

GEANT4 MODELLING OF HEAT DEPOSITION INTO THE ISIS MUON TARGET

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Abstract

The energy deposition on the ISIS muon target and the temperature profiles are analysed in this paper. The thermal modelling is performed using the GEANT4 Monte Carlo code. Heat deposition patterns are also simulated for alternative target geometries. Energy deposition in the collimators is also discussed.

THE ISIS FACILITY

ISIS is currently the world's most intense source of pulsed muons. The facility has been successfully commissioned and operated for many years as a tool for μ SR studies in condensed matter research [1]. Proton acceleration at ISIS begins with the ion source which produces negative hydrogen ions using an electric discharge. The negative ions are accelerated and separated into bunches by a Radio Frequency Quadrupole accelerator which operates at 665 keV, 202.5 MHz. Ion bunches are then further accelerated at 70 MeV using a linear accelerator. Acceleration of the ions continues in the synchrotron, a 163 m circumference ring of magnets that bend and focus the beam. As the negative ions enter the synchrotron, a thin alumina foil strips away the electrons leaving a beam of protons. Once sufficient protons have been collected, they are further accelerated to 800 MeV. After almost 10,000 revolutions the protons have separated out into two large bunches, the proton beam being double-pulsed at 50 Hz with a nominal beam current of 200 μ A. The proton bunches then travel on to collide with a tungsten target to produce neutrons by spallation. A muon target is inserted into the proton beam line about 20 m upstream of the neutron target and pions are produced as a result of the proton interaction with the target nuclei. Pions produce muons which are directed to a suite of instruments optimised to explore different properties of materials.

The Muon Target

The intermediate target used for muon production is an edge-cooled plate of graphite with dimensions 5x5x0.7 cm oriented at 45 degrees to the proton beam giving an effective length of 1 cm along the beam. The thickness of the intermediate target is limited by the fact that for thick targets the neutrons produced and the scattered protons can hit the quadrupole magnets and other equipment in the beamline downstream of the muon target, making them radioactive and possibly causing failure of insulation. In addition, the

proton transmission through the target must be kept above a reasonable level (usually 96%) to prevent the loss in neutron intensity at the neutron target facility. The requirements of an ideal muon target are firstly a high yield of muons and pions and a reduced background of unwanted particles. Thermal shock resistance, high melting point and high conductivity are also primary requirements for a muon target and previous studies showed that graphite is a good candidate for the target material [2], [3]. Table 1 summarises the properties of graphite.

Table 1: Graphite Properties

Properties	Values
Density	1.8 g/cm ³
Specific heat	0.71 J/g K
Melting temperature	3652 - 3697 C
Porosity	0.7 - 53 %
Modulus of Elasticity	8-15 GPa
Compressive Strength	20-200 MPa
Thermal conductivity	25-470 W/m K
Electrical resistivity	(5-30)x10 ⁻⁶ W m

Because ISIS is primarily a neutron source, it imposes restrictions upon the muon target which normally are not present at other muon facilities like PSI or TRIUMF. In particular it is not possible to use thicker targets because of the neutron loss at neutron instruments. The target geometry is also constrained by the accelerator beam line parameters (90 degrees extraction at the muon beam window). However, previous studies showed that the muon production can be increased by a factor of up to 37% with respect to the present target design configuration by using a multi slab target geometry and this paper analyses the energy deposition and temperature profiles for both the original ISIS target and for alternative multi-slab target geometry [4].

GEANT4 SIMULATIONS

Computer simulations have been performed using the Monte Carlo code Geant4 [5]. Previous studies of hadronic models validation applicable in the interest energy range for ISIS showed that Bertini Cascade Model, Binary Cascade and INCL-ABLA give similar predictions and all three models are in reasonably good agreement with experimental data [6]. However, the Binary Cascade model and the INCL-ABLA model have the main disadvantage of a microscopic precision that is CPU intensive compared

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to more phenomenological models. This is the reason for which the Bertini model is preferred and it was used in the current studies. The Bertini Cascade Model generates the final state for hadron inelastic scattering by simulating the intra nuclear cascade. In this model, incident hadrons collide with protons and neutrons in the target nucleus and produce secondaries which in turn collide with other nucleons, the whole cascade being stopped when all the particles which can escape the nucleus have done so. There are several different physics lists provided by the GEANT4 package for simulations of hadronic showers. The physics list which contains the Bertini Model in Geant4 is called QGSP-BERT. The QGSP-BERT was used in all simulations because it performs well for incident protons and is validated up to 10 GeV proton energy. Along with the Bertini model used to describe the hadronic processes, QGSP-BERT defines electromagnetic, decay and ion processes.

The Present Target Configuration

In GEANT4 simulations a narrow beam of 4.8×10^9 protons was sent to the graphite target and the energy deposition due to the electromagnetic shower as the protons pass through was recorded. Figure 1 represents a 3D modelling of the energy deposition inside the 50x50x7 mm muon target. In this model the target is represented as a rectangle with the target thickness on the vertical axis. The proton beam hits the lower base of the rectangle at 45 degrees and the shower is developed as the particles go through. Different colours represent different amounts of energy deposited inside the target. The plot was made on a logarithmic scale and the scale on the right represents the numerical value of $\ln(E)$. For example $\ln(E) = -16$ (green shading) corresponds to 0.0001 mJ/mm^3 with the ISIS beam. The maximum energy deposited is $\ln(E) = -10.1$ (orange shading) which corresponds to an energy deposition $E = 0.04 \text{ mJ/mm}^3$.

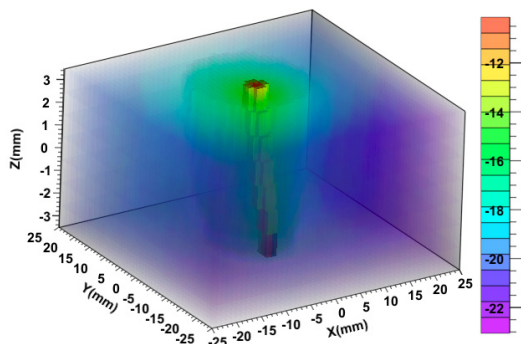


Figure 1: 3D modelling of the energy deposition inside the ISIS muon target. The scale represents the numerical value of $\ln(E)$.

The energy peak is at the central location while in the regions adjacent to the peak less energy is deposited. The

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energy deposition is useful when determining the increase in the target temperature. The temperature is calculated using the material properties (density, specific heat) and the volume of the bin size. Figure 2 represents a 3D modelling of the instantaneous temperature rise inside the target with the target thickness on the vertical axis. There is a clear asymmetry due to the angle the proton beam is coming in. The scale represents the numerical value of $\ln(\Delta T)$. For example $\ln(\Delta T) = -9$ (green shading) corresponds to $1.23 \times 10^{-4} \text{ K}$. The maximum temperature rise is $\ln(\Delta T) = -3.5$ (orange shading) which corresponds to a peak temperature rise of 0.03 K . That means that for 2.5×10^{13} protons the temperature rise will be about 150 K . The histogram bins were chosen to be sufficiently small that the temperature does not depend much on their size. This is the energy deposited in one pulse and it's unlikely that the target will have cooled completely to room temperature before the next pulse of protons comes along 20 ms later. The bottom edge of the graphite target is bonded to the water cooled mounting plate such that the heat is conducted away from the target.

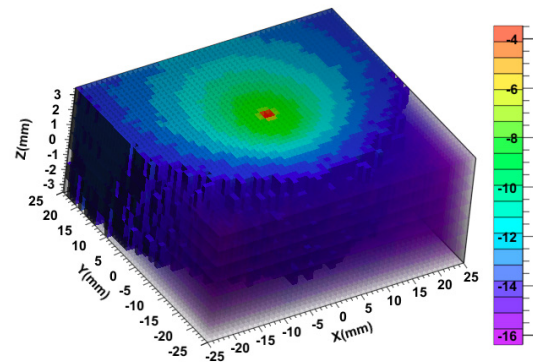


Figure 2: 3D modelling of the instantaneous temperature rise in the ISIS muon target. The scale represents the numerical value of $\ln(\Delta T)$.

The Multi-Slab Target Geometry

Having a multiple slabs target design with the slabs placed at variable distance results in a higher surface muon yield with respect to the present target design configuration. The target slabs are displaced along the proton beam axis, so they all intersect the proton beam. The total thickness of slabs in this target geometry is still 7 mm to preserve the proton transmission through the muon target. For a two slabs target geometry, for the optimum distance of 30 mm between the slabs the muon yields can be increased by up to 20% while for a three slabs target geometry and optimum distance of 20 mm between slabs there is a 37% increase in the surface muon yield [4]. Since the alternative target geometry has a better performance for ISIS, energy deposition studies and temperature rise were performed for the slabs.

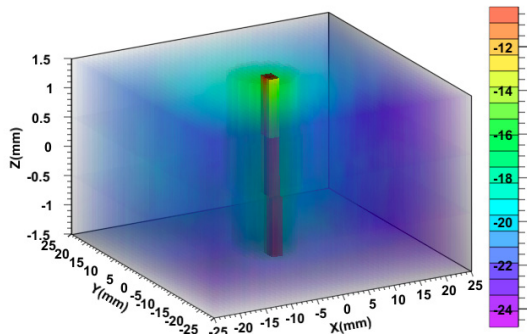


Figure 3: 3D modelling of the energy deposition inside the first slab of three slab geometry target. The scale represents the numerical value of $\ln(E)$.

Figure 3 is a 3D modelling of the energy deposited inside the first slab of the three slabs target geometry. The bin size is 1 mm in all three directions and the maximum energy deposited is $0.04 \times 10^{-3} \text{ J}$. There is no significant difference between the results for different slabs for a given configuration with respect to the energy deposited. Only additional shower development can be observed leading to a wider energy deposition region in the ISIS thicker target.

The instantaneous temperature rise caused by this energy deposited is shown in Fig. 4. The maximum temperature rise is 0.028 K for the 4.8×10^9 simulated protons. The ISIS (double) pulse at 50 Hz and $160 \mu\text{A}$ is equivalent to 2.5×10^{13} protons. Immediately after the first proton pulse hits the temperature will rise by about 150 K.

The total energy deposited inside the target is $13.27 \times 10^{-4} \text{ J}$. The proton beam intensity at ISIS is $160 \mu\text{A}$, which means that the interactions of the 4.8×10^9 protons simulated result in a total power of 276 W dissipated in the target.

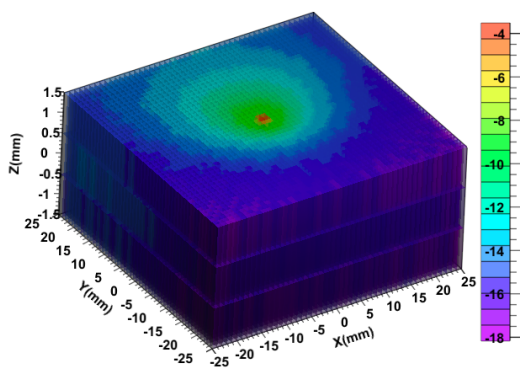


Figure 4: 3D modelling of the instantaneous temperature rise in the first slab of three slabs geometry target. The scale represents the numerical value of $\ln(\Delta T)$.

The actual ISIS proton beam profile is larger than the narrow proton beam used in Geant4 simulations so the peak

temperature may be lower. The ISIS target is then cooled both by thermal radiation and conduction to the mounting copper block. For a multiple slab target design and a larger proton beam there would be differences between slabs regarding energy deposition: transmitted protons scattered from the electrons in the first slab causes a larger beam spot in the second and subsequent slabs. Showers of direct collision products coming out of the first slab in a forward direction hits the second slab heating it, but there would be fewer particles back-scattered from the second and hitting the first slab.

In a thicker target there is more heat generated in total compared to a thinner slab because there is little extra surface area to radiate it away. This would have to be modelled to work out the steady state temperature.

Therefore the main problem to look at next is the rapid heating by the beam and the resulting material damage and this could be either melting or stress. In order to look at the materials response against time transient analysis needs to be performed. The transient shock wave resulting from rapid localised beam heating and its implications for target design must be studied with ANSYS. Geant4 provided realistic patterns of energy deposition for ANSYS input and there is ongoing work regarding this type of calculations at the moment.

CONCLUSION

The energy density and instantaneous temperature rise for the ISIS target and alternative multiple slab target geometry were modelled in this paper. It was found that the maximum instantaneous temperature rise is around 156 K. ANSYS studies will follow since the target is cooled both by thermal radiation and conduction to the mounting block in order to work out the steady state temperature and the thermal shock.

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