Monte Carlo simulation and analysis of the Faraday cup/beam dump at the Accelerator Test Facility II

Hannah Seymour

Department of Physics and Astronomy, Barnard College of Columbia University, New York, NY, 10027

Kin Yip

Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY, 11973

Abstract

The Accelerator Test Facility II (ATF-II) is a planned upgrade of the Accelerator Test Facility, an electron accelerator facility designed to test properties of particle accelerators and advance accelerator technologies. The Accelerator Test Facility II will increase the beam energy to about 110 MeV and thus increase the size and efficiency of the facility. A Faraday cup is a conductive metal cup used for capturing charged particles in a vacuum, and is also used as a beam dump. The Faraday cups used for the Accelerator Test Facility II are aluminum with a vacuum cavity. When the electron beam hits the aluminum, a current is produced in the metal, from which the energy and charge deposition as well as electron flux of the beam can be measured. The Monte Carlo N-Particle Transport Code (MCNP6/X) is a FORTRAN-based software package used for simulating nuclear processes, such as neutron capture reactions or ionizations. Using MCNP6/X and measurements from AutoCAD drawings of the components, we have been able to model the Faraday cup and the surrounding facilities and simulate the bombardment of the cup with the upgraded beam to estimate the energy deposition on the cup as well as the neutron and photon radiation doses received at different points around the ATF-II and estimate the production of tritium (^{3}H) in the soil beneath the floor and ozone (O_3) in the surrounding air. We can then determine whether the beam intensity is too high for the cup and suggest the proper shielding around the cup to minimize the doses. As a result of this summer, I am now well-versed in MCNP6/X, an industry standard, and have gained experience with AutoCAD and ROOT, as well as increased my understanding of accelerator technology and making use of simulated data and statistics.

I. Background

A. The Accelerator Test Facility

The Accelerator Test Facility (ATF) is a high-brightness electron beam user facility that has been operational since 1992. The ATF consists of three beam lines injected with electron beams from a linear accelerator. The ATF can achieve sub-picosecond electron bunches up to 80 MeV. The goal of the ATF is to develop novel accelerator technologies for accelerating electrons and ions and to research the properties of particle accelerators. Users of the ATF have studied Inverse Cherenkov Electron Acceleration, new phenomena in Inverse Compton Scattering, plasma wake fields, and x-ray free electron lasers, among other experiments [1].

The Accelerator Test Facility II (ATF-II) is a planned upgrade of the ATF, designed to increase the electron energy to around 110 MeV and explore science in energy regions not covered by low-energy electron facilities such as NLCTA at SLAC, or by multi-GeV facilities [1]. The ATF-II is currently in development, and though many of the components, such as the dipole and quadrupole magnets and beam dumps (analyzed in this paper,) have already been built, it is not known if the beam intensity at higher energies will cause the beam dump to overheat. In addition, the photon and neutron radiation produced by the beam is of interest for safety purposes. Experiments at Brookhaven National Lab must comply with national and intra-lab standards to safeguard against the leakage of radioactive materials such as tritium into soil and groundwater or the production of other health-hazardous chemicals like ozone. I have produced a computer simulation using the Monte Carlo N-Particle Transport Code (MCNP) of one of the planned ATF-II beam lines and corresponding beam dumps using the Monte-Carlo N-Particle Transport Code 6/X (MCNP6/X.) With this simulation I analyze the energy deposition in

the Faraday cup, the proper shielding to minimize neutron and photon radiation doses to the surrounding area, and the yearly production of tritium (^3H) in the soil and ozone (O_3) in the air.

B. Beam Dump/Faraday Cup

A Faraday cup (Figure 1) is a conductive metal cup (in the case of the ATF-II, aluminum,) which, once a beam of charged particles (electrons in the ATF-II) traveling in a vacuum strikes the base, has a current directly proportional to the number of electrons hitting the beam induced over its surface after the particle beam is neutralized. From this current, information such as the intensity of the beam and the energy density deposited into the cup can be calculated, and subsequently so can the temperature of the cup after the beam has dumped into it.

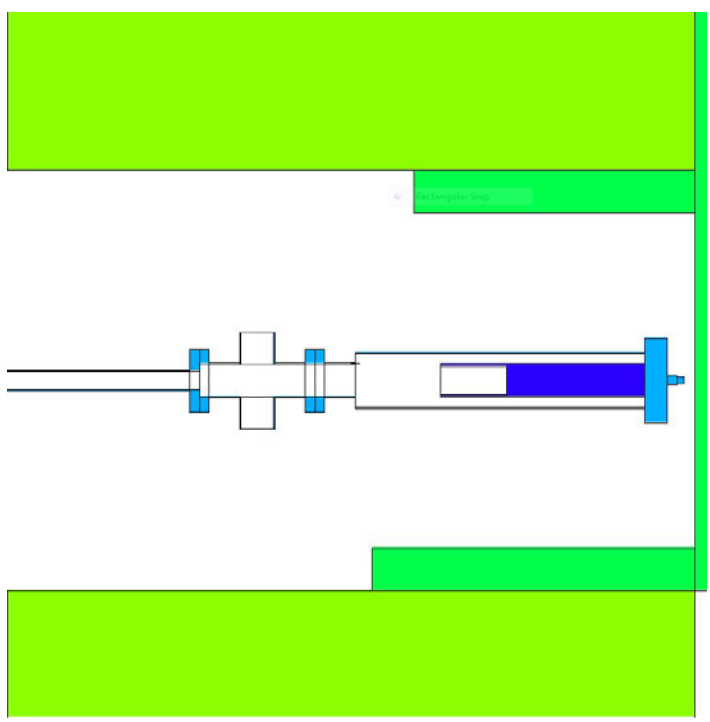

Figure 1: MCNPX model of the Faraday cup (seen in dark blue) for the ATF-II. Includes beam line geometry (light blue) and shielding (green.)

II. Methods

A. The Monte Carlo N-Particle Transport Code and Model

The Monte Carlo N-Particle Transport Code (MCNP 6/X, I utilized both versions for this project,) is a Fortran-90-based software developed at Los Alamos National Laboratory [2]. Using MCNP6/X, one can model a geometry and assign each component a material with its atomic composition detailed in the input file. The geometry can be bombarded by a selection of different particles. MCNP6/X can then perform a variety of calculations, including flux, energy deposition, charge deposition, and others, at a point or over a surface in the geometry. MCNP6/X reads the Evaluated Nuclear Data File (ENDF) and other catalogues of data files to reference relevant information such as reaction cross sections to help determine what is going to happen to each particle in a collision and transport in the Monte Carlo simulation process.

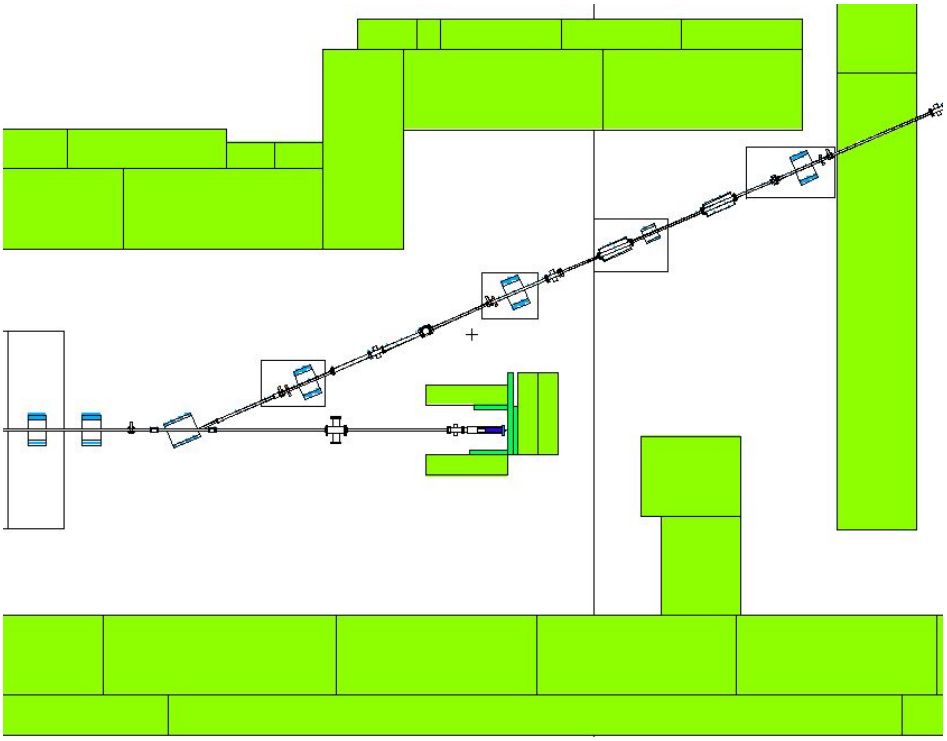

Figure 2: The complete beam geometry modeled in MCNPX, seen top-down where z is the horizontal direction and x is the vertical direction, y out of the page. The Faraday cup can be seen in dark blue at the center.

The complete model of the facility room and the Faraday cup in question (Figure 2) used in this simulation measures 25 feet (762 centimeters) above, below, and to each side of the Faraday cup, and includes the beam geometry enclosed within that volume, mostly magnets, vacuum pumps, and the beam pipes themselves. The Faraday cup is aluminum, the walls (light green,) are concrete, and the outside of the pipes, magnets, and vacuum pumps (light blue) are all stainless steel. The magnets themselves are iron and copper. Beneath the 1-foot-thick-concrete floor I placed soil. All simulations were completed assuming the geometry is surrounded by vacuum, except the simulation determining ozone concentration, in which I placed three volumes of air, one placed in front of the Faraday cup, one between the cup and the first magnet, and one behind the magnet.

B. Energy Deposition

To calculate the energy deposition in the cup, I used an RMESH3 tally over a thin slice of thickness 0.25 cm and cross-section 0.8 by 0.8 cm (a 0.16 cm^3 volume) toward the front of the Faraday cup, along the beam line. The tally produces results in units MeV/cm^3/electron, which can be multiplied by the volume and the number of electrons per second (Equation 1) to yield a power in MeV/s.

Equation 1: $\frac{number\ of\ electrons}{s} = \frac{f * n_{bunch} * q_{bunch}}{q_e}$ where f is a frequency (we assume the beam runs at peak current for this simulation, so 50Hz), n_{bunch} is the number of electron bunches (our simulation assumes 10), q_{bunch} is the charge per bunch (0.5 nC), and q_e is the elementary charge of an electron, 1.602×10^{-19} C. From this calculation, the number of electrons per second is 1.56×10^{12}, and this number can easily be converted to the number of electrons per hour or the number of electrons per year.

C. Radiation Doses

The dose calculations were done by placing a "detector" in the form of an F5 tally modified by standard dose functions for photons and neutrons at various points (one photon tally and one neutron tally for each point) level with, above, or below the beam line. The tally yields a dose in rem/electron, which, multiplied by the result for electrons/s from Equation 1, can be converted to rem/s and subsequently rem/hour, a more standard measure of radiation dose.

D. Soil Activation

In the issue of soil activation, we looked at the production of tritium in the soil over the course of a year. We used an RMESH1 tally to measure the flux in neutrons/cm^2/electron in the soil 10 cm beneath the concrete. From the neutron flux, we use Equation 2 and our standard leaching model [3] to obtain the tritium activation in the unit of pCi/L/year.

Equation 2: $\frac{Atoms}{cc*year} = \frac{\varphi}{\lambda} * N_l * N_e$ where λ is the interaction length, φ is the flux, N_l is the number of atoms per interaction (0.075 for ^{3}H) and N_e is the number of electrons per year.

Photons may also produce tritium, and we use a slightly different method of calculation to extract soil activation. We use the RMESH1 tally to find the maximum flux of tritium in the above-mentioned soil region. Dividing this flux by the thickness of the cell mesh (10 cm) and multiplying it by the number of electrons per year yields a number in atoms/cc/year, which can be converted to pCi/L/year via the leaching model. No shielding beyond the lead and concrete that is pictured around the Faraday Cup in Figure 2 was added in an attempt to reduce soil activation.

Air Activation

As stated previously, I placed three volumes of air in the simulation (Figure 3) and used an F6 tally in each to calculate the energy deposition in the air, in units of MeV/g. This can be converted to an O_3 concentration, a dimensionless fraction, via Equations 3 and 4 after calculating the volume of each region of the three regions.

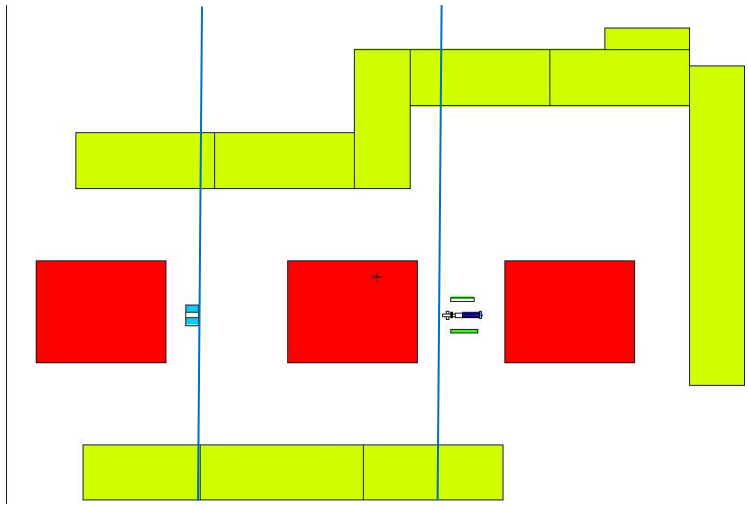

Figure 3: The three volumes of air (in red) indicate where in each region we calculate the energy depositions. The 3 "regions" used in Equation 3 are partitioned by vertical blue lines. The leftmost region (to the left of the blue line on the left) actually extends back to the edge of the room, not pictured.

Equation 3: $P\ (hourly\ production\ rate) = \frac{(\sum_{n=1}^{3} E_{dep_n} * \rho_{air} * V_n * N_e) * 74000}{V_m * N_A}$

Equation 4: $C_s\ (concentration\ saturation) = \frac{P * T}{V_{tot}}$

where the sum is over the values for each region, E_{dep_n} is the energy deposition in each region (MeV/g per electron), V_n (cm^3) is the volume of each region, ρ_{air} is the density of air, N_e is the number of electrons per hour, V_m (cm^3/mol) is the molar volume of ozone, N_A is Avogadro's number, and V_{tot} (cm^3) is the sum of the volumes of each region. 74000 is the number of O_3 molecules per MeV obtained from [4]. T is the decomposition time in hours (0.83) also obtained

from [4]. Again, no additional shielding aside from the around the Faraday cup (Figure 3) was added to reduce ozone production.

III. Results

A. Energy Deposition

Most of the energy is deposited in a small region near the front face of the Faraday cup. By multiplying the value from Equation 1, the largest value produced by the tally (4901 MeV/cm^3/e), and the mesh volume, we find the power of the beam hitting a 0.16 cm^3 volume of the cup (which is a grid between 0.25 cm and 0.5 cm in the beam axis measured from the face that is hit directly by the electron beam) is approximately 2.45x10^{11} MeV/s, or 0.04 W. We could calculate the temperature of the cup from this result using either the thermal conductivity or thermal heat capacity of aluminum, however, the first method assumes nearly all heat is conducted away and the second assumes nearly no heat is dissipated, while the reality is somewhere in between these two cases. Engineering software packages such as ANSYS are better suited to temperature calculations.

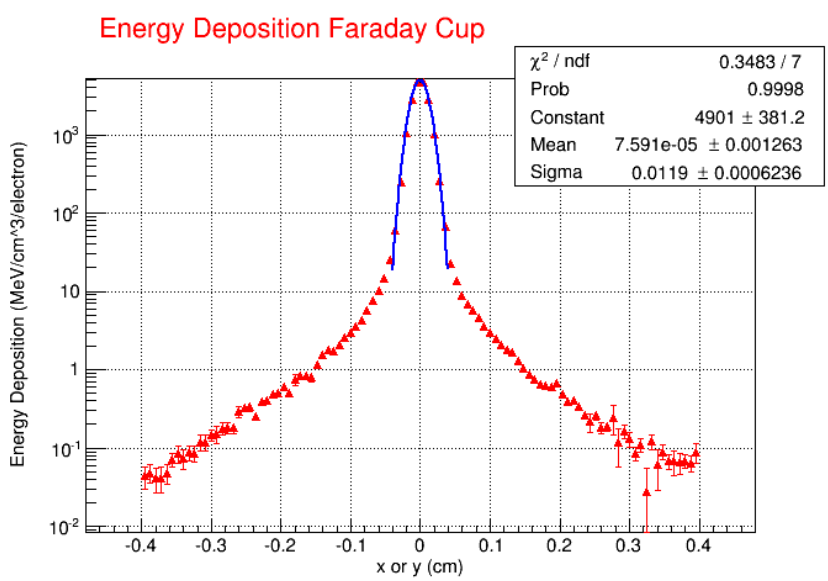

Figure 4: Log(y) plot of energy deposition over a 0.16 cm^3 volume in the Faraday Cup. The plot is fitted to a Gaussian.

B. Radiation Doses

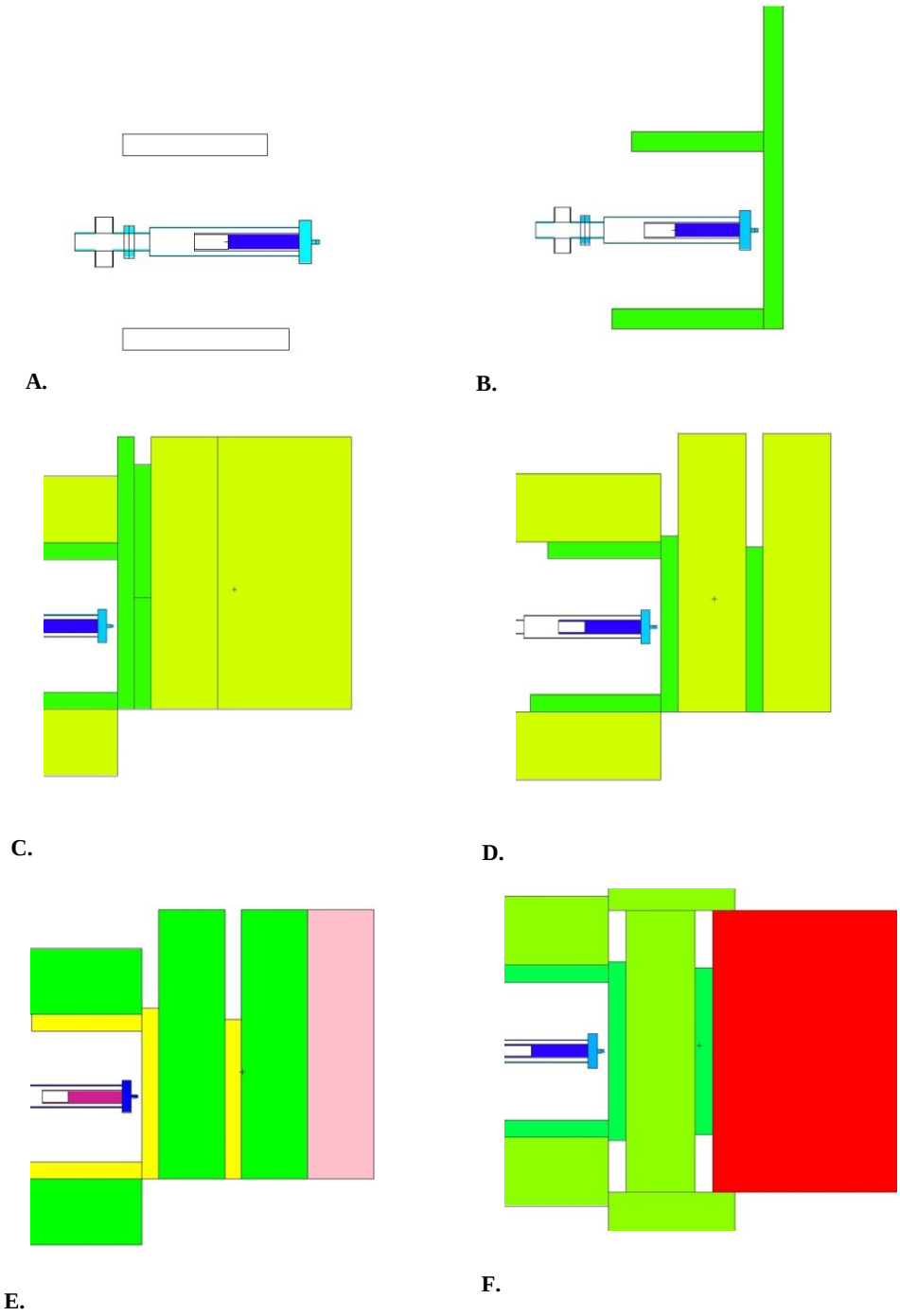

Figure 5: A. The Faraday cup with no shielding. B. 3” of lead shielding on all sides. C. 3” lead (dark green) on sides, 6” on front, 1’ concrete (light green) on sides, 3” concrete on front. D. Alternating 3” of lead and 1’ of concrete. E. Alternating 3” of lead (yellow) and 1’ of concrete (green,) with borate polyethylene at front (pink.) F. Alternating 3” lead, 1’ concrete, 4’ heavy concrete at front (red.)

One of the parameters used to decide whether a facility should be classed as a "controlled area" is a dose rate threshold of $5x10^{-5}$ rem/hr. I varied the shielding around the Faraday cup to identify which would most effectively lower the dose at the most affected "detector" (F5 tally,) placed at beam height, approximately 360 cm downstream from the Faraday cup, behind the rightmost concrete wall in Figure 2. Thick layers of lead proved effective when shielding photons, but more ineffective in shielding neutrons due to (γ, n) interactions in lead producing extra neutrons. Alternating concrete and lead layers was more effective, and finally, adding a 4ft layer of heavy concrete at the front (Figure 5F) and closing gaps in the shielding that were allowing particles to escape proved most effective, although the neutron dose is still slightly larger than the desired value. Some of the configurations tested in this simulation are described in the table below. The dimensions of the lead shields used in the simulation correspond to real lead blocks which were measured in BNL Building 729 (the NSLS Mechanical Tech building.)

Configuration	**Neutron Dose (rem/hr)**	**Photon Dose (rem/hr)**
No shielding (Fig. 5A)	$\approx 2.2x10^{-2}$ +/- 19.92%	≈2.0 +/- 3.59%
3" lead layer on all sides (Fig. 5B)	$\approx 5.1x10^{-4}$ +/- 27.01%	$\approx 9.8x10^{-4}$ +/- 7.49%
6" lead layer on front, 3" on sides (like 5B but front lead is 3" thicker)	$\approx 6.3x10^{-4}$ +/- 10.9%	$\approx 2.7x10^{-4}$ +/- 21.13%
6" lead layer on front, 3" lead on sides, 1' layer of concrete on front (like 5C but only first concrete layer on front)	$\approx 3x10^{-4}$ +/- 12.21%	$\approx 7.4x10^{-5}$ +/- 17.53%
6" lead layer on front, 3" lead on sides, 1' concrete on sides, 3' concrete on front (Fig. 5C)	$\approx 2.7x10^{-4}$ +/- 10.98%	$\approx 7.4x10^{-5}$ +/- 12.58%
Alternating 3" lead and 1' concrete layers on front, 3" lead and 1' concrete on sides (Fig. 5D)	$\approx 7.1x10^{-5}$ +/- 9.98%	$\approx 1.8x10^{-5}$ +/- 15.86%

Alternating 3” lead layers and 1’ concrete on front (frontmost concrete layer is 2’ thick,) 3” lead, 1’ concrete on all sides (like 5D but front concrete is 1’ thicker)	≈7.1×10^{-5} +/- 16.45%	≈1.04×10^{-5} +/- 9.64%
Alternating 3” lead, 1’ concrete, and 1’ borate polyethylene on front, 3” lead and 1’ concrete on sides (Fig. 5E)	≈7.4×10^{-5} +/- 15.4%	≈1.1×10^{-5} +/- 9.6%
Alternating 3” lead, 1’ concrete, and 4’ heavy concrete on front, 3” lead and 1’ concrete on sides (Fig. 5F)	≈5.5×10^{-5} +/- 13.2%	≈9.1×10^{-6} +/-22.73%

C. Soil Activation

The Brookhaven National Laboratory standard for tritium production is 1000 pCi/L/year, 5% of the drinking water standard from the Environmental Protection Agency. The simulation yielded a neutron flux of approximately 4.6×10^{-11} MeV/cm^3/electron with a statistical uncertainty of 9.8% which, converted via Equation 2, is approximately 217 pCi/L/year of tritium. Our simulations also yielded a tritium flux produced by photons of approximately 4.3×10^{-11} MeV/cm^3/e, which by the leaching model corresponds to approximately 1 pCi/L/yr of tritium. These values are far below the BNL standard, and are calculated assuming that the beam runs 24 hours a day nonstop each day of the year, always at the peak current. The ATF-II will not operate this way in reality and as such we can expect this number to be lower when the beam is actually running.

D. Air Activation

The simulation first calculated the average energy depositions in the three relatively small volumes of air (marked red in Fig. 3), in front of the Faraday cup (2.7×10^{-6} MeV/g/electron +/-

0.018%), in the middle (1.7×10^{-7} MeV/g/electron +/- 0.99%) and behind the magnet (7.7×10^{-9} MeV/g/electron +/- 0.21%). Multiplying these average energy depositions by the volumes of their respective regions (marked by the two blue lines in Fig. 3) allows us to obtain the total energy deposition in the air of the entire room. The volume of the region on the right is 1.6×10^{8} cm^3, the volume of the middle region is 1.2×10^{8} cm^3, and the volume of the region on the left is 9.0×10^{8} cm^3. Using these results and Equations 3 and 4, I obtained an ozone concentration saturation of approximately 2.2×10^{-7}, or slightly more than 2 molecules of O_3 for every 10 million air molecules. The Threshold Level Value for ozone concentration is 1×10^{-7} [4], which the simulation exceeds. However, as in the case of soil activation, this value was calculated assuming the beam runs nonstop at peak current every day of the year, which, again, is not how the ATF-II will operate in reality. Thus, it is likely that this number will be lower during an actual run.

IV. Conclusion

Based on the results of this simulation, I recommend that the Faraday cup in the ATF-II be shielded with a combination of lead, concrete, and heavy concrete, as according to my results, lead and concrete alone are enough to stop photons but only the addition of heavy concrete sufficiently lowered the neutron dose. The soil and air activation calculations are a “worst-case scenario,” in which the ATF-II operates at peak current 24 hours a day all year. Obviously, this cannot happen in reality, so we expect the production of tritium and ozone to be lower than predicted by the simulation. Nevertheless, the soil and air activation simulations may be run with alternate Faraday cup shielding, to predict if different shielding will further lower the production of ozone and tritium. Finally, we expect a mechanical engineer will use the data from the energy

deposition simulation and the ANSYS software to calculate the temperature rise and thermal and mechanical stress on the Faraday cup after it is hit by the beam.

V. References

[1] *Upgrade and Operate the Accelerator Test Facility*, proposal to the United States Department of Energy: https://www.bnl.gov/atf/docs/ATFupgrade.pdf.

[2] Computer Program MCNP6/X, (Los Alamos National Laboratory, 2014)

[3] *Design Practice for Known Beam-Loss Locations (BLLs)*, Brookhaven National Laboratory Accelerator Safety Document: https://sbms.bnl.gov/sbmsearch/subjarea/40/1r09e011.pdf.

[4] D. Beavis, *Guidance for LEReC Beam Dump Shields*, Brookhaven National Laboratory Collider-Accelerator Department Memo, May 23, 2016: http://www.c-ad.bnl.gov/esfd/RSC/Memos/5_23_16_LEReC.pdf.

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