Memo

Date: August 20, 2105

To: RSC, D. Raparia, D. Paquette, and S. Pontieri

From: D. Beavis

Subject: Review of BLIP Soil Caps

Introduction

The BLIP transport is being upgraded with the inclusion of a beam raster system in the transport immediately upstream of the BLIP target area. The raster system will paint the beam on target and is expected to allow higher beam currents to BLIP. A future project may allow for the Linac current to increase from 140 micro-amps to 240 micro-amps. The integrated beam power to BLIP has been increasing over the past few years. A review of the BLIP soil caps which protect the groundwater is warranted.

Linac to BLIP Soil Caps

The beam line transport from the end of the Linac tunnel to the BLIP target area has two soil caps to prevent leaching of long-lived radioactive atoms into the groundwater. The BLIP cap was built while the facility was operated by the Medical Department. At a later date the Y-cap was constructed to cover soil, which could be irradiated by beam losses in the dipole that bends the Linac beam towards BLIP. The design of the Y-cap was reviewed by the RSC on March 4, 2003 and March 9, 2004. Both of the soil caps are displayed in Figure 1.

The dipole that bends the beam into the BLIP transport has a shield located downstream where losses are expected to occur. The primary loss mechanism for this area is tails in the bunches that are at different energies than the main portion of the bunch. When bent by the magnet these off-momentum particles strike the downstream aperture. The shield reduces the neutron fluence into the soil on the sides of the tunnel. The neutrons/cm² per lost proton with energy above 20 MeV is shown in Figure 2 as a function of depth in the soil. The calculations were normalized to

1 A reference to the design of this cap has not been found at the time of writing this report.
2 http://www.c-ad.bnl.gov/esfd/RSC/Minutes/03_04_03%20minutes.pdf
3 http://www.c-ad.bnl.gov/esfd/RSC/Minutes/03-09-04%20minutes.pdf
4 Typically a lower limit of 20 MeV has been used for soil activation in C-AD calculations. The calculations were conducted by K. Yip and are reproduced here.
the soil activation measurements to determine\textsuperscript{5} that the cap should effectively cover soil up to 75 cm past the tunnel wall. The design guide requires that a 10 degree slope be used from the ground elevation to the activated soil. An elevation view of the Linac tunnel and the soil cap is shown in Figure 3.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Plan view of the Linac transport and BLIP spur along with the BLIP and Y caps.}
\end{figure}

\textsuperscript{5} This is based on the cap criteria in 2003 which required that the action limit for $^{22}$Na be 5\% of the drinking water standard (DWS). The present requirement is established by the action limit of 5\% of the DWS for tritium and a corresponding 25\% for $^{22}$Na. This effectively allows for five times more high energy neutron fluence in the soil.
Figure 2: The neutrons per cm$^2$ per interacting proton in the magnet as a function of depth in the soil outside the tunnel.

It is important to note that the slope of the tunnel roof was inadvertently drawn in the wrong direction. The HEBT tunnel drawings were examined and the roof slopes in a southern direction. The roof slope is an important consideration in the cap design since water that percolates to the HEBT tunnel roof can then travel underneath the cap.
The integrated yearly beam to BLIP was anticipated to be constant for future operations at BLIP when the BLIP-Y soil cap was designed in 2003. We are now operating with a yearly beam of 6 times that used in 2003 and anticipate that this may increase to twelve times of more integrated beam with present and future upgrades. Therefore, it was considered worthwhile to check the existing cap designs for the future operating intensity and to specifically check the new raster system near the end of the BLIP beam transport line. There was a commitment to extend the width of the BLIP-Y cap to at least ten feet past the tunnel wall in the NEPA Environmental Evaluation Notification From dated Oct. 10, 2013 as part of the raster project.

**Yearly Beam Expectations**

The dimensions of a soil cap can be estimated using the calculated neutron distributions coupled with the expected beam losses and the BNL action limit for tritium. The operating scenario for the BLIP was provided by D. Raparia and presented in Table I. The amount of delivered beam has been increasing in recent years. The raster system is expected to allow further increases of delivered beam on target. A phase two upgrade is expected to enable more than a factor of two increase in average beam current. The present program is dominated by operations at 117 MeV, but after Phase II the program is anticipated to be nearly evenly split between 117 MeV and 200

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6 E-mail D. Raparia to D. Beavis
MeV operations. The most conservative approach would be to assume all operations at 200 MeV. For the beam raster system\(^7\) it will be assumed that all operations are at 200 MeV and the average current is 240 micro-amperes.

**Table I: Yearly Beam and Losses to BLIP**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>2015</th>
<th>2016 Phase I (Raster)</th>
<th>Future Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Current</td>
<td>115 uA</td>
<td>140 uA</td>
<td>240 uA</td>
</tr>
<tr>
<td>Number of day @ 117 MeV</td>
<td>210</td>
<td>200</td>
<td>~130</td>
</tr>
<tr>
<td>Number of day @ 200 MeV</td>
<td>20</td>
<td>30</td>
<td>~100</td>
</tr>
<tr>
<td>Losses @750 keV</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Losses in linac</td>
<td>0.01%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Losses in transfer line</td>
<td>0.01%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Losses at Collimator</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

\(^7\) This is potentially the ultimate goal of the system. However, for the next several years the lower energy beam current and energy could be taken into account.

![Figure 4: The integrated beam in MeV Ampere hours for the last 10 years. This figure was provided by D. Raparia.](image-url)
BLIP Transport

The BLIP transport extends from the pulsed bending magnet to the BLIP target area wall. The transport contains many optics components and graphite collimators. The layout of the entire transport beam line is shown in two figures.

Figure 5: Transport from the end of tank 9 to the obsolete REF bending magnet Y. Collimator apertures are indicated on the drawing.

Figure 5 displays the upstream section of the BLIP transport. There are six graphite collimators including the one at the BLIP Y. There is typically no shielding outside of the collimators. Selected collimators and portions of beam pipe have thermocouples that are used in the Fast Beam Interrupt (FBI) system to prevent machine damage. The thermocouples are typically set to stop beam operations for a localized beam loss of 0.1% or less. Figure 6 displays the downstream section of the beam transport. The BLIP raster system near the end of the tunnel is not shown. Improvements to the soil caps should account for losses anywhere along the beam transport using the numbers given in the section above.

D. Raparia provided sample beam profiles for the BLIP beam. The most common operating energies are 117 MeV and 200 MeV. The beam envelopes for 95% of the beam are shown in Figure 7 and Figure 8. Both figures indicate that beam losses are expected to be small for a properly tuned beam.

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8 The figures were provided by D. Raparia and are from the August 12, 2004 BLIP window Failure meeting.
Figure 6: Downstream plan view of the BLIP transport. The raster components are installed in the last section downstream of the two quadrupoles.

Figure 7: 95% beam envelopes for the 200 MeV beam.

Figure 8: 95% beam envelope for the 177 MeV beam.
The BLIP Beam Raster System

The downstream section of the Linac to BLIP transport is being upgraded with a beam raster system. This system will paint the beam on the BLIP targets allowing more integrated beam on BLIP targets. The components of the downstream section are shown in Figure 9. Beam losses are expected to occur in the two carbon collimators that are placed in the beam line. The beam losses in the collimators are expected to be less than 0.1% of the delivered beam. The collimators can be used in a simple analysis to determine if the present cap is large enough.

A simple calculation was conducted in MCNPX to estimate the neutrons with energy greater than 20 MeV in the soil adjacent to the carbon collimator. A hollow cylinder of carbon with an inner radius of 3.96 cm, an outer radius of 7.24 cm, and a length of 17.8 cm was used as a crude approximation of the smaller collimator. The beam was made to strike the carbon 1 mm inside the front surface with a direction parallel to the beam line. A tunnel radius of 200 cm was used with a 30 cm thick concrete wall. The soil outside the tunnel wall has a density 1.8 gm/cc. This simple geometry is shown in Figure 10.
The neutron fluence in the peak of the distribution in longitudinal direction is shown in Figure 11. The 200 MeV results are more than a factor of ten higher than the 117 MeV results after 60 cm of soil depth. The neutron distribution has an attenuation length of 38.5 cm (28 cm) for the 200 MeV (117 MeV) proton beam. The attenuation length will be used to extrapolate to the soil depth to meet the BNL action limit for $^3$H in groundwater. The neutron fluence is substantially higher than the results of the Y dipole (see Figure 2). The BLIP-Y dipole has a thick side shield to reduce the radiation into the soil outside the side wall. The size of a cap depends on the integrated yearly beam and on the energy mix of the beam. The cap dimensions will be determined in a later section of this report.
Figure 11: The neutrons/cm**2 per lost proton as a function of depth in the soil. The green points are for 200 MeV protons striking the carbon collimator and the blue squares are for 117 MeV protons striking the carbon collimator. The solid line is an eyeball fit exponential fit to the data.

BLIP Y

The bend into the blip spur is initiated by a pulsed magnet. An additional bend occurs downstream. The losses in the first bend can be caused by tails on the proton pulse or through stripping of one electron from the H⁺ beam by residual gas upstream of the pulsed magnet. The neutral hydrogen follows the trajectory of the proton when it was neutralized. The tails of the proton beam are not at the peak energy of the distribution and their deflection is either larger or smaller than the intended angle. A carbon collimator is located downstream of the pulsed magnet. It is surrounded on the sides by concrete. Details were not available at the writing of this report so a simple steel rod 1 cm in radius and 60 cm long was used as a target. The steel rod was surrounded by a cylinder of concrete 1 foot thick and 60 cm long. The one foot thick tunnel wall starts at a radius of 200 cm and the soil at a radius of 230 cm. This is a simple representation of the area. The distribution of neutrons as a function of depth in the side wall is shown in Figure 12. The attenuation length in the soil is the same 38.5 cm shown in Figure 11.
Figure 12: The neutrons/cm$^2$ as a function of radius. The concrete side wall starts at 200 cm and the soil at 230 cm. The solid line is an eyeball fit to the data in soil. Both 200 MeV and 117 MeV protons are used. The loss is simulated as a 1 cm diameter rod 60 cm long and surrounded by 30 cm of concrete from 30 cm < r < 60 cm.

BLIP Target Area

The soil cap at BLIP was built in 1998. The cap has large dimensions to handle the 100% beam losses on the BLIP targets. A simple geometric approximation of the area was created in MCNPX to check that the cap is properly sized and can handle the increases expected in the future program. The design of the BLIP target area is shown in Figure 13. The geometry will be approximated as a perpendicular wall of soil 200 cm downstream of a copper target. The copper target used is 5 cm long and has a radius of 4 cm. The neutron and proton fluences were tallied in radial bins in 30 cm steps into the soil for energies greater than 20 MeV. This was conducted for both 200 MeV and 117 MeV protons striking the front center of the target.

The fluence of the neutrons for a radial bin of 100 cm < r < 150 cm as a function of depth in the soil is shown in Figure 14. The 200 MeV protons dominate the production of tritium at large depths. The solid curve has an exponential attenuation coefficient of 71.4 cm. The transverse distance should have the same attenuation coefficient determined in the tunnel analysis.

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9 The density used was 8 gm/cc rather than 8.96.
Figure 13: The lower section of the BLIP target area. The beam strikes the targets in a tube containing water. The lower section of the eight foot diameter tank is mainly air. The target is about six feet from the downstream wall. The cavity is 4.75 feet high.

Figure 14: Neutrons/cm$^2$ as a function of longitudinal distance in soil downstream of a copper target used to simulate the BLIP target area. The soil starts at 180 cm. The green circles are for 200 MeV protons and the blue squares are for 117 MeV protons on target. The solid curve is an eyeball fit to the distribution. The data is tallied in a radial bin from 100<r<150 cm.
Estimation of Cap Dimensions

The cap dimensions can be estimated following the guidance given in the SBMS exhibit titled Design Practices for Known Beam-Loss Locations. Table II of footnote 10 provides an estimation of the number of produced tritium atoms per cc that lead to the DWS. The BNL action limit is 5% of the DWS or 1,000 pCi/L of water. A modified version of this scheme will be used which was previously presented to the RSC.

The cap size requires the estimation of the vertical column of soil that can be leached. For the collimators in the BLIP spur tunnel the distance to the tunnel wall has been approximated as 200 cm with a concrete wall of 30 cm. A distance of 200 cm into the soil has an estimated effective column height of 420 cm. The BNL subject area uses a value of 60 cm. The goal of BNL action limit is to keep the $^3$H concentration in the groundwater to less than 1000 pCi/L.

Based on the transverse attenuation length for 200 MeV proton interactions of 38.5 cm, and 0.075 $^3$H per inelastic collision, the collimator simulation for transverse radiation, and an estimated loss of $3\times10^{19}$ protons per year limiting neutron fluence would be $3.5\times10^{-12}$ n/cm$^2$ per lost proton. This occurs at distance of 310 cm of soil into the soil. Another 140 cm is required for the ten degree angle to the surface. The cap is required to be 450 cm beyond the tunnel wall (15 feet).

A three-dimensional calculation was conducted by K. Yip and R. Seemungal with substantial details and is shown in Figure 15. The results are in agreement with the calculations presented in this report.

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10 [https://sbms.bnl.gov/sbmsearch/subjarea/40/1r09e011.pdf](https://sbms.bnl.gov/sbmsearch/subjarea/40/1r09e011.pdf)
13 Fore the side of the tunnel facing HEBT 130 cm was used. There is only a small impact on the effective column height.
14 The estimate uses the 38 cm attenuation length in soil obtained using 200 MeV. The integration is conducted with a simple spread sheet.
15 Based on Table I.
16 It is assumed that all losses are at 200 MeV.
17 The value at the mid-plan is 6.7E-11 n/cm$^2$ with E>20 MeV.
18 The edge of cap is 17 feet upstream of the BLIP-Y. This was checked and meets the design goals. This is also supported by Figure 15.
The beam transport closer to the north wall and the cap towards the HEBT tunnel should extend 16 feet beyond the tunnel wall. If this distance ends over the HEBT tunnel then the cap must be extended 4.5 feet beyond the north side of the HEBT tunnel to prevent water from flowing to the HEBT tunnel roof and under the BLIP cap. The cap location on the north side must also account for the lack neutrons that are generated in the BLIP line that travel though the HEBT tunnel walls.

The cap dimension in the forward direction can be estimated using the attenuation length of 71 cm and normalization results from Figure 14. A distance of 1060 cm is required. The neutron fluence required to meet the BNL action limit is $3.5 \times 10^{-15} \text{ n/cm}^2$ with energy greater than 20 MeV. The effective column height is 780 cm. With the 4.5 feet to account for vertical dispersion the cap should extend 39 feet past the end of the BLIP tank. This is approximately the location of the monitor wells. This area is covered with an asphalt road/parking area.

The transverse dimension of BLIP target cap was estimated using the same target as the forward beam direction except the soil wall was four feet away. If 4.5 feet is used for the 10 degree angle then the cap must be 30 feet to the side of the BLIP tank. The present cap extends to a distance of 35 feet from the tank. The raster upgrade is well under the BLIP cap. The wide portion of the BLIP cap starts 24 feet upstream of the concrete end wall of the tunnel. The raster upgrade begins at 17.5 feet upstream of the wall. It is concluded that the BLIP cap is large enough to accommodate future upgrades in beam intensity.

20 Based on drawing D25-M-1652 with the raster project laid on the print.
The location where the BLIP cap joins the asphalt paving is about 35 feet and is close to the required distance as it is about 300 to 400 cm offset to the beam axis. The ground is also very sloped in this region and there is a guard rail. It is suggested that this area be left uncovered considering the conservative nature of the calculations.

Summary

The cap around the BLIP target area is large enough to accommodate future beam increases to BLIP. The cap over the BLIP transport, BLIP-Y cap, needs to be widened to accommodate intensity increases. The BLIP-Y cap needs to ensure that water cannot travel under the cap via the slope in the Linac tunnel roof and the HEBT tunnel roof. A final drawing of the cap changes is being prepared.