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A Numerical Study of On-Axis Dose Rate from Ta and W Bremsstrahlung Converter Targets

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I. Introduction

The bremsstrahlung converter target in radiographic accelerators is not, in general, considered a high-technology piece of equipment. In its essential form it is merely a solid plate of high-Z metal, usually tungsten (W) or tantalum (Ta); electrons go in, X-rays come out [1]. However, there are some important factors to keep in mind for this kind of target system. One is a constraint on the target itself: the proper thickness of material. Too little material reduces the probability that an electron will have a significant nuclear collision before exiting the plate. Too much material has a number of effects: small-angle scattering will occur to such an extent that bremsstrahlung photons will not be pointed in the forward direction. Electrons which small-angle scatter away and then back to the forward direction will have moved to larger radii as they traverse the target, increasing the effective source size. Electrons "backscattered" from the target – primaries or secondaries ejected from the upstream surface after sufficient angular scatter – exert a defocusing force on the incoming beam due to increased space charge at fixed (or even slightly reduced) current. Finally, a sufficiently thick target will begin to self-attenuate the X-ray photons produced in the upstream portion of the plate.

A second constraint is obvious but is harder to accommodate when designing a radiographic accelerator system. The angular distribution of the incoming electron beam will change the forward dose. Just as electrons which have undergone small-angle scatter will no longer produce forward dose, electrons which have large angles before they ever enter the target cannot produce forward dose. Accurate prediction of dose requires incorporating the effect of the initial angle of the electron coming into the target material. The further step of controlling the angular distribution – which means keeping it as close to zero as possible – is difficult since it tends to drive important beam parameters in directions we do not want (large spot size) or cannot achieve (very low emittance).

In this report we characterize the bremsstrahlung performance of Ta and W converter targets over a range of electron energies (2-20 MeV) and angles. The studies are all performed with the MCNP radiation transport code [2], version 4b. A number of steps are involved in the process. First, we must construct the absorption properties of air given photons of various energies, so that the distribution of photons produced by the incoming electrons can be converted into a dose rate as commonly used in radiography. Then we study the dose rate of various electron energies in Ta and W, as a function of target thickness, and find that there is an optimum for a given energy. Following that, we describe how to incorporate angular dependence in the (rather obtuse) MCNP interface, and then study how the dose rate varies with the distribution of incoming angles. The major results and useful curve fits are summarized at the end. The appendix contains listings of useful scripts and MCNP templates.

This report does not address the backscattered electron issue [3]. That problem is complex because it requires self-consistent treatment of the electrons in the external electric fields once they are ejected from the target. Suffice it to say that a thicker target produces more backscatter and therefore more defocusing. When choosing a target thickness, rather than selecting from the peak output given below, one may prefer to choose a (usually much thinner) target corresponding to the 95% output level, or even lower as desired. Of course, a target which must withstand multiple beam pulses has constraints driving the thickness in the opposite direction, in order to maintain sufficient line density during the hydrodynamic evolution of the material.

II. A Comment on Units

The figure of merit for the strength of a radiographic source is “dose,” which can be given in a variety of units but the most common one in the community today is the *rad*. One rad is defined as 100 ergs deposited into one gram of a specified material; giving a number of rads without also naming the material is not meaningful. The standard used here is rads in air – even though transmission radiography is generally used to study materials quite different in character.

More specifically, the quantities given herein will be dose *rates* in units of rads per nanosecond, measured at a location one meter from the converter target, along the trajectory of the electron beam (the “radiographic axis.”), and assuming a beam current of 2 kA. The dose rate is linear in beam current and so is easily scaled to other values. Since the outgoing photons have a finite angular distribution, the dose rate will also have a typical $1/r^2$ dependence with distance. We have chosen the above convention since quoting dose rates per kA per steradian, or something similar, quickly becomes tiring.

Finally, as detailed below, the conversion of the “absolute” quantities output by MCNP (number of photons in a certain energy range) to dose rate in air is done by simulating the properties of air. This conversion has not been validated experimentally; I am relying on the many years of usage and testing that MCNP has undergone by others.

II. Simulated Absorption Characteristics of Air

The most physical quantity involved in radiation transport is the cross section of a target particle, given a certain incoming particle, for a particular reaction. A “certain incoming particle” is very specific – not just an electron, say, but an electron of a particular energy coming in with a particular direction with respect to a reference. Likewise for the reaction – not just production of a photon, but a photon of a specific energy going out with a specific direction with respect to a reference. Also likewise for the target particle, but in this case the target particles are treated as cold (motionless). Since both the incoming and outgoing parameters are continuous (as opposed to being interested in a discrete set of energies or angles), the cross section is differential – an area per unit incoming energy, per unit incoming angle, per unit outgoing energy, per unit outgoing angle, etc. MCNP uses Monte Carlo techniques to build up a discretization of the differential cross section. (Since it tracks individual particles impinging on finite-sized volumes of material, the output is expressed as a fractional occurrence per input particle rather than as a cross section.)

Thus, given an input spectrum (over energy, position, and angle) of electrons, the output is a spectrum of photons. To convert that to a dose rate in air, we need to know the absorption properties of air given photons of various energies. MCNP can be used in turn to provide that information. Conceptually, we build it up as follows: Suppose we start with a photon with an energy E_γ. We transport that photon through a certain column length L of air at density ρ and use MCNP's energy deposition model (we do not consider any of the physics of this model here) to determine how much is absorbed, $E_{abs}(E_\gamma,\rho,L)$.

To use this in a dose rate calculation, start with the output from an MCNP detector placed on the radiographic axis one meter from the target. This will report the number of photons per unit area, produced per source electron: $N_\gamma/(\text{Area-}e^-)$. It can also be energy-resolved (at least approximately via discrete binning) into a distribution, $N_\gamma(E)/(\text{Area-}e^-)$, where the energy is in units of MeV; this can be converted "by hand" to a dose rate given the instantaneous beam current I:

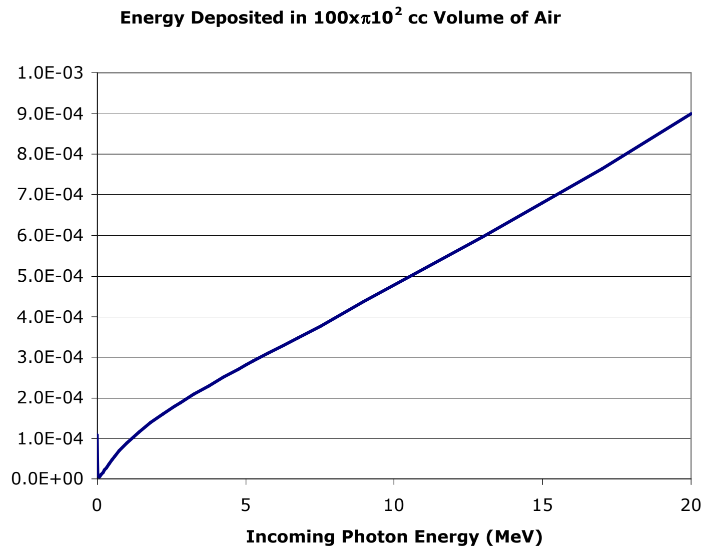
$$\frac{dD}{dt} = \int_0^\infty dE_{e^-} \int_0^\infty dE_\gamma \frac{10^6 10^5 10^{-9} q \frac{dN}{dE_\gamma dA}(E_\gamma; E_{e^-}) \frac{dI}{dE_{e^-}}(E_{e^-}) E_{abs}(E_\gamma, \rho, L)}{q\rho L}$$

The form as written includes an extra integration to allow for a distribution of beam energies (which in the case of radiographic accelerators is not needed since the instantaneous current is essentially monoenergetic – even if that energy is varying with *time*). The factors of q in the numerator and denominator cancel, but were left in explicitly because they come from two different sources. The factor in the numerator converts eV to Joules; the factor in the denominator converts the differential beam current dI from coulombs per second to electrons per second. The numerical factors in the numerator obviously combine to 10^2 but were left distinct for clarity: 10^6 to convert MeV to eV, 10^{-9} to convert electrons per second to electrons per ns, and 10^5 to convert Joules to units of 100 ergs. The differential area dA in the photon number flux is per square centimeter, L is in cm, and ρ is in grams per cm^3. The result comes out in rads per ns.

The calculation of E_{abs} is done by injecting monoenergetic photons into a cylinder of air that is 100 cm long and 10 cm in radius. The output is done using an F6 MCNP tally, which gives energy deposition averaged over a cell, in units of MeV/g. The "air" in the volume is 78.45% N, 21.09% O, and 0.46% Ar by atomic fraction, with density 1.225 g/cc. A table and plot of the results of simulations in the range 0.01-20 MeV is given below.

Included in the table is the converted value that would be used directly in an MCNP dose function (DF) card modifying a detector (F5), eliminating the "by hand" process. The conversion is $2\pi \times 10^7$, which is composed of 2000 for a beam current of 2 kA, a factor of 10^2 as described above, and a factor of $\pi(10\text{ cm})^2$, which is the cylinder area, to convert the energy per gram from the F6 tally to energy per (density times length). Note that this data assumes nothing about the location of the detector – it can be used in other modeling to produce dose rates at something other than one meter from the target. A sample MCNP input file is given in the appendix.

Photon E (MeV)	MeV/g	(rad/ns)/(detector flux [phot/(e-cm^2)])
0.01	1.09E-04	6.85E+03
0.03	1.31E-05	8.23E+02
0.05	6.01E-06	3.78E+02
0.07	5.66E-06	3.56E+02
0.1	7.29E-06	4.58E+02
0.15	1.18E-05	7.41E+02
0.2	1.69E-05	1.06E+03
0.25	2.20E-05	1.38E+03
0.3	2.73E-05	1.72E+03
0.4	3.74E-05	2.35E+03
0.5	4.71E-05	2.96E+03
0.6	5.63E-05	3.54E+03
0.75	6.91E-05	4.34E+03
1	8.87E-05	5.57E+03
1.4	1.15E-04	7.23E+03
1.8	1.39E-04	8.73E+03
2.2	1.60E-04	1.01E+04
2.6	1.79E-04	1.12E+04
2.8	1.88E-04	1.18E+04
3.25	2.09E-04	1.31E+04
3.75	2.30E-04	1.45E+04
4.25	2.51E-04	1.58E+04
4.75	2.71E-04	1.70E+04
5	2.82E-04	1.77E+04
5.25	2.91E-04	1.83E+04
5.75	3.10E-04	1.95E+04
6.25	3.29E-04	2.07E+04
6.75	3.48E-04	2.19E+04
7.5	3.77E-04	2.37E+04
9	4.37E-04	2.75E+04
11	5.17E-04	3.25E+04
13	5.96E-04	3.74E+04
15	6.79E-04	4.27E+04
17	7.64E-04	4.80E+04
20	9.00E-04	5.65E+04



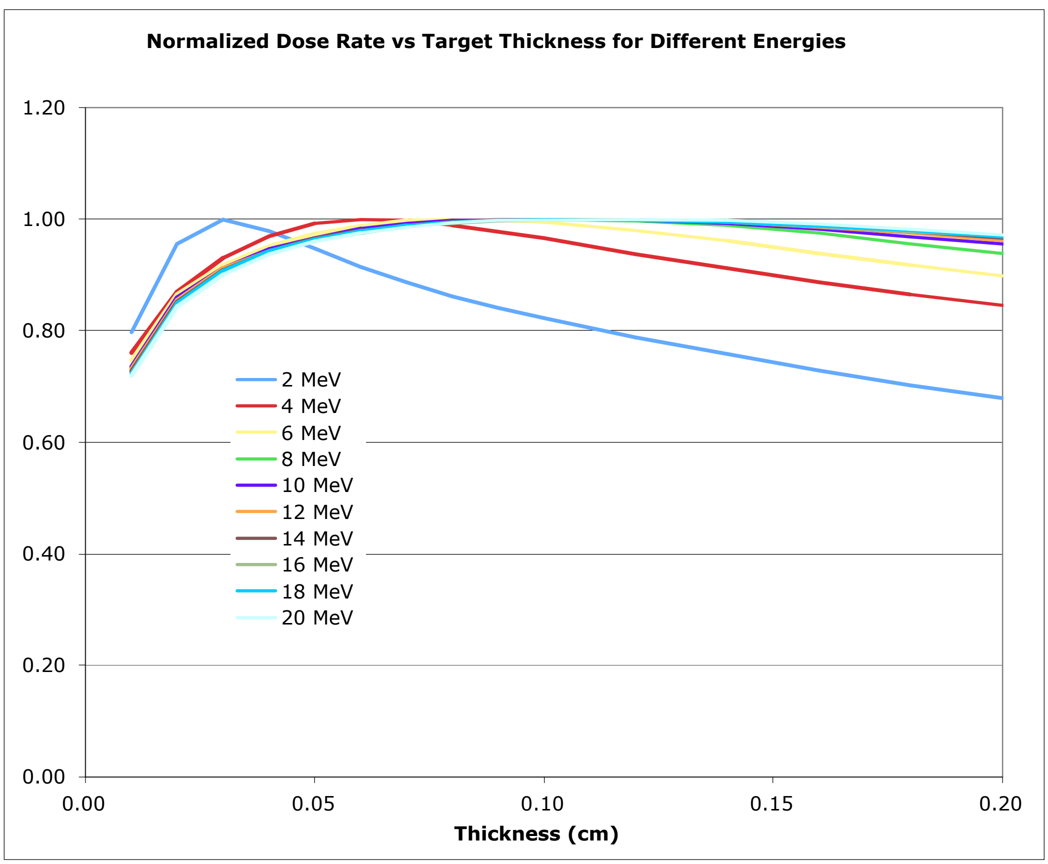
III. Dose rate vs. energy for various target thicknesses – Ta

The dose calibration from the previous section can now be used in actual bremsstrahlung studies of electrons impinging on a given target. The first question to address when choosing a target is the desired thickness given the beam energy. A batch of MCNP runs have been performed to look at the dose rate of various electron energies (in the range 2-20 MeV) and various target thicknesses (up to 2 mm) for Ta. This set of calculations assumes the electrons are all cold, i.e., all parallel to the axis and normal to the target surface.

A sequence of steps is required to do this large number of runs efficiently. First, a single MCNP input file is written as a template. The problem consists of electrons starting just off the upstream surface of a Ta plate. One meter downstream, on axis, is a photon point detector modified by a dose function as described previously. A UNIX tcsh script is used in conjunction with awk to generate all the input files based on the template. The awk program parses the template and sets the desired electron energy and target thickness; the shell script calls awk repeatedly with a set of energy and thickness values. Another shell script runs all the thicknesses at a given energy in sequence, deleting the large restart files as it goes. Finally, another shell script/awk program pairing extracts the dose rate from the rather verbose MCNP output files. The following tables show the results.

Tantalum	E (MeV)	These are dose rates in rad/ns in air for a beam current of 2 kA			
d (cm)	2	4	6	8	10
1.00E-02	1.378E-02	8.559E-02	2.721E-01	5.877E-01	1.153E+00
2.00E-02	1.652E-02	9.794E-02	3.151E-01	6.835E-01	1.347E+00
3.00E-02	1.728E-02	1.047E-01	3.344E-01	7.257E-01	1.429E+00
4.00E-02	1.691E-02	1.092E-01	3.468E-01	7.548E-01	1.484E+00
5.00E-02	1.637E-02	1.117E-01	3.547E-01	7.710E-01	1.515E+00
6.00E-02	1.579E-02	1.126E-01	3.597E-01	7.819E-01	1.542E+00
7.00E-02	1.532E-02	1.123E-01	3.638E-01	7.921E-01	1.556E+00
8.00E-02	1.490E-02	1.114E-01	3.642E-01	7.963E-01	1.564E+00
9.00E-02	1.453E-02	1.101E-01	3.638E-01	8.005E-01	1.566E+00
1.00E-01	1.421E-02	1.087E-01	3.622E-01	8.018E-01	1.568E+00
1.20E-01	1.362E-02	1.055E-01	3.567E-01	7.988E-01	1.566E+00
1.40E-01	1.310E-02	1.026E-01	3.499E-01	7.922E-01	1.555E+00
1.60E-01	1.259E-02	9.982E-02	3.419E-01	7.815E-01	1.540E+00
1.80E-01	1.213E-02	9.742E-02	3.344E-01	7.657E-01	1.518E+00
2.00E-01	1.173E-02	9.516E-02	3.271E-01	7.521E-01	1.499E+00
Peak:	1.73E-02	1.13E-01	3.64E-01	8.02E-01	1.57E+00
Thickness at peak (mm):	0.30	0.60	0.80	1.00	1.00
Thickness at 95% (mm):	0.20	0.35	0.40	0.45	0.45

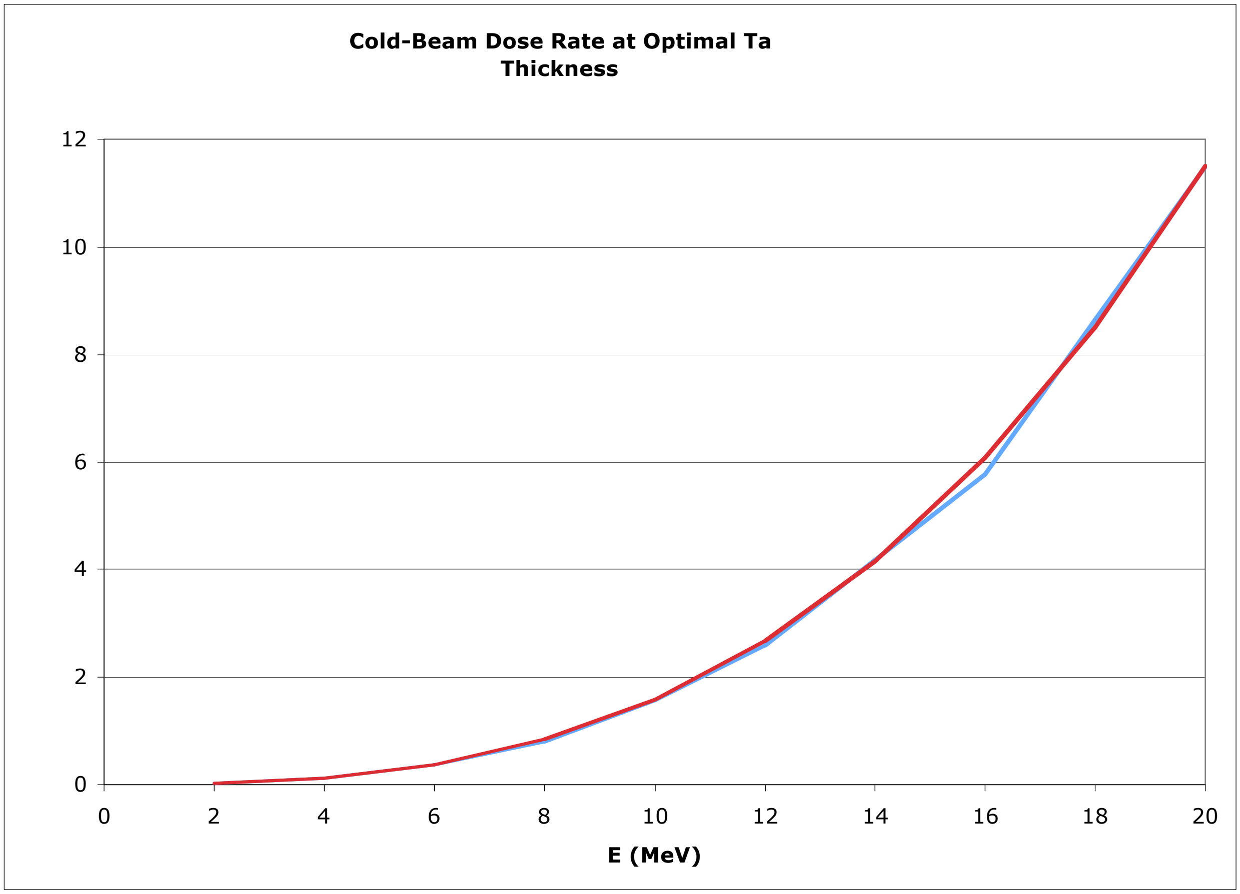
Tantalum	E (MeV)	These are dose rates in rad/ns in air for a beam current of 2 kA			
d (cm)	12	14	16	18	20
1.00E-02	1.895E+00	3.029E+00	4.172E+00	6.258E+00	8.272E+00
2.00E-02	2.213E+00	3.545E+00	4.892E+00	7.345E+00	9.690E+00
3.00E-02	2.360E+00	3.781E+00	5.209E+00	7.854E+00	1.035E+01
4.00E-02	2.440E+00	3.926E+00	5.408E+00	8.154E+00	1.076E+01
5.00E-02	2.497E+00	4.024E+00	5.542E+00	8.343E+00	1.103E+01
6.00E-02	2.536E+00	4.079E+00	5.619E+00	8.467E+00	1.121E+01
7.00E-02	2.556E+00	4.119E+00	5.689E+00	8.558E+00	1.132E+01
8.00E-02	2.572E+00	4.146E+00	5.713E+00	8.608E+00	1.141E+01
9.00E-02	2.584E+00	4.164E+00	5.739E+00	8.640E+00	1.146E+01
1.00E-01	2.588E+00	4.164E+00	5.750E+00	8.655E+00	1.147E+01
1.20E-01	2.589E+00	4.158E+00	5.760E+00	8.649E+00	1.149E+01
1.40E-01	2.573E+00	4.139E+00	5.727E+00	8.611E+00	1.147E+01
1.60E-01	2.550E+00	4.109E+00	5.681E+00	8.550E+00	1.139E+01
1.80E-01	2.523E+00	4.067E+00	5.631E+00	8.476E+00	1.128E+01
2.00E-01	2.490E+00	4.023E+00	5.580E+00	8.380E+00	1.116E+01
Peak:	2.59E+00	4.16E+00	5.76E+00	8.66E+00	1.15E+01
Thickness at peak (mm):	1.10	0.95	1.20	1.00	1.20
Thickness at 95% (mm):	0.45	0.45	0.45	0.45	0.45



Another plot of interest is the dose rate at the optimal thickness, which is given below. Note that a very good fit to the data is given by

$$\frac{dD}{dt} = 11.5(\frac{E}{20})^{2.86}$$

where E is in MeV. This is the red curve in the figure.

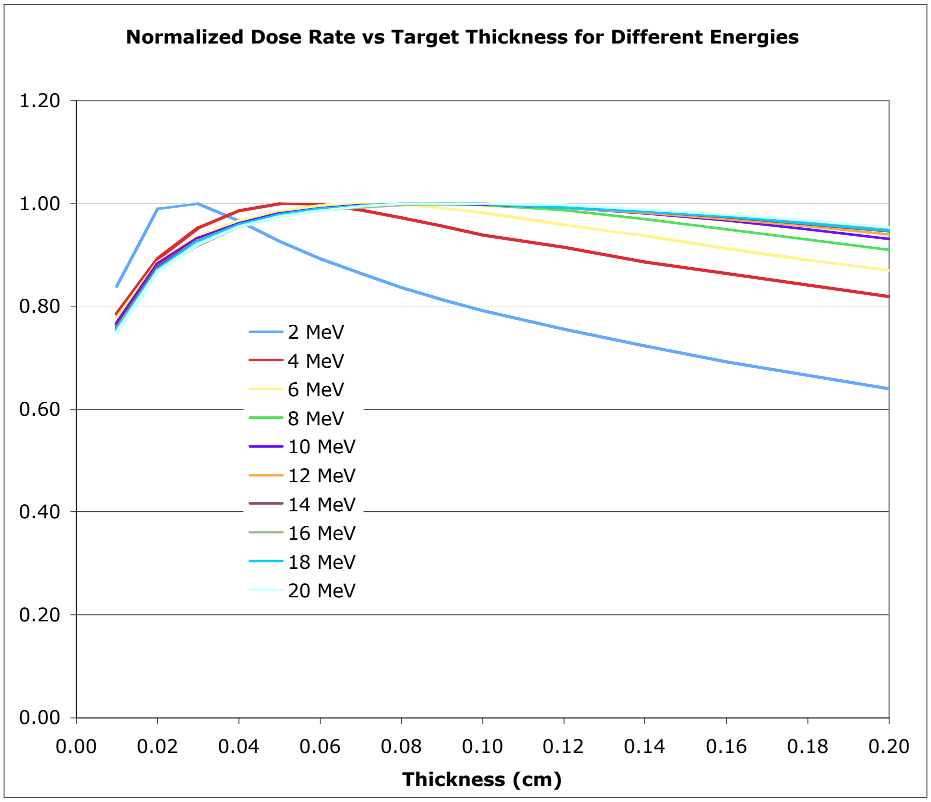


IV. Dose rate vs. energy for various target thicknesses – W

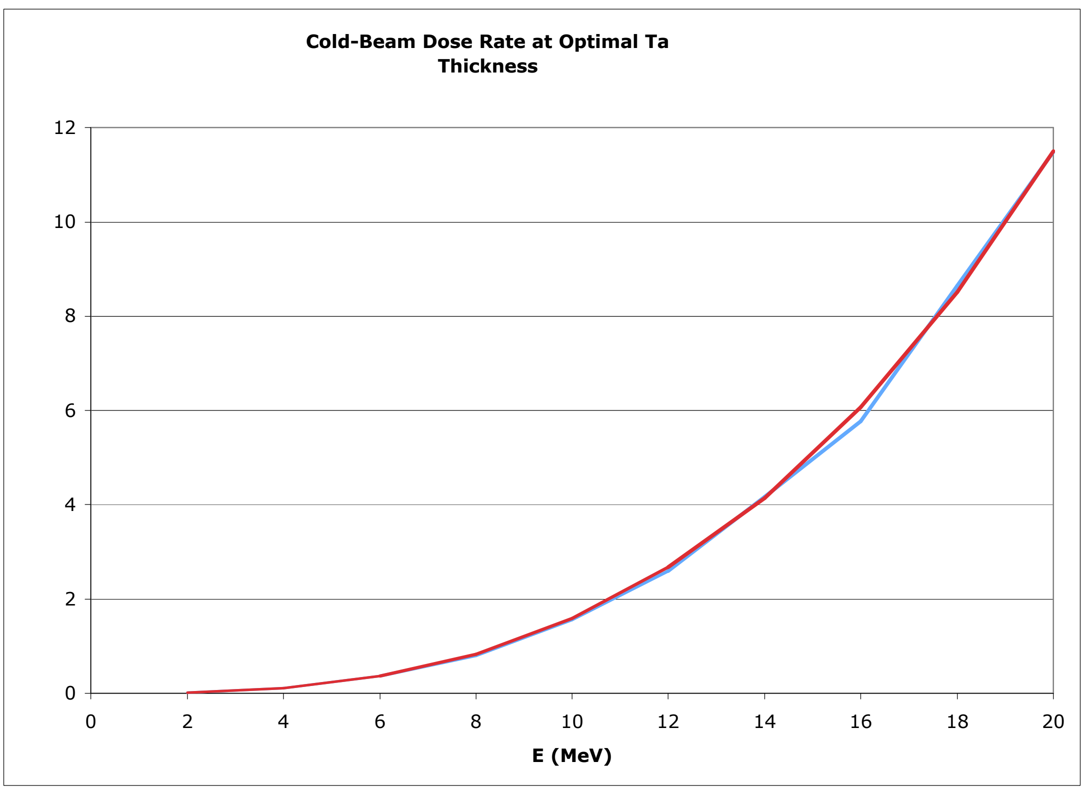
The same process can be repeated for W. The optimal rates are not significantly different.

Tantalum	E (MeV)	These are dose rates in rad/ns in air for a beam current of 2 kA			
d (cm)	2	4	6	8	10
1.00E-02	1.440E-02	8.866E-02	2.833E-01	6.100E-01	1.199E+00
2.00E-02	1.699E-02	1.008E-01	3.228E-01	6.977E-01	1.382E+00
3.00E-02	1.717E-02	1.076E-01	3.419E-01	7.403E-01	1.459E+00
4.00E-02	1.660E-02	1.113E-01	3.528E-01	7.654E-01	1.505E+00
5.00E-02	1.590E-02	1.129E-01	3.592E-01	7.801E-01	1.535E+00
6.00E-02	1.533E-02	1.127E-01	3.632E-01	7.895E-01	1.551E+00
7.00E-02	1.484E-02	1.114E-01	3.649E-01	7.957E-01	1.560E+00
8.00E-02	1.437E-02	1.098E-01	3.643E-01	7.985E-01	1.562E+00
9.00E-02	1.396E-02	1.079E-01	3.613E-01	7.972E-01	1.565E+00
1.00E-01	1.359E-02	1.060E-01	3.582E-01	7.961E-01	1.563E+00
1.20E-01	1.297E-02	1.033E-01	3.497E-01	7.882E-01	1.554E+00
1.40E-01	1.241E-02	1.001E-01	3.421E-01	7.741E-01	1.535E+00
1.60E-01	1.189E-02	9.752E-02	3.330E-01	7.587E-01	1.514E+00
1.80E-01	1.144E-02	9.498E-02	3.250E-01	7.429E-01	1.486E+00
2.00E-01	1.098E-02	9.252E-02	3.176E-01	7.272E-01	1.458E+00
Peak:	1.72E-02	1.13E-01	3.65E-01	7.99E-01	1.57E+00
Thickness at peak (mm):	0.30	0.50	0.70	0.80	0.90
Thickness at 95% (mm):	0.17	0.30	0.35	0.36	0.36

Tantalum	E (MeV)	These are dose rates in rad/ns in air for a beam current of 2 kA			
d (cm)	12	14	16	18	20
1.00E-02	1.966E+00	3.162E+00	4.365E+00	6.502E+00	8.618E+00
2.00E-02	2.273E+00	3.645E+00	5.034E+00	7.534E+00	9.968E+00
3.00E-02	2.406E+00	3.852E+00	5.311E+00	8.009E+00	1.059E+01
4.00E-02	2.486E+00	3.987E+00	5.513E+00	8.282E+00	1.097E+01
5.00E-02	2.533E+00	4.065E+00	5.626E+00	8.456E+00	1.120E+01
6.00E-02	2.559E+00	4.114E+00	5.701E+00	8.553E+00	1.133E+01
7.00E-02	2.578E+00	4.139E+00	5.730E+00	8.610E+00	1.143E+01
8.00E-02	2.587E+00	4.157E+00	5.760E+00	8.638E+00	1.148E+01
9.00E-02	2.594E+00	4.160E+00	5.767E+00	8.643E+00	1.149E+01
1.00E-01	2.593E+00	4.156E+00	5.775E+00	8.634E+00	1.149E+01
1.20E-01	2.575E+00	4.140E+00	5.745E+00	8.577E+00	1.146E+01
1.40E-01	2.549E+00	4.098E+00	5.701E+00	8.508E+00	1.136E+01
1.60E-01	2.516E+00	4.048E+00	5.637E+00	8.420E+00	1.124E+01
1.80E-01	2.479E+00	3.995E+00	5.570E+00	8.306E+00	1.112E+01
2.00E-01	2.440E+00	3.935E+00	5.489E+00	8.183E+00	1.096E+01
Peak:	2.59E+00	4.16E+00	5.78E+00	8.64E+00	1.15E+01
Thickness at peak (mm):	0.95	0.90	1.00	0.90	0.95
Thickness at 95% (mm):	0.38	0.38	0.40	0.38	0.40



Normalized Dose Rate vs Target Thickness for Different Energies
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20
Thickness (cm)
2 MeV
4 MeV
6 MeV
8 MeV
10 MeV
12 MeV
14 MeV
16 MeV
18 MeV
20 MeV



Cold-Beam Dose Rate at Optimal Ta Thickness
12
10
8
6
4
2
0
0 2 4 6 8 10 12 14 16 18 20
E (MeV)

V. Including angular dependence in MCNP

MCNP version 4b is a radiation transport code, not a beam physics code. The facilities for describing the source particles have some difficult constraints when it comes to easily describing something like the phase space of a finite-emittance electron beam. With suitable machinations, however, it is possible to describe an azimuthally symmetric Gaussian beam with finite emittance, provided that beam starts at a waist.

For starters, let us consider the constraints. User access to the distribution from which particles are drawn is characterized by the following:

- Access to the X, Y, Z coordinates;
- Access to a radial coordinate R with respect to a specified cylindrical axis, but not to the azimuthal coordinate (ϕ);
- The particle direction is specified relative to a local reference; you can supply a distribution in $\mu=\cos(\theta)$ where θ is the polar angle, but it must be uniform in ϕ, the azimuth
- Individual variables can be correlated to one, but only one, other variable.

What are the requirements for an emittance-dominated Gaussian beam? We would like it to satisfy the RMS envelope equation,

$$\ddot{R}_{rms} = \frac{\epsilon_{rms}^2}{R_{rms}^3}$$

which has solution

$$R_{rms}^2 = R_{o,rms}^2 + \frac{\epsilon_{rms}^2}{R_{o,rms}^2}(z - z_o)^2$$

where $R_{o,rms}$ is the waist size at $z=z_o$. For a Gaussian profile, $\sigma=R_{rms}$, so the current density should have the form

$$J(r,z) = \frac{I}{\pi(\sigma_o^2 + \frac{\epsilon_{rms}^2}{\sigma_o^2}(z - z_o)^2)} exp(-\frac{r^2}{\sigma_o^2 + \frac{\epsilon_{rms}^2}{\sigma_o^2}(z - z_o)^2})$$

We find a distribution function that fits this form by guessing. Suppose we have a waist, $\sigma = \sigma_o$, at $z=z_o$, described by

$$f_o(x_o, y_o, x'_o, y'_o) = \frac{I}{\pi^2 \sigma_o^2 \alpha^2} exp(-\frac{x_o^2 + y_o^2}{\sigma_o^2}) exp(-\frac{x_o'^2 + y_o'^2}{\alpha^2})$$

The Vlasov equation for a force-free beam solves trivially to

$$f(x, y, x', y', z) = f_o(x_o = x - x'(z - z_o), y_o = y - y'(z - z_o), x'_o = x', y'_o = y')$$

which in our case gives

$$f = \frac{I}{\pi^2\sigma_o^2\alpha^2} exp(-\frac{x^2+y^2}{\sigma_o^2}) exp(\frac{2(z-z_o)}{\sigma_o^2}(xx'+yy') - (x'^2+y'^2)(\frac{1}{\alpha^2}+\frac{(z-z_o)^2}{\sigma_o^2}))$$

Calculating the current density

$$J = \int\int f dx'dy' = \frac{I}{\pi(\sigma_o^2+\alpha^2(z-z_o)^2)} exp(-\frac{r^2}{\sigma_o^2+\alpha^2(z-z_o)^2})$$

gives a match to the required profile if $\alpha=\varepsilon/\sigma_o$.

Unfortunately, this form still does not conform to the MCNP constraints. It is not clear whether the (x',y') dependence is azimuthally symmetric about a local reference. At arbitrary z, (x',y') are coupled to (x,y). Since we do have access to a radial coordinate in symmetric cases, we can reduce the spatial dependence to a single variable:

$$f = \frac{I}{\pi^2\epsilon^2} exp(-\frac{r^2}{\sigma_o^2}) exp[\frac{2(z-z_o)}{\sigma_o^2} rr' - (x'^2+y'^2)(\frac{\sigma_o^2}{\epsilon^2} + \frac{(z-z_o)^2}{\sigma_o^2})]$$

However, the directional dependence is still coupled to the spatial dependence since the unit vector associated with r' is dependent on position. The only way around that is to always start at a waist, $z=z_o$:

$$f = \frac{I}{\pi^2\epsilon^2} exp(-\frac{r^2}{\sigma_o^2}) exp(-\frac{\sigma_o^2(x'^2+y'^2)}{\epsilon^2})$$

If the beam starts from a planar surface, the reference direction $\mathbf{e}_{ref}$ is not a function of space: $\mathbf{e}_{ref} = \mathbf{e}_z$. The direction vector of a particle with x' and y' is

$$\hat{e}_p = \frac{x'\hat{e}_x + y'\hat{e}_y + \hat{e}_z}{\sqrt{1+x'^2+y'^2}}$$

so that μ is given by

$$\mu = \hat{e}_{ref} \cdot \hat{e}_p = \frac{1}{\sqrt{1+x'^2+y'^2}}$$

and $\tan(\phi)$ by y'/x'. These relations can be inverted,

$$x' = cos\phi\sqrt{\frac{1}{\mu^2}-1}, y' = sin\phi\sqrt{\frac{1}{\mu^2}-1}$$

and it follows that the Jacobian determinant gives

$$dx'dy' = \frac{1}{\mu^3} d\mu d\phi$$

The final answer is that a Gaussian beam of RMS waist size σ_o and RMS emittance ε can be generated by the distribution function

$$f dx dy dx' dy' = \frac{I}{\pi^2 \epsilon^2} exp(-\frac{r^2}{\sigma_o^2}) exp[-\frac{\sigma_o^2}{\epsilon^2}(\frac{1}{\mu^2} - 1)] \frac{r}{\mu^3} dr d\theta d\mu d\phi$$

which is composed entirely of variables that MCNP understands, and the functional forms of the independent variables are not correlated. Note that the Jacobian factors (r/μ^3, etc) must be included (and in fact the above normalization may be off by various factors of π, but MCNP does not require a normalized distribution).

Finally, when it is desired to describe a distribution simply by the RMS angle of the distribution, θ_{rms}, rather than the combination of emittance and waist size (since the phase information is not always given at a waist), note that

$$\theta_{rms}^2 = \frac{\epsilon_{rms}^2}{\sigma_o^2}$$

This is useful in cases where the correlation in the distribution function between angle and position is not important, which is the case for a dose calculation that is not also a spot size calculation – the very cases considered below.

VI. Dose rate vs. RMS angle for various energies

The incoming angle of the electrons also plays a role in the dose rate. Ideally one would like to be able to put an exact beam phase space into MCNP in order to calculate a fully self-consistent dose rate and spot size; however, as indicated above, there is no easy way to put an arbitrary phase space into MCNP, at least as of version 4b. The next best option is to study the dose rate independent of the spot size; this can be done by starting all electrons at the same point but with a distribution in μ. This avoids the need to resolve correlations between position and angle that would be important for spot size.

While it is possible with reasonable effort to describe an arbitrary distribution in μ with the MCNP general source, it would be convenient to have a reference of some sort that gives "ballpark" numbers without requiring additional simulation. Therefore this section details results of a study assuming a Gaussian distribution, characterized by a width θ_{rms} which can be related to other known beam parameters as given above, or calculated directly from a distribution in a PIC simulation if the beam is not at a waist at the location of interest.

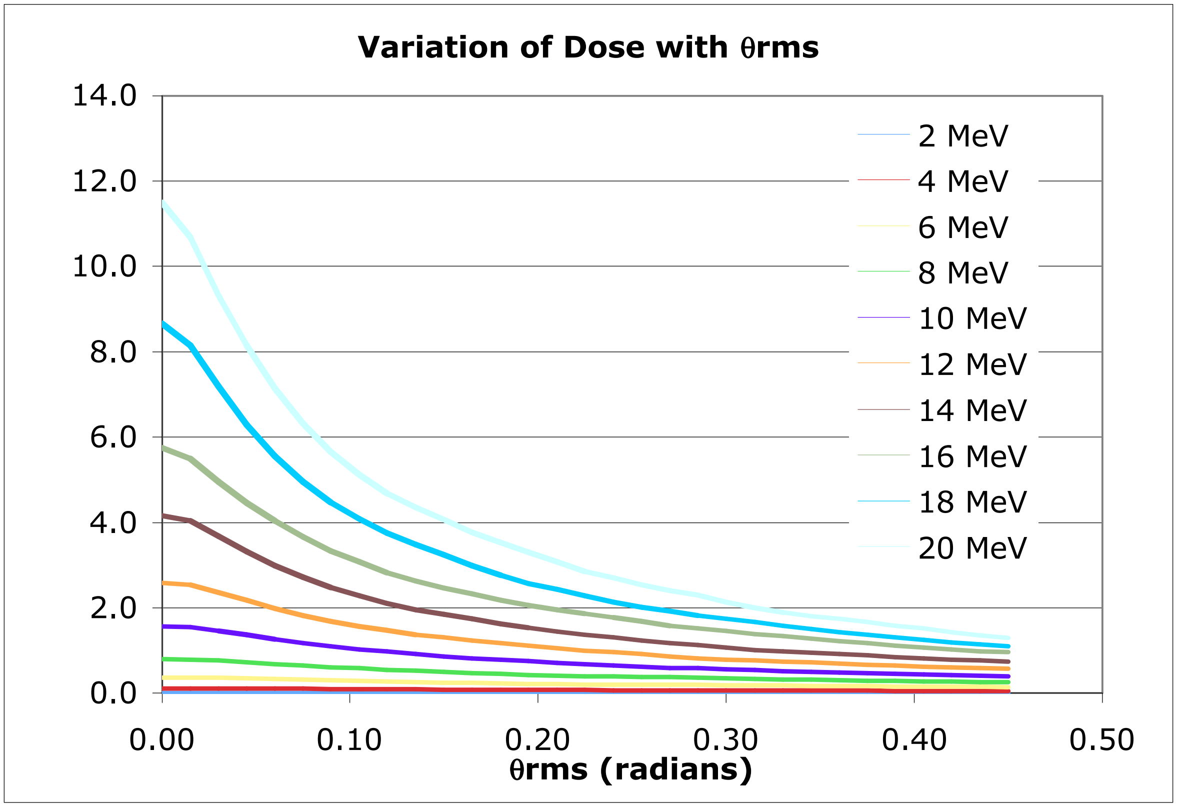
The study is done for energies in the range 2-20 MeV, using the optimal Ta target thickness for each energy, for values of θ_{rms} from 0 to 0.45 radians in increments of 15 milliradians. Note that this procedure must be modified if the system of interest is a beam with an energy sweep, which would be impinging on a *fixed* target thickness for all energies. An example of such a calculation is given at the end of this section.

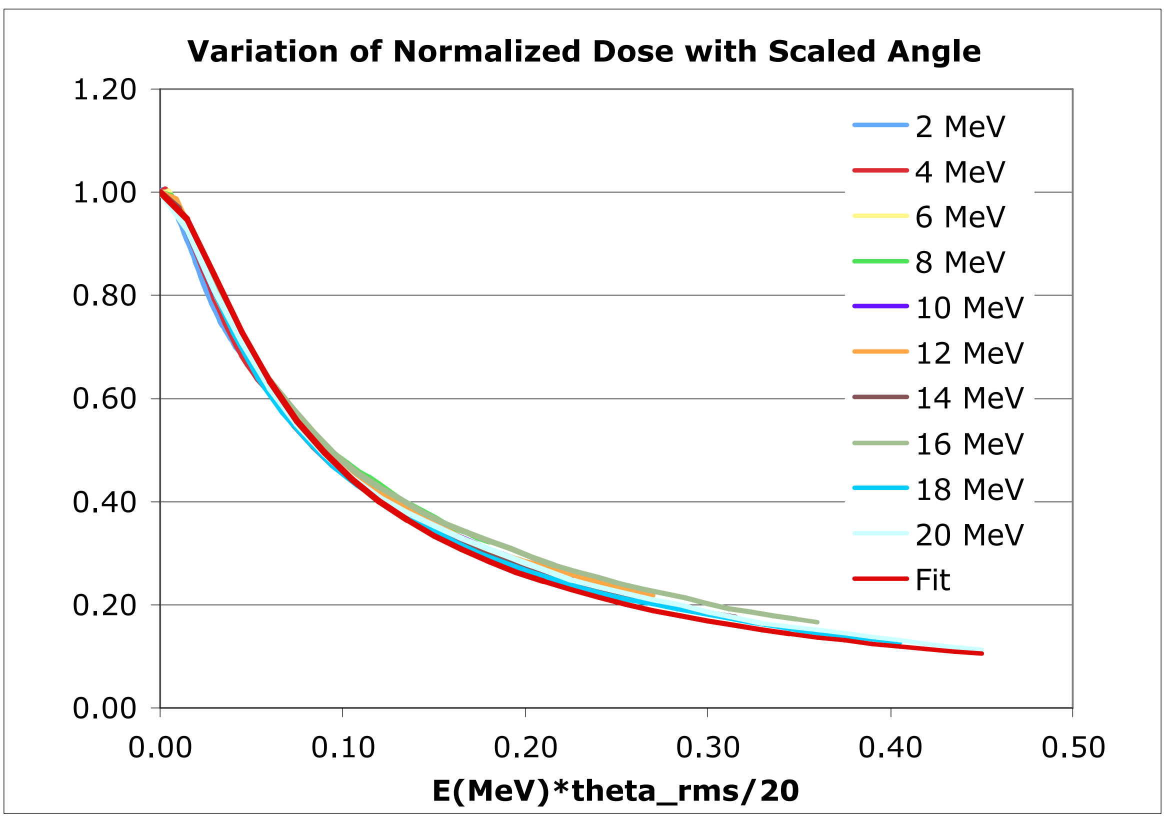
The procedure is similar to that for the target thickness studies. A shell script/awk program pair generates the input files; another script runs the cases; another script/awk pair parses the output.

Below is the data in tabular form, followed by plots.

angle (radians)					
Energy (MeV)	2	4	6	8	10
0.00E+00	1.728E-02	1.126E-01	3.642E-01	8.018E-01	1.568E+00
1.50E-02	1.736E-02	1.133E-01	3.647E-01	7.972E-01	1.541E+00
3.00E-02	1.732E-02	1.119E-01	3.556E-01	7.665E-01	1.457E+00
4.50E-02	1.719E-02	1.098E-01	3.442E-01	7.277E-01	1.361E+00
6.00E-02	1.708E-02	1.073E-01	3.309E-01	6.875E-01	1.265E+00
7.50E-02	1.690E-02	1.045E-01	3.164E-01	6.478E-01	1.179E+00
9.00E-02	1.684E-02	1.014E-01	3.026E-01	6.116E-01	1.101E+00
1.05E-01	1.639E-02	9.841E-02	2.899E-01	5.786E-01	1.032E+00
1.20E-01	1.617E-02	9.544E-02	2.776E-01	5.492E-01	9.727E-01
1.35E-01	1.593E-02	9.238E-02	2.656E-01	5.227E-01	9.195E-01
1.50E-01	1.570E-02	8.941E-02	2.548E-01	5.004E-01	8.704E-01
1.65E-01	1.546E-02	8.671E-02	2.447E-01	4.773E-01	8.271E-01
1.80E-01	1.523E-02	8.396E-02	2.355E-01	4.572E-01	7.881E-01
1.95E-01	1.498E-02	8.153E-02	2.272E-01	4.381E-01	7.523E-01
2.10E-01	1.472E-02	7.919E-02	2.197E-01	4.217E-01	7.163E-01
2.25E-01	1.446E-02	7.706E-02	2.127E-01	4.072E-01	6.847E-01
2.40E-01	1.423E-02	7.512E-02	2.057E-01	3.935E-01	6.554E-01
2.55E-01	1.400E-02	7.346E-02	1.998E-01	3.811E-01	6.279E-01
2.70E-01	1.377E-02	7.179E-02	1.946E-01	3.692E-01	6.023E-01
2.85E-01	1.356E-02	7.044E-02	1.893E-01	3.585E-01	5.790E-01
3.00E-01	1.338E-02	6.894E-02	1.843E-01	3.475E-01	5.563E-01
3.15E-01	1.320E-02	6.752E-02	1.794E-01	3.352E-01	5.373E-01
3.30E-01	1.299E-02	6.619E-02	1.747E-01	3.237E-01	5.195E-01
3.45E-01	1.282E-02	6.521E-02	1.699E-01	3.150E-01	5.005E-01
3.60E-01	1.268E-02	6.385E-02	1.655E-01	3.058E-01	4.820E-01
3.75E-01	1.252E-02	6.280E-02	1.611E-01	2.964E-01	4.679E-01
3.90E-01	1.238E-02	6.184E-02	1.571E-01	2.875E-01	4.529E-01
4.05E-01	1.223E-02	6.066E-02	1.534E-01	2.796E-01	4.397E-01
4.20E-01	1.209E-02	5.967E-02	1.499E-01	2.726E-01	4.264E-01
4.35E-01	1.195E-02	5.863E-02	1.466E-01	2.658E-01	4.133E-01
4.50E-01	1.181E-02	5.763E-02	1.435E-01	2.588E-01	4.001E-01

angle (radians)					
Energy (MeV)	12	14	16	18	20
0.00E+00	2.592E+00	4.164E+00	5.760E+00	8.655E+00	1.149E+01
1.50E-02	2.556E+00	4.035E+00	5.508E+00	8.129E+00	1.068E+01
3.00E-02	2.375E+00	3.684E+00	4.963E+00	7.183E+00	9.299E+00
4.50E-02	2.181E+00	3.324E+00	4.462E+00	6.298E+00	8.143E+00
6.00E-02	1.996E+00	2.998E+00	4.035E+00	5.556E+00	7.128E+00
7.50E-02	1.831E+00	2.719E+00	3.657E+00	4.962E+00	6.327E+00
9.00E-02	1.691E+00	2.484E+00	3.350E+00	4.486E+00	5.665E+00
1.05E-01	1.572E+00	2.280E+00	3.079E+00	4.082E+00	5.129E+00
1.20E-01	1.470E+00	2.109E+00	2.829E+00	3.756E+00	4.694E+00
1.35E-01	1.382E+00	1.965E+00	2.631E+00	3.485E+00	4.357E+00
1.50E-01	1.303E+00	1.852E+00	2.472E+00	3.239E+00	4.065E+00
1.65E-01	1.235E+00	1.739E+00	2.333E+00	3.001E+00	3.780E+00
1.80E-01	1.172E+00	1.632E+00	2.184E+00	2.774E+00	3.545E+00
1.95E-01	1.111E+00	1.536E+00	2.062E+00	2.579E+00	3.315E+00
2.10E-01	1.055E+00	1.450E+00	1.958E+00	2.433E+00	3.080E+00
2.25E-01	1.002E+00	1.375E+00	1.869E+00	2.286E+00	2.862E+00
2.40E-01	9.546E-01	1.305E+00	1.782E+00	2.152E+00	2.698E+00
2.55E-01	9.142E-01	1.243E+00	1.684E+00	2.021E+00	2.552E+00
2.70E-01	8.703E-01	1.185E+00	1.595E+00	1.921E+00	2.415E+00
2.85E-01	8.275E-01	1.124E+00	1.525E+00	1.821E+00	2.296E+00
3.00E-01	7.964E-01	1.070E+00	1.457E+00	1.750E+00	2.142E+00
3.15E-01	7.676E-01	1.021E+00	1.389E+00	1.671E+00	2.002E+00
3.30E-01	7.394E-01	9.837E-01	1.334E+00	1.588E+00	1.895E+00
3.45E-01	7.218E-01	9.524E-01	1.281E+00	1.508E+00	1.809E+00
3.60E-01	6.973E-01	9.228E-01	1.227E+00	1.439E+00	1.741E+00
3.75E-01	6.728E-01	8.888E-01	1.167E+00	1.373E+00	1.665E+00
3.90E-01	6.494E-01	8.559E-01	1.113E+00	1.308E+00	1.589E+00
4.05E-01	6.266E-01	8.238E-01	1.069E+00	1.247E+00	1.512E+00
4.20E-01	6.077E-01	7.928E-01	1.034E+00	1.195E+00	1.433E+00
4.35E-01	5.880E-01	7.616E-01	9.933E-01	1.143E+00	1.353E+00
4.50E-01	5.688E-01	7.348E-01	9.611E-01	1.101E+00	1.295E+00


Variation of Dose with θrms
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.00
0.10
0.20
0.30
0.40
0.50
θrms (radians)
2 MeV
4 MeV
6 MeV
8 MeV
10 MeV
12 MeV
14 MeV
16 MeV
18 MeV
20 MeV


Variation of Normalized Dose with Scaled Angle
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00
0.10
0.20
0.30
0.40
0.50
E(MeV)*theta_rms/20
2 MeV
4 MeV
6 MeV
8 MeV
10 MeV
12 MeV
14 MeV
16 MeV
18 MeV
20 MeV
Fit

Note that the curves for all energies are nearly self-similar when normalized to the peak dose for that energy and plotted versus a scaled variable x = $E\theta_{rms}/20$, where E is in MeV. The lower plot shows this scaled form, along with the following three-parameter fit:

$$\frac{D}{D_o} = \frac{1}{(1 + ax^2 + bx^4)^{\beta}}$$

A very good initial guess for the fit parameters can be found with the following. Let x_L be the last value of θ_{rms} (0.45 in this case) and let f_L and f_L' be the value and slope of the 20 MeV curve at that point; the latter can be estimated using finite differences of the data, $(f_L - f_{L-1})/\Delta x$. Let f_0" be the curvature at x=0, also estimated using finite differences of the data, $(2f_1 - 2f_0)/\Delta x^2$. Then

$$\beta \approx -\frac{x_L f'_L}{4 f_L}, \qquad a \approx \frac{2 f''_0}{x_L f'_L}, \qquad b \approx \frac{1}{x_L^4 f_L^{\frac{1}{\beta}}}$$

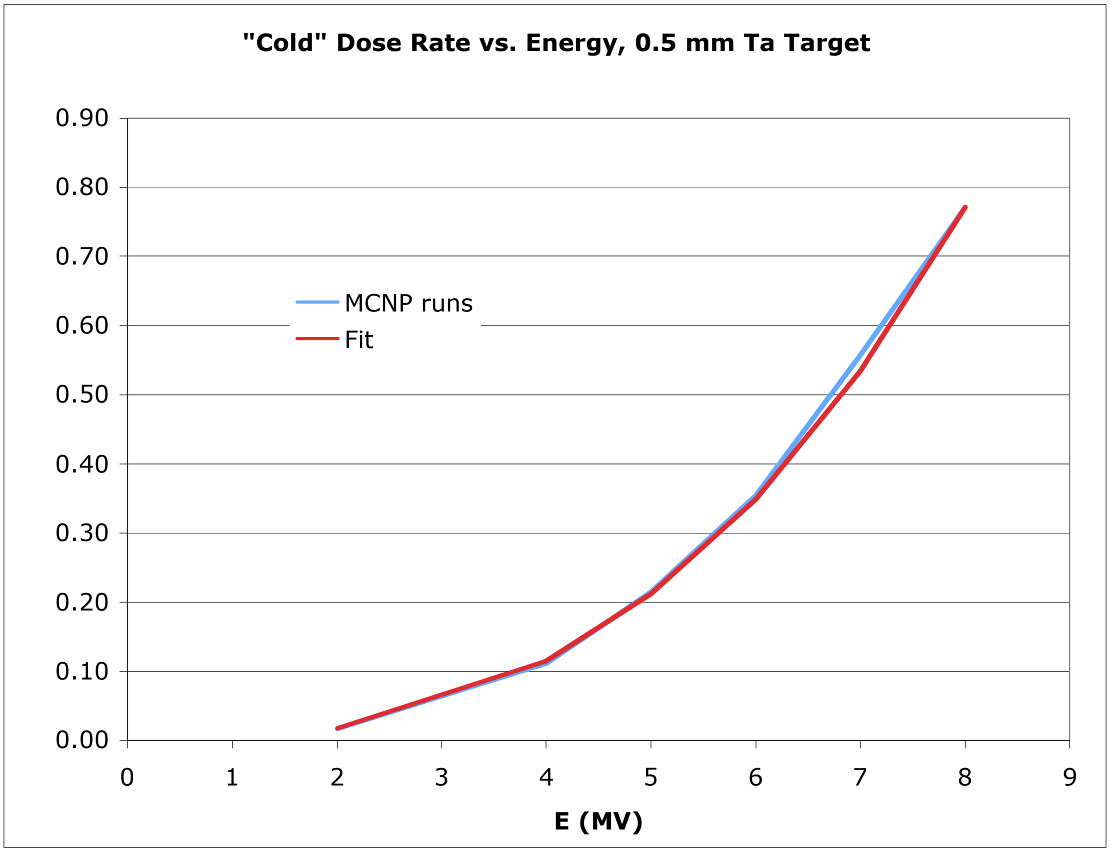
Typically only the value of *a* needs to be adjusted from these initial values, at least for an "eyeball"-quality fit. This curve can then be combined with the expression for the peak dose at zero angle, given earlier, to yield the dose rate as a function of energy and angle at peak target thickness. Plugging in the numerical values for this data,

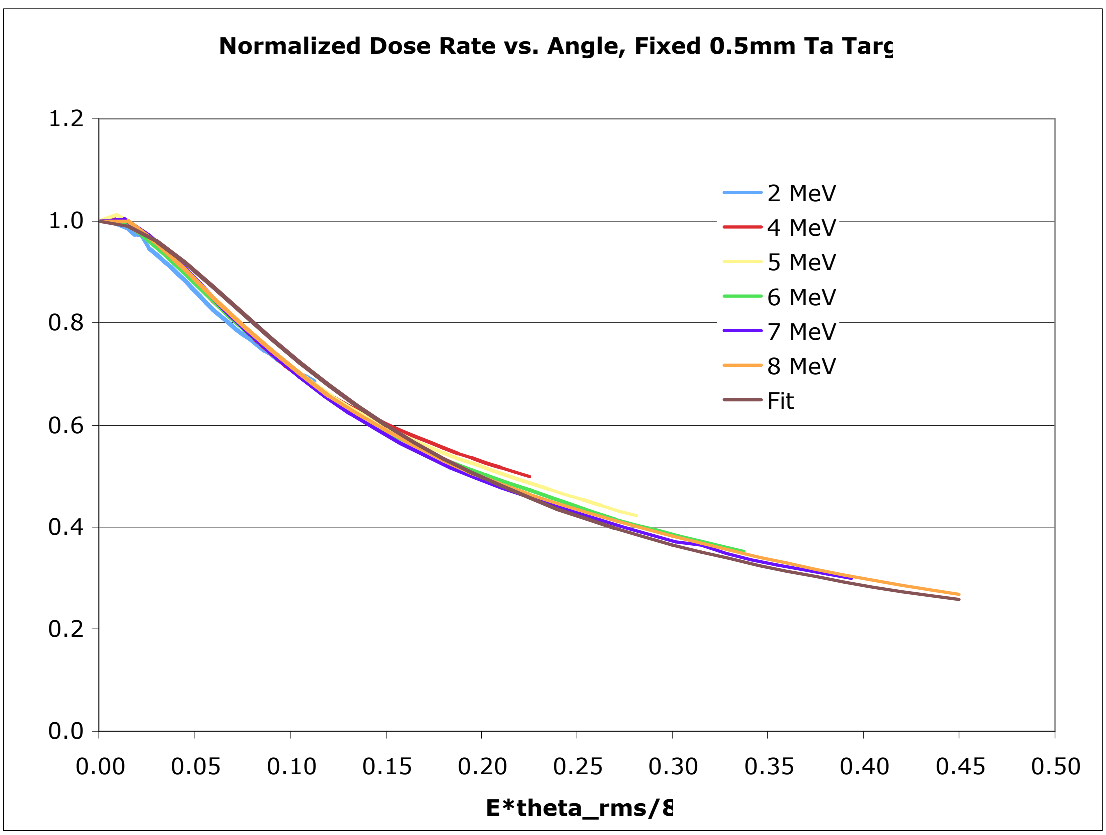
$$\dot{D} = \frac{11.5(\frac{E}{20})^{2.86}}{(1 + 744(\frac{E\theta_{rms}}{20})^2 + 16200(\frac{E\theta_{rms}}{20})^4)^{0.336}}$$

For the energy sweep case at fixed target thickness, the numerical coefficients will change but the process is the same. For a fixed 0.5 mm Ta target, in the range 2-8 MeV, the fit is

$$\dot{D} = \frac{0.771(\frac{E}{8})^{2.75}}{(1 + 197(\frac{E\theta_{rms}}{8})^2 + 5490(\frac{E\theta_{rms}}{8})^4)^{0.243}}$$

Plots of the data for this case are shown below (no table is included).


"Cold" Dose Rate vs. Energy, 0.5 mm Ta Target
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
1
2
3
4
5
6
7
8
9
E (MV)
MCNP runs
Fit


Normalized Dose Rate vs. Angle, Fixed 0.5mm Ta Targ
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
E*theta_rms/8
2 MeV
4 MeV
5 MeV
6 MeV
7 MeV
8 MeV
Fit

VII. Summary

The dose rate from a bremsstrahlung converter target is a function of the incoming beam energy, its angular distribution, and the thickness of the target. For a fixed beam energy, there is an optimal target thickness that balances bremsstrahlung collisions versus small angle scatter and self attenuation. The peak of the curve of dose rate versus thickness is broad, so for a single-pulse radiographic accelerator it may be beneficial to back down to 95% of peak or even less so as to reduce the effects of spot dilution and electron backscatter.

The MCNP code is a useful tool for dose calculations but it is non-trivial to incorporate a realistic incoming beam phase space. A process is given here for describing a Gaussian beam with finite emittance, starting at a waist.

The dependence of dose rate on the angular distribution of the beam has also been investigated here, for the case of a Gaussian beam. Assuming that the optimal target thickness (peak, not 95% of peak) is used for each energy, a good estimate of the dose of the target system as a function of both energy (in MeV) and θ_{rms} is given by

$$\dot{D} = \frac{11.5(\frac{E}{20})^{2.86}}{(1 + 744(\frac{E\theta_{rms}}{20})^2 + 16200(\frac{E\theta_{rms}}{20})^4)^{0.336}}$$

The process used to find this fit can easily be repeated for other cases, such as varying beam energy impinging on a fixed-thickness target.

VIII. References

[1] J. D. Jackson, Classical Electrodynamics, 2nd Edition. John Wiley & Sons, New York, 1975.

[2] J.F. Breismeister (Ed.), "MCNP – A General N-Particle Monte Carlo Transport Code." Los Alamos manual LA 12625 M, Version 4b.

[3] S. Falabella, et. al., "Effect of Backscattered Electrons on Electron Beam Focus." Proceedings of 20th International Linac Conference, Monterey, CA, August 2000.

Appendix. Useful Scripts and MCNP Templates

UNIX shell scripts and the awk programming language have proven invaluable in performing the large number of MCNP runs which produced the results in this study. The ability to automate the construction of MCNP input files and then parse the output files for the individual numbers of interest is key to efficiency. This appendix contains listings of most of the files used in the process. As a general reminder, when MCNP is invoked with something like "mcnp64.sgi n=name" it will produce a restart file called namer and an output file called nameo.

The first file is a sample input file for finding the energy deposited in air, used to build up the conversion function from photon energy to dose. Note that the output from the F8 card is unused.

<u>Sample MCNP input file “a1” for deposition in simulated air</u>

```
Dose curve for air
c Vacuum
1 0 -1:3:4          $ Outside everything
2 0  1 -2 -4        $ left edge to air
3 1 -1.225e-3 2 -3 -4 $ air
c end of cell cards

c Surfaces
1  PX   -1.0 $ left boundary
2  PX   0.0 $ edge of air
3  PX   100.0 $ right boundary
4  CX   10.0 $ outer boundary
c End of surfaces

mode p
imp:p 0 1 1
cut:p 1.e37 0.001
fcl:p 0 0 -1
c 3456789012345678901234567890123456789012345678901234567890123456789012
c Source-------------------------------------------------------------
sdef pos=-0.1 0.0 0.0 vec=1 0 0 dir=1 erg=0.01 par=2
c Tallies------------------------------------------------------------
f6:p 3
*f8:p 3
c Materials----------------------------------------------------------
M1  7000  0.7845 8000 0.2109 18000 0.0046 $ Air, density 1.225e-3 g/cc
NPS 500000
```

The following file is a template used for building the input files for the studies in target thickness and beam energy. It illustrates the use of the DF card to provide dose in air. Although the beam spot size is not important in these particular calculations, note that the source cards contain a description of a beam that is Gaussian in spatial distribution.

<u>Template MCNP input file “template_Ta” for thickness, energy, and angle studies</u>

```
Ta solid 20 mil, with dose calc, finite emittance, sig=1 mm
c Vacuum
1 0 -1 $ left of birth surface
2 0 1 -2 $ birth surface to targ
3 0 3 -4 $ targ to domain edge
4 0 4 $ right of domain
c Target as radial profiles at various z
5 1 -16.6 2 -3
c end of cell cards

c Surfaces
1 PX -0.05
2 PX  0.0
3 PX  0.05
4 PX 100.001
c End of surfaces

mode p e
imp:p 0 1 1 0 1
imp:e 0 1 1 0 1
cut:p j 0.02
cut:e j 0.02
c Format for phys:e card is
c phys:e emax ides iphot ibad istrg bnum xnum rnok enum
c where EMAX is upper energy limit, IDES toggles production of e's by p's
c IPHOT toggles production of p's by e's, IBAD pertains to brem. angular
c distr., ISTRG pertains to electron straggling, BNUM changes the weight
c of brem production, XNUM changes the rate of x-ray production,
c RNOK weighs the production of knock-ons, and ENUM weighs the production
c of photoelectrons.
phys:e j 0 0 0 0 1 1 0 0
c 3456789012345678901234567890123456789012345678901234567890123456789012
```

```
c Source-------------------------------------------------------------
sdef sur=1 pos=-0.001 0 0 rad=d1 vec=1 0 0 dir=1 erg=2 par=3
si1 a 0.000 0.017 0.033 0.050 0.067 0.083 0.100 0.117 0.133 0.150 &
0.167 0.183 0.200 0.217 0.233 0.250 0.267 0.283 0.300
sp1   0.00E+00 1.62E-02 2.98E-02 3.89E-02 4.26E-02 4.14E-02 &
3.65E-02 2.96E-02 2.22E-02 1.55E-02 1.01E-02 6.19E-03 3.55E-03 &
1.91E-03 9.65E-04 4.59E-04 2.05E-04 8.67E-05 3.44E-05
c Tallies-------------------------------------------------------------
f5:p 100 0 0 0 ND $ dose in (rad/ns) at 2kA
# de5 df5
 0.01 6.85e3
 0.03 8.23e2
 0.05 3.78e2
 0.07 3.56e2
 0.10 4.58e2
 0.15 7.41e2
 0.20 1.06e3
 0.25 1.38e3
 0.30 1.72e3
 0.40 2.35e3
 0.50 2.96e3
 0.60 3.54e3
 0.75 4.34e3
 1.00 5.57e3
 1.40 7.23e3
 1.80 8.73e3
 2.20 1.01e4
 2.60 1.12e4
 2.80 1.18e4
 3.25 1.31e4
 3.75 1.45e4
 4.25 1.58e4
 4.75 1.70e4
 5.00 1.77e4
 5.25 1.83e4
 5.75 1.95e4
 6.25 2.07e4
 6.75 2.19e4
 7.50 2.37e4
 9.00 2.75e4
 11.0 3.25e4
 13.0 3.74e4
 15.0 4.27e4
 17.0 4.80e4
 20.0 5.65e4
c Materials-----------------------------------------------------------
M1  73000  1.0 $ Ta, density 16.6 g/cc
NPS 500000
```

To turn this template into an input file for a particular case, the target thickness (which is given by the coordinate of surface 3) and electron energy must be input. This is done with an awk program which is passed two variables, th and en; th is in hundredths of a cm and en is in MeV.

<u>Awk program "awk_build" for turning thickness/energy template into MCNP input:</u>

```
BEGIN{
}{
if (($1=="3")&&($2=="PX")) printf("3 PX %4.2f\n",0.01*th);
else if ($1=="sdef") printf("sdef sur=1 pos=-0.001 0 0 rad=d1 vec=1 0 0 dir=1 erg=%1d
par=3\n",en);
else print $0;
}
END{
}
```

This awk program is called repeatedly by the following shell (tsch) script, which passes the desired values of thickness and energy to it and gives systematic names to the output.

Shell script "build_script" for building the thickness-study input files:

```
#!/bin/csh
set energy = ( 2 4 6 8 10 12 14 16 18 20 )
set thick  = ( 1 2 3 4 5 6 7 8 9 10 12 14 16 18 20 )
foreach e ($energy)
   foreach t ($thick)
      awk -v en=$e -v th=$t -f awk_build template >! e"$e"t"$t"
   end
end
exit
```

The following script will run all of the thicknesses for a given energy in sequence. It deletes the restart files, which are generally large and in this case not needed for later use.

Shell script "go" for running all cases at a given energy, for the thickness study:

```
#!/bin/csh
set list = (`/bin/ls e"$1"t*`)
foreach file ( $list )
   mcnp64.sgi n=$file
   /bin/rm "$file"r
#   echo $file
end
```

Once the output is generated, another awk program parses it for the single number of interest, namely the dose rate. The thickness is input to awk so it can print it out as the independent variable. The program works by setting a flag when it encounters "detector located" so that it knows to find the data on the next line.

Awk program "awk_dose" for parsing the dose from a single output file:

```
BEGIN{
n=0
}{
if (n==1) {
   printf("%10.3e\t%10.3e\n",0.01*th,$1);
   n = 0;
} else if(($1=="detector")&&($2=="located")) n=1;
}
END{
}
```

This program is in turn called repeatedly by a shell script, so that the results from a single beam energy can be collected in a single file. The output of this script is a set of files named sequentially by energy, containing two columns, the thickness and the dose.

Shell script "dose_script" to extract the dose from all the output:

```
#!/bin/csh
set energy = ( 2 4 6 8 10 12 14 16 18 20 )
set thick  = ( 1 2 3 4 5 6 7 8 9 10 12 14 16 18 20 )
foreach e ( $energy )
   foreach t ( $thick )
      awk -v th=$t -f awk_dose e"$e"t"$t"o >> dose"$e".txt
   end
end
exit
```

The studies versus angle are slightly different. The input template contains a placeholder line ("distributionhere") that is easy for awk to find and replace with the Gaussian angular distribution.

<u>Template file "template" for the angular studies:</u>

```
Ta solid 20 mil, with dose calc, finite emittance, sig=1 mm
c Vacuum
1 0 -1 $ left of birth surface
2 0 1 -2 $ birth surface to targ
3 0 3 -4 $ targ to domain edge
4 0 4 $ right of domain
c Target as radial profiles at various z
5 1 -16.6 2 -3
c end of cell cards

c Surfaces
1 PX -0.05
2 PX  0.0
3 PX  0.05
4 PX 100.001
c End of surfaces

mode p e
imp:p 0 1 1 0 1
imp:e 0 1 1 0 1
cut:p j 0.02
cut:e j 0.02
c Format for phys:e card is
c phys:e emax ides iphot ibad istrg bnum xnum rnok enum
c where EMAX is upper energy limit, IDES toggles production of e's by p's
c IPHOT toggles production of p's by e's, IBAD pertains to brem. angular
c distr., ISTRG pertains to electron straggling, BNUM changes the weight
c of brem production, XNUM changes the rate of x-ray production,
c RNOK weighs the production of knock-ons, and ENUM weighs the production
c of photoelectrons.
phys:e j 0 0 0 0 1 1 0 0
c 345678901234567890123456789012345678901234567890123456789012345678901 2
c Source------------------------------------------------------------
sdef sur=1 pos=-0.001 0 0 rad=d1 vec=1 0 0 dir=1 erg=2 par=3
si1 a 0.000 0.017 0.033 0.050 0.067 0.083 0.100 0.117 0.133 0.150 &
0.167 0.183 0.200 0.217 0.233 0.250 0.267 0.283 0.300
sp1   0.00E+00 1.62E-02 2.98E-02 3.89E-02 4.26E-02 4.14E-02 &
3.65E-02 2.96E-02 2.22E-02 1.55E-02 1.01E-02 6.19E-03 3.55E-03 &
1.91E-03 9.65E-04 4.59E-04 2.05E-04 8.67E-05 3.44E-05
distributionhere
c Tallies------------------------------------------------------------
f5:p 100 0 0 0 ND $ dose in (rad/ns) at 2kA
# de5 df5
 0.01 6.85e3
 0.03 8.23e2
 0.05 3.78e2
 0.07 3.56e2
 0.10 4.58e2
 0.15 7.41e2
 0.20 1.06e3
 0.25 1.38e3
 0.30 1.72e3
 0.40 2.35e3
 0.50 2.96e3
 0.60 3.54e3
 0.75 4.34e3
 1.00 5.57e3
 1.40 7.23e3
 1.80 8.73e3
 2.20 1.01e4
 2.60 1.12e4
 2.80 1.18e4
 3.25 1.31e4
```

```
 3.75 1.45e4
 4.25 1.58e4
 4.75 1.70e4
 5.00 1.77e4
 5.25 1.83e4
 5.75 1.95e4
 6.25 2.07e4
 6.75 2.19e4
 7.50 2.37e4
 9.00 2.75e4
 11.0 3.25e4
 13.0 3.74e4
 15.0 4.27e4
 17.0 4.80e4
 20.0 5.65e4
c Materials----------------------------------------------------------
M1  73000  1.0 $ Ta, density 16.6 g/cc
NPS 500000
```

The awk program to put the desired distribution into the input file works by calculating an array of values at the beginning, then implanting them at the right location in the file, working within the limitations of the length of an MCNP input line. The zero-angle case is treated separately. The angle variable ang is assumed to be in milliradians (see the shell script).

Awk program "awk_build" for the angular studies:

```
BEGIN{
if (ang!=0) {
   fang = 0.001*ang;
   mu_min = sqrt(1.0/(10.0*fang*fang+1.0));
   dmu = (1.0-mu_min)*0.05;
   for(i=0; i<21; ++i) {
      mu[i] = mu_min+i*dmu;
      p[i]  = exp(-(1.0/(mu[i]*mu[i])-1.0)/(fang*fang))/(mu[i]*mu[i]*mu[i]);
   }
}
}{
if (($1=="3")&&($2=="PX")) {
   printf("3 PX %4.2f\n",0.01*th);
} else if ($1=="sdef") {
   if (ang!=0) {
      printf("sdef sur=1 pos=-0.001 0 0 rad=d1 vec=1 0 0 dir=d2 erg=%1d par=3\n",en);
   } else printf("sdef sur=1 pos=-0.001 0 0 rad=d1 vec=1 0 0 dir=1 erg=%1d par=3\n",en);
} else if ($1=="distributionhere") {
   if (ang!=0) {
      printf("si2 a %8.6f %8.6f %8.6f %8.6f %8.6f &\n",mu[0],mu[1],mu[2],mu[3],mu[4]);
      printf("%8.6f %8.6f %8.6f %8.6f %8.6f &\n",mu[5],mu[6],mu[7],mu[8],mu[9]);
      printf("%8.6f %8.6f %8.6f %8.6f %8.6f &\n",mu[10],mu[11],mu[12],mu[13],mu[14]);
      printf("%8.6f %8.6f %8.6f %8.6f %8.6f %8.6f\n",mu[15],mu[16],mu[17],mu[18],mu[19],mu[20]);
      printf("sp2 0.0 %9.3e %9.3e %9.3e %9.3e %9.3e &\n",p[1],p[2],p[3],p[4],p[5]);
      printf("%9.3e %9.3e %9.3e %9.3e %9.3e &\n",p[6],p[7],p[8],p[9],p[10]);
      printf("%9.3e %9.3e %9.3e %9.3e %9.3e &\n",p[11],p[12],p[13],p[14],p[15]);
      printf("%9.3e %9.3e %9.3e %9.3e %9.3e\n",p[16],p[17],p[18],p[19],p[20]);
   }
} else print $0;
}
END{
}
```

The shell script which calls this now has to pass a pair of values, energy and optimal thickness, for each angle, so the loop structure is different than in the thickness study:

Shell script "build_script" for the angular cases:

```
#!/bin/csh
set energy = ( 02 04 06 08 10 12 14 16 18 20 )
set thick  = ( 3  6  8  10 10 11 10 12 10 11 )
```

```
set angle  = ( 000 015 030 045 060 075 090 105 120 135 150 165 180 195 210 225 240 255 270 285
300 315 330 345 360 375 390 405 420 435 450 )
foreach n ( 1 2 3 4 5 6 7 8 9 10 )
   foreach a ($angle)
      awk -v en=$energy[$n] -v th=$thick[$n] -v ang=$a -f awk_build template >!
e"$energy[$n]"a"$a"
   end
end
exit
```

The files to run the cases and parse the output are very similar to the thickness case, the only difference being the file naming convention:

Shell script "go" to run the angle study:

```
#!/bin/csh
set list = (`/bin/ls e"$1"a*`)
foreach file ( $list )
   mcnp64.sgi n=$file
   /bin/rm "$file"r
#   echo $file
end
```

Awk program "awk_dose" to parse a single angle-study output file:

```
BEGIN{
n=0
}{
if (n==1) {
   printf("%10.3e\t%10.3e\n",0.001*ang,$1);
   n = 0;
} else if(($1=="detector")&&($2=="located")) n=1;
}
END{
}
```

Shell script "dose_script" to parse all of the dose output in the angle study:

```
#!/bin/csh
set energy = ( 02 04 06 08 10 12 14 16 18 20 )
set angle  = ( 000 015 030 045 060 075 090 105 120 135 150 165 180 195 210 225 240 255 270 285
300 315 330 345 360 375 390 405 420 435 450 )
foreach n ( 1 2 3 4 5 6 7 8 9 10 )
   foreach a ($angle)
      awk -v ang=$a -f awk_dose e"$energy[$n]"a"$a"o >> dose"$energy[$n]".txt
   end
end
exit
```

The simulated air studies could clearly benefit from a similar scripting process, but no such scripts were written at the time. The runs for fixed target thickness in the 2-8 MeV range were done in the same fashion as the general angle study, but with the target thicknesses all the same in the script list.