GEANT4 Simulations of the Radiation Induced Heating and Dose on the Horizontal Bending Magnet in the Hall C Super High Momentum Spectrometer

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1 Summary

The GEANT4 simulation and results discussed in this document were initiated as a follow-up study associated with the Horizontal Bender (HB) fringe-field beam steering problems described in [3]. Concerns were raised that earlier studies of radiation induced beam dose and heating issues [1], [4], [5] did not take the large fringe-fields into consideration. Over the course of these recent studies it was found that:

- The 20-year dose of $10^8$ Rad indicated in Ref. [7] and Ref. [5] appears to be wrong by a factor 10$^5$. Ref. [5] quotes a nominal 1 W radiation induced heat load. **Using that heat load and the power-to-dose formula in the same document gives a 20-year dose on the order of $10^{10}$ Rad into a nominal 1 kg of material.**

- **The new GEANT4 simulation predicts an annual dose rates on the order of $10^9$ Rad/year** (see Sec.6), in rough agreement with the corrected calculation from the old documents, as indicated in the previous bullet. **This worst-case annual dose appears to be at the limit of what some of the materials used in the construction can withstand (eg. epoxies and insulating materials).**

- The oft-reported heat-load ‘limit’ of 10 W for the HB appears to be based on a simple study outlined in Ref. [6]. Using the same study, we feel that a 5 W local heat-load is a more realistic upper maximum. (see Sec.2).

- The new GEANT4 simulation predicts a worst-case radiation induced localized heat deposition in the HB coil of roughly 0.37 W into a 7.6 cm$^3$ region of the coil pack for a 20 cm LH2 target at 11 GeV and 100 $\mu$A beam current (see Sec.5). If we look at a 3.5 x 3.5 cm$^2$ region to compare with the heat model in Ref. [6], then we estimate a maximum of 0.8 W into a region corresponding to the pink line of Fig.3. **That leaves significant margin, so we conclude that the local radiation heat load at this hot-spot should be manageable.**

- The new GEANT4 simulation estimates the **total radiation-induced power load on both HB coils from a 20 cm LH2 target at 11 GeV and 100 $\mu$A to be 11 W.** This is an order of magnitude larger than the peak heat load of $\approx$1 W predicted by the old model for the (longer) 30 cm LH2 target. It should also be noted that the new simulation estimates an additional 37 W radiation-induced heat load on the cryo-box under the same conditions.

- The dose estimates given in this document do not take into account the differences in the doses from neutrons and electrons. In addition, due to limitations in GEANT4 v4.9.6, the simulation of the low energy electrons maybe under estimated (see Sec.4).

*Note: the $10^8$ Rad for the HB is in a comment at the end of paragraph 3 in Section II, p. 1 of Ref. [5]. It is unclear how that number was arrived at. The majority of that document discusses radiation dose associated with a Rulon plastic seal in an unrelated gate valve.*
Therefore, the given dose estimates should be considered as a lower limit on what can be expected during realistic running conditions.

- The dose estimates on the HB suggests the operations of the SHMS should be metered to prolong the life time of the horizontal bending magnet. Ultimately, plans should be made to built a replacement horizontal bending magnet with higher radiation hardiness and perhaps lower fringe-fields.

2 SHMS Fringe-Fields Overview

The Super High Momentum Spectrometer (SHMS) at the experimental Hall C is being designed as a part of the 12 GeV upgrade of the Jefferson Lab accelerator. By design, the SHMS has an acceptance range of 5.5° to 40° in the scattering plane with a 5 msr solid angle. Together with the existing Hall C High Momentum Spectrometer (HMS), the SHMS will enable the study of deep exclusive reactions of up to 18 (GeV/c)^2. The SHMS use five magnets, a horizontal bending magnet (HB), three quadripoles (Q1,Q2,Q3) and a dipole, in its guidance system (see Fig. 1). The dipole HB is used to bend the electrons by 3°, which allows SHMS to reach angles down up to 5.5°, and the quadripoles are used to focus the scattered electron envelop onto the detectors.

![Figure 1: A CAD drawing of the side view of SHMS showing the magnets and their specifications. The beam enters from the right.](image)

During SHMS magnet studies [9] performed in 2012, it was noted that there was a fringe-field generated by the magnet system which will result in a deflection of the primary
beam at the beam dump. The beam dump is located $\approx 50\,\text{m}$ downstream of the target and has a circular area of $\approx 5\,\text{cm}$ in diameter in which the beam is passed through to the dump. The calculated beam deflection at the dump due to the fringe-fields was $\approx 30\,\text{cm}$. A deflection of such magnitude surpasses the safety limits for proper beam operations at the accelerator and therefore is not permitted. For the successful operation of the SHMS, the fringe-fields need to be suppressed and studies are being carried out with the help of simulations to identify solutions to this beam steering problem. Initial fringe-field simulations performed using TOSCA identified the horizontal bender and the Q2 to be the main contributors to the fringe-fields (see Fig. 2).

$B_y$ Along The Beam Line for $\theta = \{5.5, 6, 7, 8, 9, 10\}$

![Graph](image)

Figure 2: The vertical component of the magnetic field ($B_y$) along the beamline at different scattering angles with the "as built" horizontal bender magnet. The different magnetic components of the SHMS are marked along the horizontal axis. The highest fringe-fields are seen around HB and Q2. An integral field of $-12664\,\text{G}$ causes the electron beam to deflect to beam left at the dump. Figure from Ref. [3].

In addition to beam steering, the fringe-fields were suspected of increasing the radiation induced heat load on the HB. An upper estimate for the localized heat load on the HB coils which is tolerable for operations can be inferred from Fig. 3 extracted from Ref. [6]. The pink line in the figure is the equilibrium temperature of the hot spot under the heat load specified on the horizontal axis. Note that this may be an optimistic model since the effective critical temperature will be probably lower than the nominal 7.75 K under high field, and the heat load is unlikely to be uniformly distributed across the $3.5 \times 3.5\,\text{cm}^2$ region. Given that the same figure shows a local quench for a 5 W from a "small point source" under ideal
conditions, we feel that a 5 W local heat load is a more realistic upper maximum. To determine whether the radiation induced localized heat deposition on the HB magnet with fringe fields is within these limits required for the safe operation of HB was the goal of performing these GEANT4 simulations.

Figure 3: Temperature distribution in Horizontal Bender coil due to an applied heat load (reproduced from Ref. [6]). Top: Heat map associated with a 10 W load distributed over an $1.23 \times 10^{-3}$ m$^2$ area (3.5 x 3.5 cm$^2$). Bottom: Peak temperature as a function of applied heat load. The lower line (pink) represents a load applied over the larger $1.23 \times 10^{-3}$ m$^2$ area. The steeper blue line is associated with a “point” source. The horizontal line line at 7.75 K is the (nominal) critical temperature at which the superconductor will become resistive.
3 GEANT4 Simulation Program

The results presented in this document were obtained from a new simulation package specifically designed using GEANT4 v4.9.6 to study radiative heating on the SHMS magnets and the beam deflection at the beam dump. The simulation program can be downloaded from the hallogit repository by using

```bash
git clone git@hallogit.jlab.org/buddhini/shms_geant.git
```

For reference, following is a summary of the structure of the simulation program and its outputs.

- **Physics List**
  GEANT4 Physics List simulation engine: QGSP_BERT_HP 3.0. The default cuts used in the physics list have a cut off value of 0.7*CLHEP::mm.

- **Geometry**
  Geometry information is read in via GDML (Geometry Description Mark-up Language). The geometry uses a coordinate system centered at the HB parallel to the optics coordinate system. Currently, the radiation induced heat simulations performed on the HB only. Therefore the geometry included in the program is the horizontal bender magnet (coils, bore, cryostat and the yoke), the beam pipe, beam dump vacuum window, beam dump helium vessel and the dump face (see Fig. 4). All of these have rough geometric shapes based on the real dimensions of the components.

- **Primary Generator**
  The default kinematics is 11 GeV electrons randomly distributed on a 4 mm × 4 mm square in the (X,Y) plane.

- **Magnetic field values are read in from a table generated by TOSCA.**

- **Outputs**
  - ntuples (step by step information): local and global position of the hits (cm), initial kinetic energy (MeV), final kinetic energy (MeV), energy deposition (MeV), particle ID and parent ID.
  - histograms (event by event information) of energy deposited in the sensitive volumes in (MeV)
  - text output with the total energy deposited on all the sensitive volumes.

**General Simulation Parameters**

Following is a list of general simulation parameters used for the studies presented in this document.
Each simulation run uses $10^5$ primary events. The simulation is repeated with different random seeds until sufficient statistics are obtained.

The SHMS is set for $5.5^\circ$ scattering angles.

For the purpose of reducing simulation time, when studying radiation induced heating on the HB, the field is limited to the region around the HB identified by $X=(40 \text{ cm}, 60 \text{ cm})$, $Y=(30 \text{ cm}, -30 \text{ cm})$, $Z=(60 \text{ cm}, -80 \text{ cm})$.

## 4 Simulation Benchmarking

### Radiation Induced Heat Load on Targets

A simple method of testing the simulation program is to compare a simulated radiation induced heating on a target to what is calculated using the stopping power of the target material given by

$$\text{Power (W)} = I(\mu A) \times L(\text{cm}) \times \rho(\text{g/cm}^3) \times \text{Stopping power (MeV cm}^{-2})$$

For this, we select the targets used during the 2007 bender heating measurements presented in Ref. [1]. Tab. 1 summarizes the expected radiation induced heat load calculated using Eqn. 1 for liquid hydrogen (LH2), carbon (C12) and aluminum (Al) targets at 4.133 GeV.
Table 1: Calculated radiation induced heat load on selected targets from a 4.133 GeV beam.

<table>
<thead>
<tr>
<th>Target</th>
<th>Stopping Power</th>
<th>I (µA)</th>
<th>L (cm)</th>
<th>ρ (g cm(^{-3}))</th>
<th>Calculated Heat (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH2</td>
<td>4.821</td>
<td>80</td>
<td>4.0</td>
<td>0.071</td>
<td>109.3</td>
</tr>
<tr>
<td>C12</td>
<td>2.214</td>
<td>20</td>
<td>0.2</td>
<td>2.267</td>
<td>20.1</td>
</tr>
<tr>
<td>Al</td>
<td>2.126</td>
<td>40</td>
<td>0.2</td>
<td>2.700</td>
<td>45.9</td>
</tr>
</tbody>
</table>

The simulation using a total of 10\(^6\) electrons (for each target) yielded the results shown in Tab. 2. The results under-predicts the calculated radiation induced heat load by at least 26%. But the discrepancy is consistent for all targets and maybe caused by a limitation of GEANT4. Therefore, for the purpose of radiation induced heat estimates, the value given by this simulation program should be taken as a lower bound on what can be expected in reality.

Table 2: Comparing simulated radiation induced heat load on the targets to calculations in Tab. 1.

<table>
<thead>
<tr>
<th>Target</th>
<th>I (µA)</th>
<th>Radiation Induced Heat Load (W)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Calculated</td>
<td>Simulated</td>
</tr>
<tr>
<td>4cm LH2</td>
<td>80</td>
<td>109.3</td>
<td>83.2</td>
</tr>
<tr>
<td>0.2cm C12</td>
<td>20</td>
<td>20.1</td>
<td>14.8</td>
</tr>
<tr>
<td>0.2cm Al</td>
<td>40</td>
<td>45.9</td>
<td>34.0</td>
</tr>
</tbody>
</table>

Radiation Induced Heat Load on HB at 4.133 GeV

In the next step of the benchmarking process, the radiation induced heat load on the HB coils from a 4.133 GeV beam in the absence of the magnetic field was simulated and was compared to results from realistic measurements performed in 2007 [1].

The realistic measurements were performed on a prototype of the 1/2th of a single HB coil placed in the Hall C at the proposed location during experiments E05-017, E04-001 and E06-009. The prototype did not generate a magnetic field and the 1/2th of the coil was suspended using Rohacell foam supports inside a vacuum tank. The placement of the coil inside the vacuum tank is similar to placement of the bottom 1/2th of the HB coil on the beam side (see Fig. 5).

In the simulation, the field was turned off and the program was run separately for the three targets, LH2, Al and C12. Fig. 6 shows the simulated radiation induced heat load densities on the beam side and far side of the HB coils from each of these targets. The beam side sees a region (~ 1.5 cm × 2.7 cm) of relatively large radiative heating around Z ≈ -44 cm. This is expected from electrons scattering into the HB in the absence of the bending field. Tab. 3 shows simulated results for the radiation induced heating rate integrated over the full
Figure 5: Prototype of the bender used during 2007 radiation heat measurements. *Left:* the 1/2th of a single coil pack used in the prototype. *Right:* The vacuum tank with the beam-pipe cutout (b). Figures from Ref. [1].

HB magnet from the selected targets. The differences between the rates can be explained by the length of the targets and the size of the target nucleus.

Table 3: Simulated integrated radiative heating rate over the full HB magnet from selected targets at 4.133 GeV. The magnetic field is off.

<table>
<thead>
<tr>
<th>Target</th>
<th>Radiative Induced Heating Rate ($W \mu A^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0 cm LH2</td>
<td>0.017</td>
</tr>
<tr>
<td>0.2 cm Al</td>
<td>0.031</td>
</tr>
<tr>
<td>0.2 cm C12</td>
<td>0.019</td>
</tr>
</tbody>
</table>

Tab. 4 shows the comparison between the integrated radiative heating results from the above simulation and the realistic studies done in 2007. Since the simulation uses the full HB magnet, the integrated radiative heating on the bottom section on the beam side was estimated by applying cuts on the X and Y magnet coordinates. From the table, the LH2 and Al simulation differ from the measurements by at least a factor of 2. The C12 simulation seems to agree with the measurement reasonably well however Ref. [1] claims the C12 target measurements are incomplete due to lack of data. Moreover, due to inconsistencies in the Table 4: Measured and simulated integrated radiative heating over the 1/2 of a bender coil from selected targets at 4.133 GeV. The magnetic field is off.

<table>
<thead>
<tr>
<th>Target</th>
<th>I ($\mu A$)</th>
<th>Radiative Heat on 1/2 of a Coil (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured [1]</td>
<td>Simulated</td>
</tr>
<tr>
<td>4.0 cm LH2</td>
<td>80</td>
<td>0.20 ± 0.05</td>
</tr>
<tr>
<td>0.2 cm Al</td>
<td>40</td>
<td>0.17 ± 0.05</td>
</tr>
<tr>
<td>0.2 cm C12</td>
<td>20</td>
<td>0.10 ± 0.05</td>
</tr>
</tbody>
</table>
details of the analysis presented in Ref. [1], the systematic uncertainties on the measurements can be expected to be an order of magnitude larger. Under these circumstances, we are unable to perform a proper comparison between the simulations and the measurements.

(a) 4 cm Liquid Hydrogen

(b) 0.2 cm Carbon

(c) 0.2 cm Aluminum

Figure 6: Field off, simulated radiative heat load densities on the HB coils in the vertical plane along the beam axis (Z axis). Beam energy = 4.133 GeV. Coil thickness = 1.36 cm.
5 Radiation Induced Heating on the HB

The horizontal bender being the main generator of the fringe-fields and the closest to the target and the beamline, experiences a higher radiation dose than other magnets in SHMS. Previous GEANT3 simulations have claimed that the maximum integrated radiation induced heat load on the HB coils is $\approx 1\, \text{W}$ for an 11 GeV beam on a 30 cm LH2 target. However, with the introduction of fringe-fields, this amount is expected to increase considerably as shown in the following sections.

5.1 Target Length Dependence

Tab. 5 gives the simulated radiation induced heating rates on the HB coils and cryo-box for varying LH2 target lengths at 11 GeV and different field configurations.

Table 5: Radiation induced heating rate from simulation integrated over the HB coils and cryo-box (separately) for varying LH2 target lengths at off, positive, negative field polarity. See figure below for graphical representation. Beam energy is 11 GeV.

<table>
<thead>
<tr>
<th>Target L (cm)</th>
<th>HB Coils ($W_{\mu A^{-1}}$)</th>
<th>Cryo-Box ($W_{\mu A^{-1}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Negative</td>
<td>Positive</td>
</tr>
<tr>
<td>4</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>15</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>20</td>
<td>0.11</td>
<td>0.09</td>
</tr>
</tbody>
</table>
For a given energy, the electron/positron flux scattered from the target is roughly proportional to the target length. Therefore, the amount of radiation heat deposited on the HB coils and the cryo-box is expected to scale with the target length as observed from the simulation. However, most of the radiation induced heating is deposited on the cryo-box limiting the integrated radiation heating rate on the HB coils to below $0.11 \text{ W} \mu\text{A}^{-1}$. Therefore, from this simulation the highest radiation induced integrated heat load of 11 W on the HB magnet is seen for the 20 cm LH2 target at 100 $\mu$A. This is much larger than $\approx 1$ W reported in Ref. [1] from the early GEANT model for the 30 cm LH2 target.

5.2 Beam Energy Dependence

Tab. 6 shows the variation of integrated radiation induced heating rates on the HB Coils and the cryo-box from a 20 cm LH2 target at varying beam energies. As expected, at 4 GeV beam energy, with the increase in low energy electrons, the heat deposition rates on the bender coils and the cryo-box are increased compared to what was observed at 11 GeV. This can be seen in Fig. 7 by comparing the beam side heat density plots at 4 GeV and 11 GeV. Comparing the simulated results from Tab. 5 and Tab. 6, we conclude that the integrated radiation heat deposition on the HB coils under the worst-case scenario is 13 W at 100 $\mu$A from 4 GeV beam on a 20 cm LH2 target.

Figure 7: Radiation induced heat rate densities on the HB coils in the vertical plane along the beam axis (Z axis) from simulation. Target is 20 cm LH2 and the field was set to detect 5.5° electrons. Top row represents a simulation done at 4 GeV and bottom row at 11 GeV. Left column is the far side of the HB coils and right column is the beam side.
Table 6: Integrated radiation induced heating rate on the HB coils and cryo-box for varying beam energy on a 20 cm LH2 target and negative field polarity. See figure below for graphical representation.

<table>
<thead>
<tr>
<th>Beam E (GeV)</th>
<th>HB Coils (W(\mu A^{-1}))</th>
<th>Cryo-Box (W(\mu A^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.13</td>
<td>0.39</td>
</tr>
<tr>
<td>11</td>
<td>0.11</td>
<td>0.37</td>
</tr>
</tbody>
</table>

6 Radiation Induced Dose on the HB

6.1 Localized Dose on the Hot Spot

Based on the results from the previous section, the hottest region with the smallest area of exposure on the HB coil is observed at 11 GeV from 20 cm LH2 target (see Fig. 7 bottom right plot). This simulation will be used to estimate the radiation heat dose on the HB coils.

The amount of power deposited on the hot spot on the beam side when the SHMS is setup to detect 11 GeV electrons scattered at 5.5° from a 20 cm LH2 target is

\[
\text{Power} \approx 0.37 \text{ W at } 100\mu A.
\]
Therefore, the total energy deposited on the hot spot during a full accelerator year (52 weeks) of operation at 100% duty factor is,

\[
\text{Energy} = 0.37 \times 52 \times 7 \times 24 \times 3600 \text{ J} = 11636352 \text{ J (3)}
\]

To estimate the dose, we need to know the mass of the material in the hot spot. From Fig. 7, the approximate dimensions of the volume is 3 cm × 1.8 cm × 1.4 cm (thickness of the coil). The coils of the bender magnet in the simulation program is built from Copper (density = 8.96 g cm\(^{-3}\)). Therefore, the mass of the hot spot is,

\[
\text{Mass} = 8.96 \times 3 \times 1.8 \times 1.4 = 67.7 \text{ g (4)}
\]

Then the dose on Copper in the hot spot is,

\[
\text{Dose} = \frac{\text{Energy}}{\text{Mass}} = 171881 \text{ J g}^{-1} \quad \text{(5)}
\]

Since 1 Rad = 1 × 10\(^{-5}\) J g\(^{-1}\),

\[
\text{Dose on Copper} \approx 17.2 \text{ GRad (6)}
\]

If we assume the hot spot is composed of Mylar (epoxy), the dose on Mylar (density = 1.38 g cm\(^{-3}\)) for full year of accelerator running with 100 µA beam on a 20 cm LH2 target is,

\[
\text{Dose on Mylar} = 17.2 \text{ GRad} \times \frac{1.38}{8.96} \approx 2.7 \text{ GRad. (7)}
\]

Due to limitations in GEANT4 low energy electron modeling and the simplification of the HB geometry in the simulation, above dose estimates should be taken as lower limits on what can be expected in reality.

### 6.2 Changes in the Critical Current Density due to Neutrons.

The dose estimates presented in the previous section are a sum of doses from both charged and neutral particles. It does not give the differences between the neutron and electron doses. Since high neutron fluences are known to change the transition temperature and the critical current density of superconductors \[11\], we provide a rough worst-case estimate of their effect on the critical current of the HB.

Derivations in Ref. \[11\] are for NbTi alloy but can be argued to be applicable to copper due to closeness in the densities\[†\]. Then the change \(\Delta J\) in the critical current density \(J\) caused by a neutron fluence of \(\phi t\) is given by

\[
\frac{\Delta J}{J_{c0}} = e^{-\alpha \phi t} - 1 \quad \text{(8)}
\]

\[†\]If the HB is wound of inner SSC strand the Cu:SC ratio is 2:1. If it is wound from outer SSC material then the ratio is roughly 2.7:1. Nb53Ti47 (weight %) is the alloy used. The average density is comparable to that of copper (≈90% of “all copper” for inner-strand material, somewhat higher for outer-strand material). see Figure 6 in Ref. \[12\] Ref. \[10\].
where $J_{c0}$ is the unirradiated value of the critical current density, $\phi$ is the neutron flux, $t$ is the length of operational time and $\alpha=3.5 \times 10^{-24} \text{m}^2$.

Now assume, the 0.37 W at 100 $\mu$A deposited on the hot-spot of the HB coil given in Sec.6 comes from neutrons only (surely an over estimate). Then, for a 14 MeV electron,

$$\text{Neutron flux} = \frac{0.37 \times 6.24 \times 10^{18} \text{eV}}{14 \times 10^6 \text{eV}} = 1.65 \times 10^{11} \text{m}^{-2} \quad (9)$$

For a one year of accelerator operation,

$$\text{Neutron fluence} = \frac{1.65 \times 10^{11} \times 365 \times 24 \times 3600}{3 \times 1.8 \times 10^{-4} \text{m}^2} = 9.64 \times 10^{21} \text{m}^{-2} \quad (10)$$

Using Eqn.8

$$\frac{\Delta J}{J_{c0}} \approx -0.033. \quad (11)$$

Therefore, under the worst-case assumption that the 0.37 W on the HB hot spot came from 14 MeV neutrons, the reduction in the critical current density of the HB over an accelerator year would be 3.3%. While this degradation of the conductor characteristics is certainly significant, it will be overshadowed by the more severe impacts discussed elsewhere in this document.
References


[8] Michael H. Moore, Buddhini Waidyawansa, Silviu Covrig, Roger Carlini, Jay Benesch Primary Beam Steering Due To Field Leakage From Superconducting SHMS Magnets, To be published in NIM, TBA.


