Calculation of radiation produced by dark current in the Cornell ERL Cryomodules

Lisa M. Nash*
UNC Chapel Hill

August 15, 2011

Electrons in the Cornell Energy Recovery Linac (ERL) will be accelerated to energies as high as 5 GeV. Because of the existence of dark current due to field emitted electrons in the SRF cavities, there may be significant radiation produced even when the electron beam is off. This project aimed to model radiation fields produced by dark current within the cavities using the Monte-Carlo progam MCNPX. In addition to energy deposition and neutron and gamma production in niobium, neutron and gamma fluxes were studied for a simplified cryomodule geometry and source. A complex cryomodule geometry was prepared for eventual simulation using dark current sources recently obtained with the help of BMAD.

1 Introduction

1.1 Motivation

The ERL under development at Cornell University presents new opportunities for research in x-ray imaging. While traditional linear accelerators (Linacs) accelerate electrons along a linear path, the Cornell ERL will harvest the energy given to electrons after they have completed a trip through two linear accelerating portions and two bending regions. [1].

Dark current is due to field emitted electrons or ions which are present in the accelerating cavities and exists even when the beam is off. Recently, simulation tools have been developed to track these stray electrons [2]. Validation of dark current models is not possible by direct measurement of dark current tracks. However, a measurement of the gamma and neutron radiations emittted from SRF cavities is planned at similar cryomodules at Jefferson Laboratory in late August 2011. Since it is only possible to measure neutron and gamma flux for small solid angles, simulation becomes necessary to gain a wider spatial distribution of the field.

As with any source of radiation, the usual questions of safety and shielding arise. High energy electrons produce photons and neutrons which have harmful biological effects. Radiation fields must be studied and accounted for in the development of any new facility.

1.2 Interaction of radiation and matter

To study the radiation produced at an electron accelerator, it is necessary to consider the interactions of electrons and matter. Electrons interact via the electromagnetic force and can either lose energy through inelastic collisions with other electrons in a material or by emission of bremsstrahlung photons in collisions with both nuclei and electrons. The term 'bremsstrahlung', effectively means "braking radiation". Although bremsstrahlung can occur with any charged particle, it is only significant for electrons and positrons at the energy ranges studied. Bremsstrahlung photons can vary in energy from very small values up to the incident electron energy. The yield of radiation produced increases linearly with incident electron energy and quadratically with increasing atomic number of the material [3].

Collisional and radiative energy losses dominate in different energy regimes. Cross-sections for energy loss due to collisions is a nearly constant function of energy. However, as previously mentioned, radiative losses depend nearly linearly on energy. A critical energy E_c can be defined at which radiative losses are approximately equal to collisional losses. Above E_c, radiative losses dominate. This energy can be calculated for a given material and is given by the following equation from [3]:

$$E_c = \frac{800MeV}{Z+1.2} \tag{1}$$

For niobium this energy is predicted to be around 18 MeV. Stopping power data from the NIST website confirms this estimation [4].

Bremsstrahlung photons produced by the high energy electrons continue in matter and can lose energy via Compton scattering and

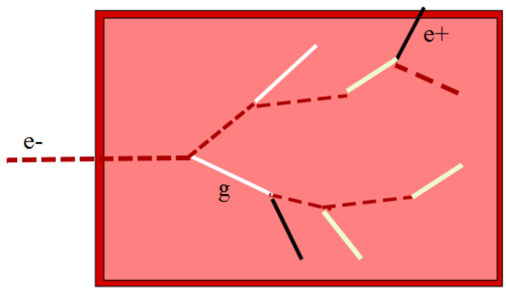

Figure 1: Monte-Carlo simulations track particles individually and determine interactions and secondaries by randomly sampling probability distributions

the photoelectric effect. Electron-positron pairs may also be produced in the fields of nuclei (pair-production) when the gamma energy exceeds 1.022 MeV. Both electrons and positrons lose energy through bremsstrahlung (in addition to ionization), producing more photons in an electromagnetic shower. Neutron production becomes possible for most materials above photon energies greater than 8 or 9 MeV, the typical binding energy in nuclei. The photo-nuclear cross-sections are typically of magnitude lower than those for photon production. Even though the number of neutrons produced is smaller, they are an especially dangerous form of radiation.

The electromagnetic showers and neutrons produced by high energy electrons can be complex and impossible to predict analytically, especially for complicated geometries. Methods developed to deal with this issue include Monte-Carlo simulations, discussed in§2.

2 Monte-Carlo

Monte-Carlo-like methods using random sampling to solve problems have been documented as early as the 1770s. However, techniques involving particle simulations developed later during the 1930s and 1940s mostly at Los Alamos National Laboratory (LANL) [6]. In general, a Monte-Carlo program is one which randomly samples probability distributions to find a solution. This method differs completely from deterministic methods,which may solve an equation or set of equations to determine the outcome of a situation. Unlike deterministic methods, Monte-Carlo simulations produce "random" results that more faithfully mimic situations. The exact reproduciablity, however, is not a concern; the statistical behavior in a situation concerning particles is all that is predictable.

Test particles are tracked individually in a Monte-Carlo program, Fig. 1. A particle may be tracked from generation at the source until a set cut-off energy. Subsequent secondary particles produced at interaction points will be stored to be tracked later. The exact mechanism of tracking may vary from program to program, but the philosophy is the same. Each particle undergoes reactions and produces secondaries according to randomly sampled probability distributions. In the case of particle interactions, these probability distributions come in the form of reaction cross-section data libraries or models if these libraries are unavailable. Programs will converge to the sampled probability distribution theoretically after an infinite number of test particles have been tracked. However, it is not possible and often not necessary to simulate this number of events to find solutions with good statistical confidence. The simulated data can be arbitrarily precise, but the reliability of the simulation is dependent on the accuracy of the probability distribution. [5]

Reduction techniques can be implemented to save computational time. Methods include simplifying the problem geometry and variance reduction such as leading particle biasing. While variance reduction techniques save computational time, they can severley affect the accuracy of results and must be used cautiously. These reduction techniques were not implemented in the simulations discussed in this report.

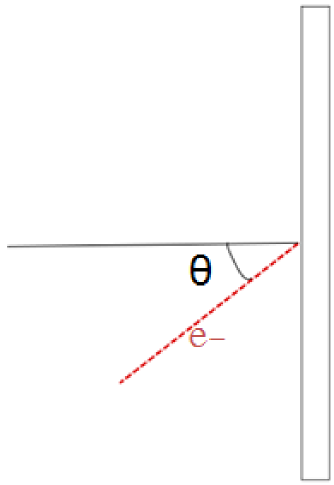

Figure 2: Energies of mono-energetic electrons were varied in increments of 10 from 10 to 100 MeV and angles from 0 to 80 in increments of 10 degrees (10^5 primaries per simulation).

3 Niobium calculations

The accelerating cavities will be constructed of 0.3 cm thick niobium. A slab of niobium corresponding to this thickness was simulated using MCNPX. The energy deposition and electron and photon current from the surfaces of the slab were tracked for varying energies and incident electron angles. Simulations were performed at angles from 0 to 80 degrees from the normal to the surface in increments of 10 degrees. Energies ranged from 10 to 100 MeV, Fig. 2.

Secondary electrons scattered backwards were tallied. The number of secondaries of this kind correlates with the angle of impact. The data for secondary electrons is summarized in the top row of Fig. 3. At an

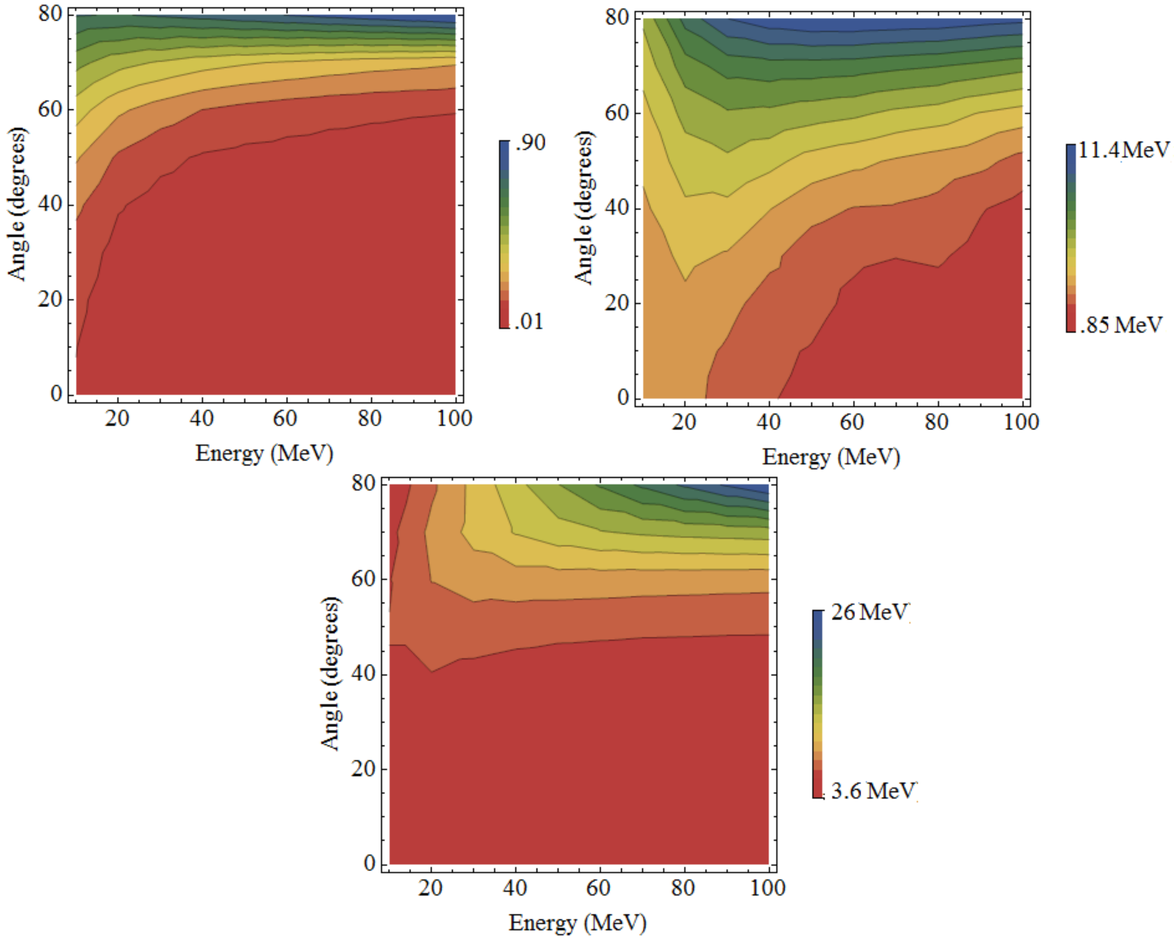

Figure 3: Contour plots summarizing niobium simulations. Top: Number and average energy of electrons passing backwards through niobium. Bottom:Energy deposited in niobium. Each x-axis is energy of incident electrons while y is angle from the surface normal.

angle of 80 degrees relative to the surface normal, as many as 0.90 electrons (per incident electron) are predicted to re-enter the cavity at 100 MeV. The energy of these electrons may vary up to the incident particle energy, but the averages are usually around 10 percent of this value. The simulations show that there is significant emission of secondary electrons, especially at high angles of incidence and energies. These secondaries may be of further interest when modeling dark current. These will re-enter the cavity and depending on angle and phase, could be accelerated by the fields.

Energy deposited by the electrons may affect the performance of accelerating cavities. Fig. 3 (bottom) shows the total energy deposited in niobium as a function of angle and energy. At low energies the energy deposited is correlated with incident energy and independent of angle, as shown by the vertical bands in the top left of the figure. However the top right shows bands which are nearly horizontal, indicating that in this regime the energy deposited is dependent on angle of impact. This effect is most likely due to the fact that the amount of energy lost in collisions vs. energy lost due to radiation is dependent on electron energy. At high energies radiative losses dominate while collisional losses remain nearly constant as can be seen from stopping power

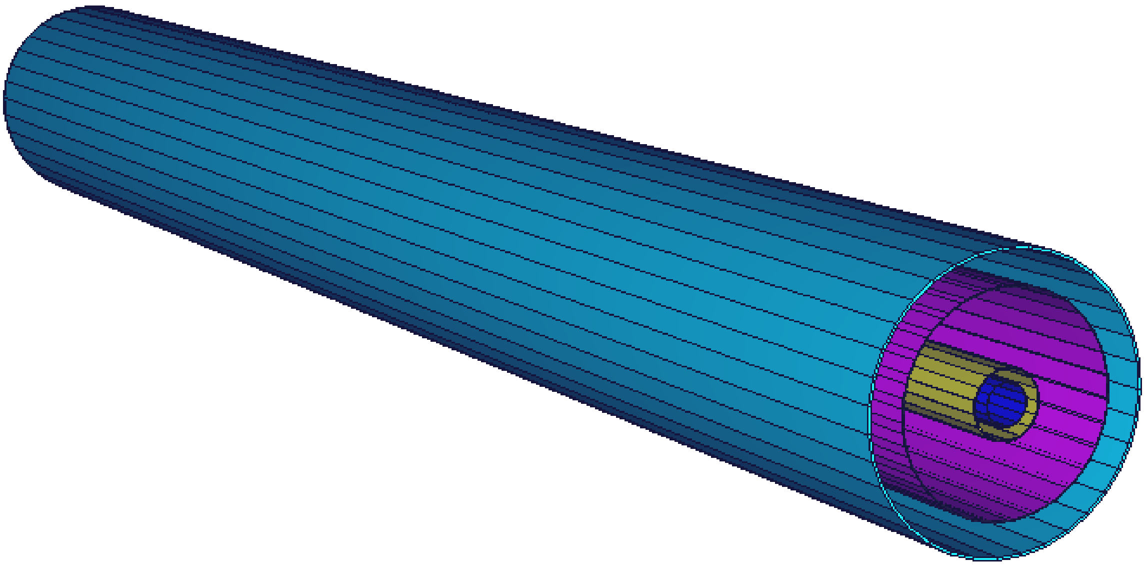

Figure 4: 3D visualization of simplified cryomodule from MCNPX. Electrons were uniformly incident in a line down the cryomodule on the surface of the niobium cylinder

data [4]. High angles of impact make the electron must effectively travel through more niobium and therefore deposit more of its energy. Since energy lost due to radiation is not typically deposited within the niobium, energy deposition becomes dependent on incident angle.

Photon and neutron production is not forward peaked at high angles. At some angles a nearly equal number of photons exit the forwards face of niobium. These will produce further radiation inside the cavities so more complicated geometries must be simulated to gather an idea of the radiation fields produced by dark current.

4 Cryomodule Simulations

Although this project involved modeling the exact cavity geometry in MCNPX, the complexity of the cavity did not lend itself well to preliminary tests. To find rough estimates of the radiation fields a simplified cavity geometry consisting of coaxial cylinders was created in MCNPX, Fig. 4. The accelerating cavities were approximated using a niobium cylinder of $6.94cm$, the average distance between the iris and cavity equator. This was surrounded by titanium and aluminum, which was encased in stainless steel. For these, radii were taken from the actual dimensions of the cryomodules.

Electrons were incident along the z direction at constant x and y on the surface of the niobium cylinder. Runs were performed, each with mono-energetic electrons and a fixed angle relative to the z-axis. Photon and neutron currents were tallied on each surface. In what follows only tallies on the steel case ends of the cryomodule are discussed. The average energy gamma exiting is shown in Fig. 5. While the electron energies in the simulations ranged up to 150 MeV, the highest average photon energy recorded was around 7 MeV. It is expected that the photons measured will be primarily of lower energies. (The number through the each surface was normalized per square centimeter.) The measured flux,

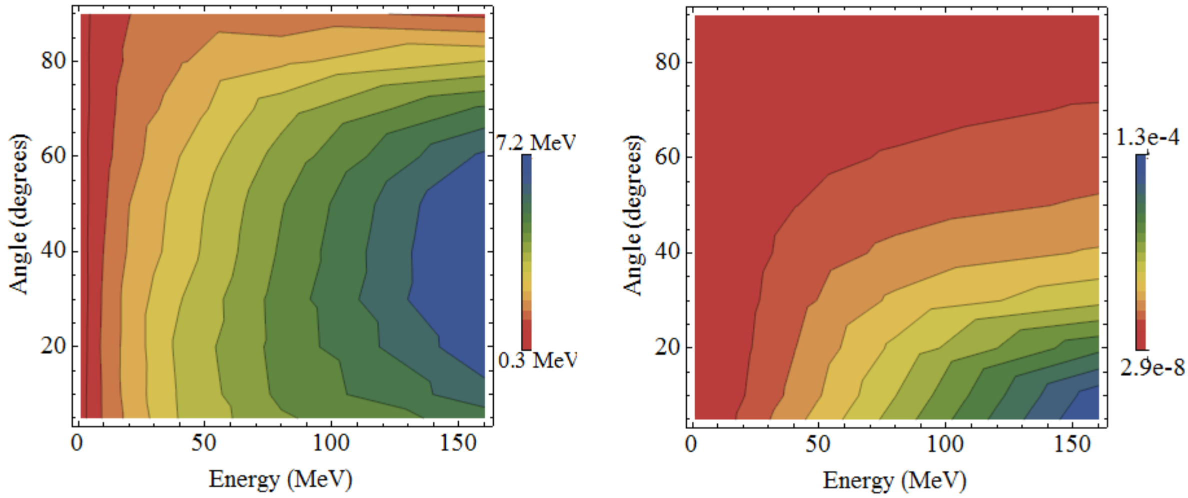

Figure 5: Contour plots of average gamma energy and number/cm^2 for simplified cryomodule simulation steel end-cap

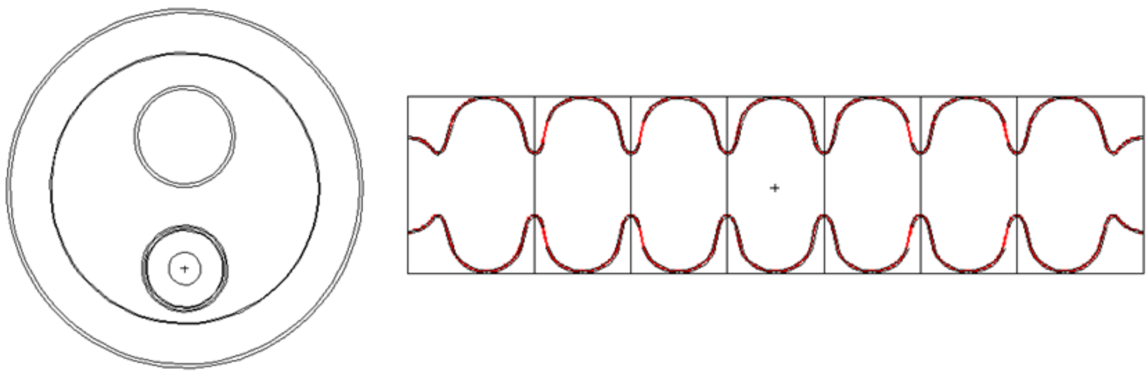

Figure 6: View down z-axis of cryomodule and single cavity geometry created for MCNPX simulation

however, will be dependent on the electron current.

Because the average energies of the photons is so low, it is not surprising that there is only small neutron current through the end surfaces. The simulation count data for neutrons is three to four powers of ten less than that for photons. (There were not enough counts to predict neutron data with good statistical confidence.)

A cryomodule geometry that includes six accelerating cavities was created to represent an actual cryomodule more realistically Fig. 6. Preliminary tests were conducted to ensure the simulation ran without geometry errors. Currently the input file consists of over one-thousand lines in MCNPX. Routines were also created in MATHEMATICA to parse data from dark current simulations and create input files.

5 Conclusions and Further Directions

MCNPX was used to study production of photons and electrons by energetic electrons incident on a nioium plate, 0.3 cm thick.

Significant numbers of electrons were found to scatter backwards. Future work could involve using Monte-Carlo data with dark current simulations to account for secondary production.

Although photon fluxes through the ends of the cryomodule were predicted with good statistical confidence for the simplified geometry and source, the same cannot be said for the neutrons. It is likely that neutron radiation will be difficult to predict and variance reduction techniques will have to be used. Actual dark current in a cryomodule results in electrons of many energies and angles. This means that simulated results need to be convolved with dark current simulation data in order to have an idea of expected radiation from an actual cryomodule.

Currently the cryomodule geometry has been created using no repeated structures. Because of the trusted accuracy of simulated data, complicated geometry of the cells probably does not need to be modeled so accurately. However, methods of duplicating geometries in MCNPX can be implemented and may allow for this.

Preliminary results from the dark current tracker have been obtained and should be used to predict resulting photon and neutron radiations.

6 Acknowledgements

Several people have helped me this summer. My adviser, Val Kostroun, taught me a good deal about experimental nuclear physics and MCNPX. I have enjoyed our discussions about the topic and have come to understand more about the difficulties and limitations of neutron spectroscopy.

Chris Mayes deserves an acknowledgement for helping me while Val was gone on vacation. I would never know so much about MATHEMATICA without him.

I would also like to thank Lora Hine whose outreach program showed me how much I enjoy working with students.

This work has been supported by the NSF.

References

[1] Hoffstaetter, G. H., S. Gruner, & M. Tigner, *eds.*, Cornell ERL Project Definition Design Report (2011) erl.chess.cornell.edu/PDDR

[2] Chiu, C. , “Dark Current Simulations for the Cornell ERL” CLASSE REU Report, Cornell University (2011)

[3] Leo, W.R., ”Techniques for Nuclear and Particle Physics Experiments: A How-to Approach”, (1994)

[4] National Institute of Standards and Technology, Stopping power data http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

[5] Briesmeister, J.F. *ed.*,MCNP-A General Monte Carlo N-Particle Transport Code, LA13709M (2000)

[6] Giesler, G.C., ”MCNP Software Quality: Then and Now”, Proc. of the 10th International Conference on Software Quality, (2000)