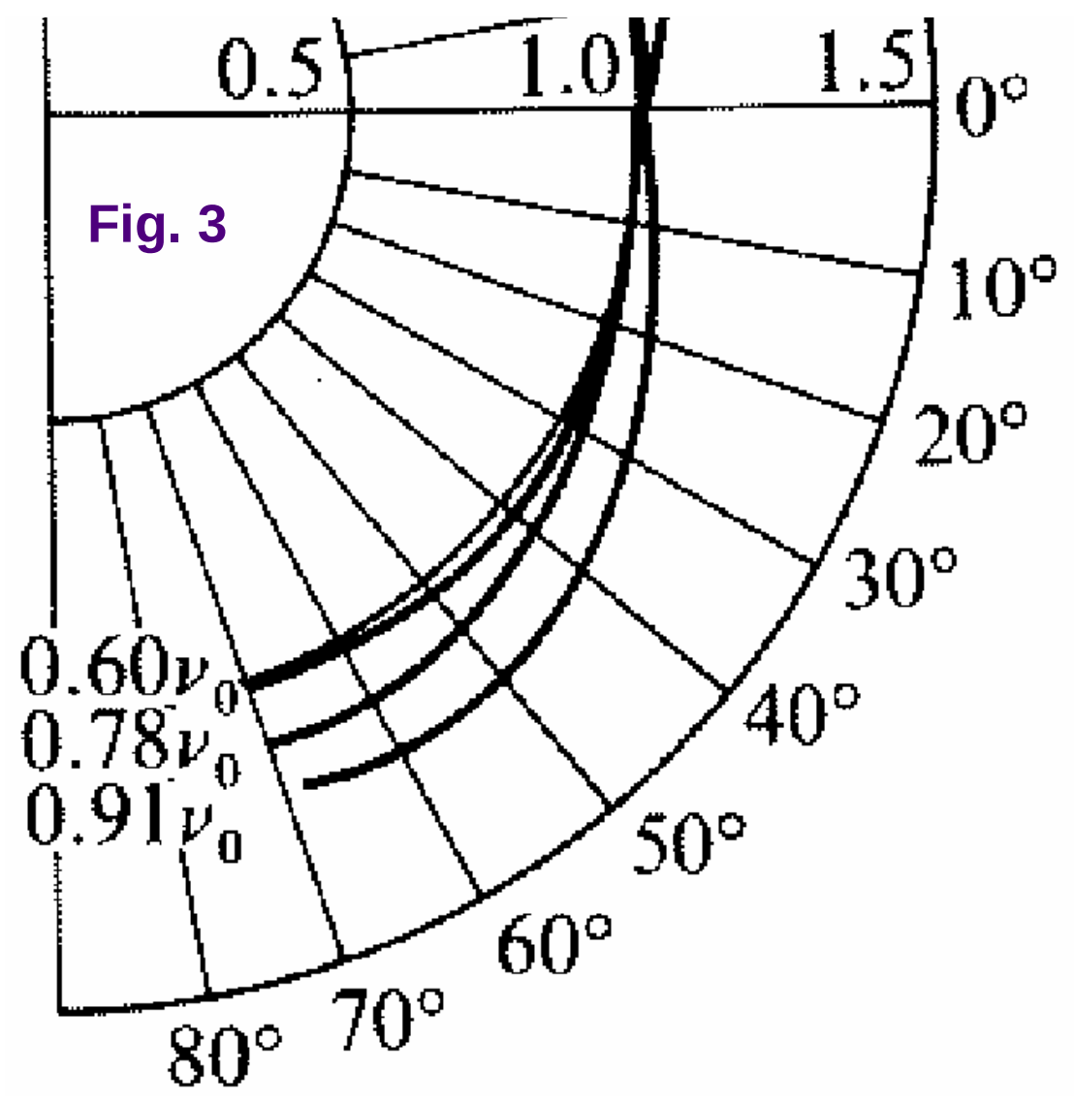
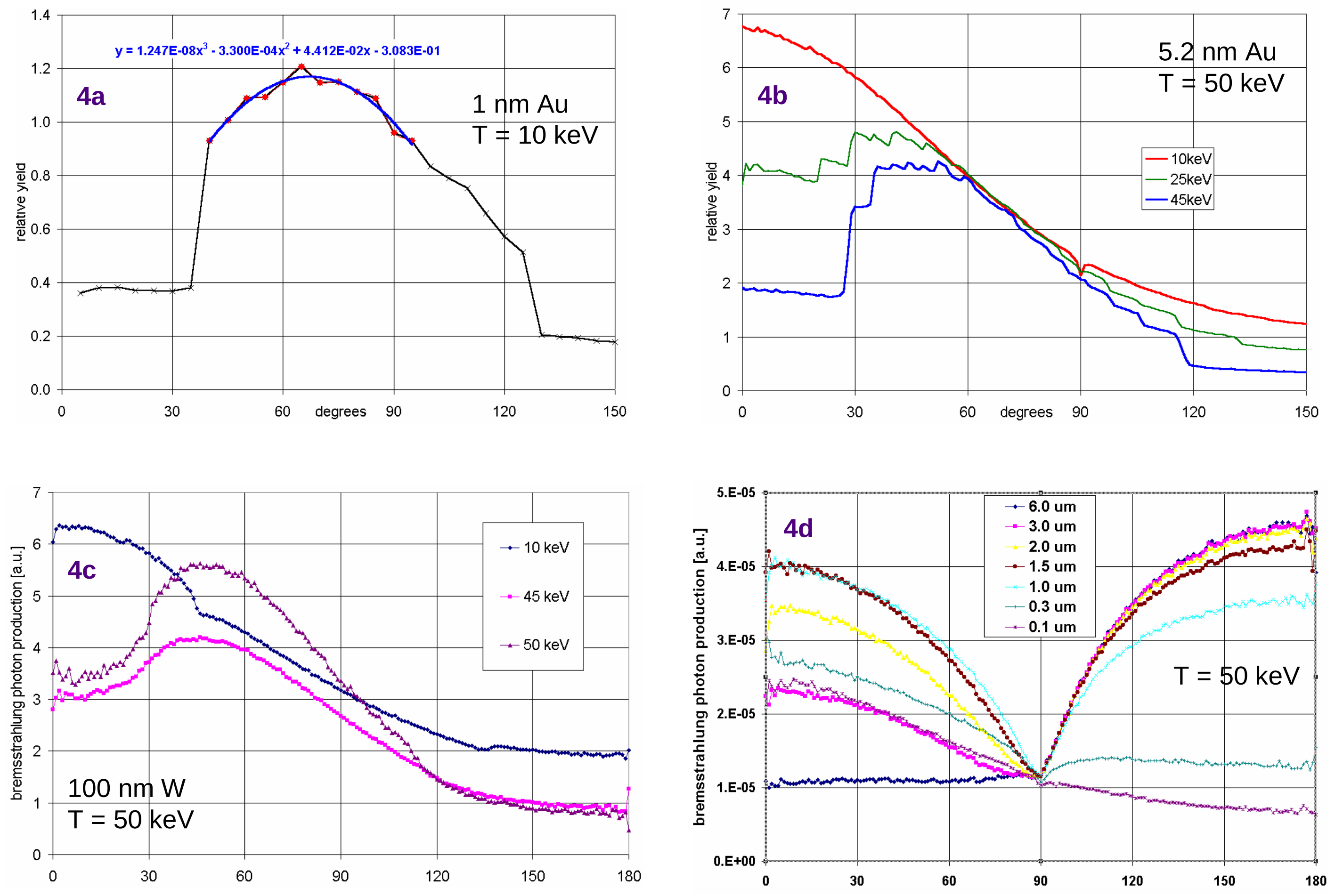


Fig. 3

Figure 3. MCNP5 calculations were compared with measured results from Cosslett and Dyson. The relativistically-corrected bremsstrahlung anisotropy for 8, 10, and 12 kV electrons bombarding a gold target are illustrated. The $0.78\nu_0$ curve, corresponding to the 10 kV high-energy limit, has a maximum (1.13) occurring at 65°. This agrees well with the calculated (RHS) maximum of 1.17 ± 0.08 at 67°. Though measurements were corrected for electron absorption, differences between measured and calculated forward direction (0°) results are attributed to the thick (electron-opaque, ~ 1 μm) Au target, while a thin (1.0 nm) Au target was used in the simulations to glean a more fundamental understanding of the MCNP bremsstrahlung handling.



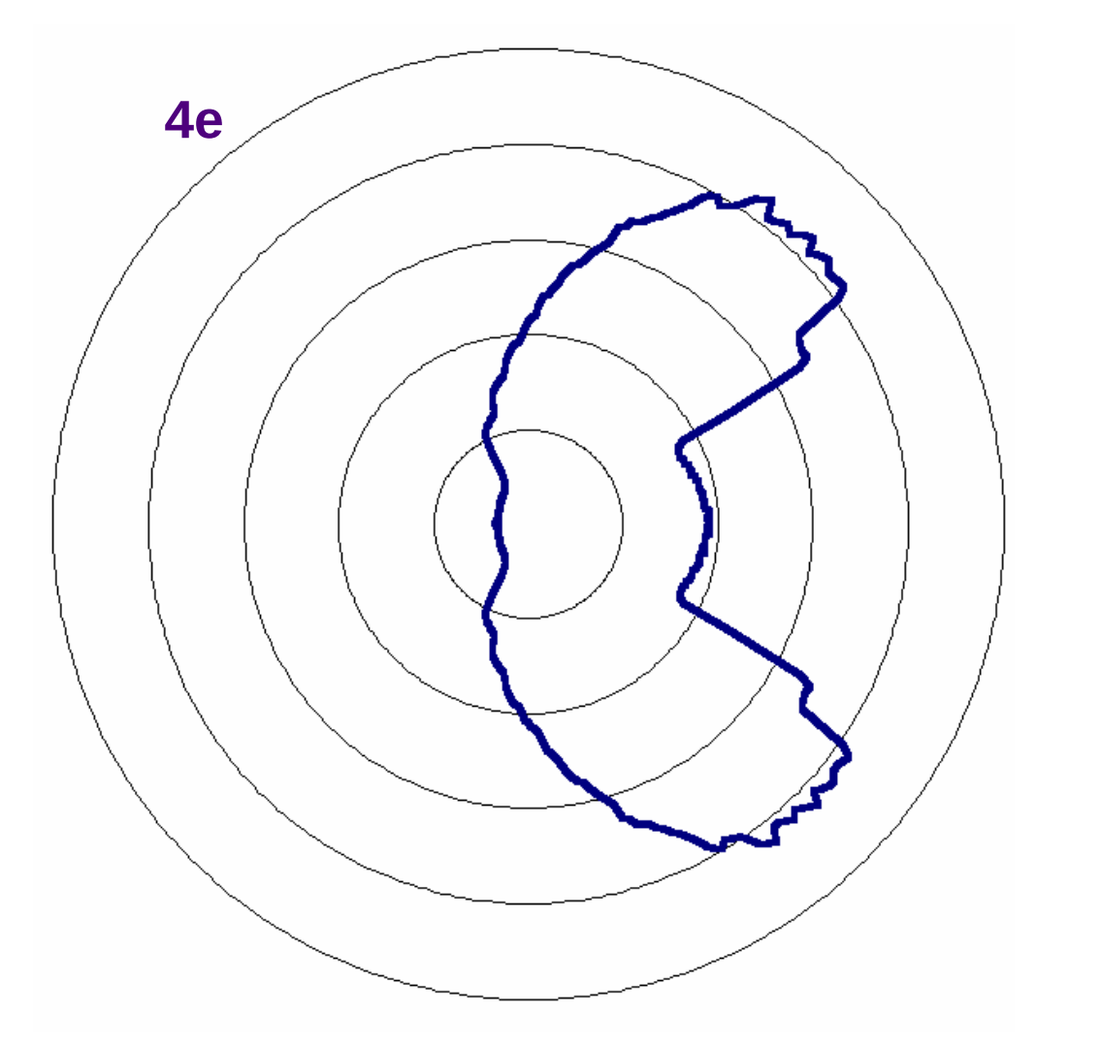


Fig. 4 Going clockwise from the right are calculated bremsstrahlung photon yields for a variety of target materials, thicknesses, and electron impingement energies. First are results directly comparable to **Fig. 2e** (5.2 nm Au with T = 50 keV). Comparing the peaks for 45 keV (0.9 ν_0), both give a max ratio at 50° of 1.8 ± 0.2. The next graph is for T = 50 keV and a 100 nm W target tilted at 45° like **Fig. 2a**. For 0.9 and 1.0 ν_0, the peaks occur at 45° and 50° with values of 1.6 and 1.7, respectively. The lower right graph shows the impact of target thickness on angular emission of bremsstrahlung photons for T = 50 keV on W. In the forward direction, $\theta < 90^o$, photon emissions peak for t ~ 1 μm. In the backward direction, $\theta > 90^o$, photon emissions level off for t > 2 μm. The graph below depicts a "radar" plot of T = 50 keV and 0.9 ν_0 from **Fig. 4a**. Visually, there is good agreement with **Fig. 2e** but the data exhibit structure indicative of the finite bin width used in MCNP physics libraries for modeling bremsstrahlung photon emissions.

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SUMMARY

- An extensive literature review covering over 50 years summarizes the state-of-the-art for simulating bremsstrahlung photon production near T = 50 keV.
- Reference measurements and calculations of bremsstrahlung photon production are in good agreement, and warrant usage of MCNP5 for simulating bremsstrahlung photon production for the Axxent™ electronic brachytherapy application.
- Simple tests of the MCNP physics evaluating normalized bremsstrahlung photon production in an angular context have shown good agreement with the published measured results of Motz and Placious, Dyson, and Doffin and Kuhlenkampff.
- Studies will be conducted to evaluate the simulated bremsstrahlung photon spectra in a manner similar to Ay, et al.
- Work is underway to compare the bremsstrahlung photon cross-section libraries with the MCNP output for simple, thin-film targets as a means to confirm proper execution of the MCNP simulations towards interpreting the accuracy of MCNP physics.
- For more information on related projects, please see Poster #380 at AAPM 2006, "Radiological Dependence of Electronic Brachytherapy Simulation on Input Parameters", M.J. Rivard, T.W. Rusch, and S. Axelrod.

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