Date: June 23, 2017

To: M. Palmer, C. Cullen, C. Folz, J. Skaritka, K. Kusche, and RSC

From: D. Beavis

Subject: ATFII Radiological Design

There has been essentially no radiological design for ATFII since the middle of 2015 when the project started reorganizing. This note provides some remarks on the status of the design and good practices to consider. Some of the discussions below are from documents that were never distributed.

Design Parameters

The present understanding is that Phase I will include the Linac and Experimental Hall 1 (EH1). The top energy will be 110 MeV and maximum beam power will be 165 Watts. Phase II will have the downstream portion of the Linac increased in beam energy and beam power to 300 MeV and 450 Watts, respectively.

The previous design had higher energy and beam power. The Table 1 below was prepared in Jan. 2015 listing the beam parameters and the device that limited the beam maximal conditions. An updated Table should be prepared for the Safety Analysis Document (SAD). The initial layout of the Linac vault side wall shielding was based on Table 1. The initial layout was based on a 1% routine beam loss at any location, a routine dose rate exterior to the side wall shielding of 0.05 mrem/hr, and the shield supplemented with radiation monitors to terminate large beam losses.

<table>
<thead>
<tr>
<th></th>
<th>Single-pulse mode</th>
<th>Multiple-pulse mode</th>
<th>Limited by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) SDL Gun</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Routine energy, MeV</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. energy, MeV</td>
<td>7</td>
<td>RF breakdown in gun</td>
<td></td>
</tr>
<tr>
<td>Routine charge/bunch, nC</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. charge/bunch, nC</td>
<td>4</td>
<td>400</td>
<td>Laser. Failure mode limit ~1000 nC.</td>
</tr>
</tbody>
</table>

Table 1: ATFII Linac Beam Parameters

1 Provided by e-mail by K. Kusche April 29, 2014.
Minimum energy, MeV | 15 (Or zero) |  
Routine energy, MeV | 100 |  
Max. energy, MeV | 160 (see Note 2) | Saturated power of klystrons; modulator limitation, etc.  
Routine AVG current, nA | 0.75 | (0.5 nC, 1.5 Hz)  
Max. AVG current, nA | 4000 | (4 nC, 10 Hz, 100 micropulse)  

3) Repetition rate  
Routine, Hz | 1.5 |  
Maximum, Hz | 10 | Modulators  

4) Micropulse mode  
Routine | 1 |  
Maximum | 100 | Laser configuration  

The project requested that the dose rate outside the shield or portions of the shield be less the 0.05 mrad/hr. This is motivated to allow guests to use the facility for substantial time without requiring a TLD. It also avoids training issues for using that come for a brief period of time. A thicker shield will results in less reliance on radiation monitors. The lowest interlock rate for the present chipmunks is 2.5 mrad/hr and the baseline is on the order of 0.1-0.2 mrad/hr. The chipmunks are typically not used to alarm at dose rates below 1 mrad/hr but alarm levels to 0.5 mrad/hr should be practicable. The present side wall designs are expected to meet the design request, especially with the reduced beam energy and power.

**Linac Enclosure**

The Linac vault was planned to have a wide labyrinth near the gun to accommodate equipment and a downstream labyrinth, which would have a smaller width. Both labyrinths were initially intended to be for entrance and exit, but the downstream labyrinth could have the interlocks designed for exit only. The upstream labyrinth was designed to meet the necessary criteria but the calculations have not been documented. The calculations should be conducted and documented for the new operating beam parameters, including the gun capability. The radiological design of the downstream labyrinth was not conducted nor an appropriate location selected. In general, the labyrinths provide better attenuation if the cross-sectional area is kept as small as reasonable.

The laser port attenuation was calculated with associated shielding on the floor around the laser beam transport tube. The floor shielding is not shown on any prints nor was the calculation documented. The port is expected to have shielding on the floor both inside the Linac enclosure and outside to sufficiently attenuate radiation.

Penetrations have been discussed in the past for Klystron waveguides and utilities but final designs were not completed.

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2 In a simple approximation for photons the attenuation of a three-legged labyrinth with fixed lengths goes as $A^3$. 
There has been no documentation provided on the shields for the Klystrons intended for use for the Linac. It is not clear if the existing shields on these existing devices are sufficient. The area classification around the Klystrons should be designated. It would probably be appropriate to make it a Radiation Area pending experience with the devices and documentation.

Local shielding has not been designed for any local sources such as collimators, shutters, dumps, and energy slits.

The transverse shielding was based on initial analysis for a range of electron energies and given in Footnote 3. A substantial portion of the shielding has four feet of heavy concrete backed by two feet of light concrete. The design was changed from “standard” two-foot thick concrete blocks to the use of roof beams. The roof beams introduce a large gap in some locations that has not been analyzed but are expected to be satisfactory.

The peak photon dose rates for full beam faults for the seven energies are given in Table 2 for wall thicknesses of 120cm l.c., 160cm l.c., and 120cm h.c. +40 cm l.c. Heavy concrete attenuation was estimated using the ratio of the densities of heavy to light concrete. The results demonstrate that the doses rates though four feet of light concrete are relatively low. For energies of 160 MeV and below the design criteria of less than 0.05 mrads/hr is met when the concrete walls are treated as homogeneous concrete.

Table 2: Peak Photon Dose Rate created by four micro-amps of lost electrons with concrete walls.

<table>
<thead>
<tr>
<th>Beam Energy (MeV)</th>
<th>Dose Rate (rads/e)</th>
<th>120 cm of l.c. Dose Rate (mrads/hr)</th>
<th>160 cm of l.c. Dose Rate (mrads/hr)</th>
<th>120 cm h.c. + 40 cm l.c. Dose Rate (mrads/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1.37*10^{-18}</td>
<td>124</td>
<td>10.</td>
<td>0.25</td>
</tr>
<tr>
<td>160</td>
<td>4.63*10^{-19}</td>
<td>42</td>
<td>3.</td>
<td>0.06</td>
</tr>
<tr>
<td>80</td>
<td>3.60*10^{-19}</td>
<td>32</td>
<td>2.4</td>
<td>0.05</td>
</tr>
<tr>
<td>20</td>
<td>1.60*10^{-19}</td>
<td>14</td>
<td>0.8</td>
<td>0.01</td>
</tr>
<tr>
<td>5</td>
<td>1.38*10^{-21}</td>
<td>0.12</td>
<td>0.003</td>
<td>-</td>
</tr>
<tr>
<td>3.5</td>
<td>1.76*10^{-22}</td>
<td>0.015</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.0</td>
<td>3.0*10^{-24}</td>
<td>0.0003</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The initial design of the side wall shielding and roof eliminated essentially all gaps that allow direct line-of-sight to beam loss locations. Cracks can create large dose rates, although typically small in area. A seam 1 cm wide was placed into the analysis and the target aligned with the seam for the “old beam parameters”. When a seam provides line-of-sight from the outside to a

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3 D. Beavis, August 29, 2016; [http://www.e-ad.bnl.gov/esfd/RSC/Memos/8_29_16_PhotonDose.pdf](http://www.e-ad.bnl.gov/esfd/RSC/Memos/8_29_16_PhotonDose.pdf). These estimates were conducted as part of the initial design in 2014.

4 The distance has not been changed from that used in Footnote 3. Scaling with 1/distance squared can be used to adjust for distance changes. The transverse TVLs given in Error! Reference source not found. are used for the extrapolation.

5 Heavy concrete with a density of 3.5 gm/cc and light concrete has a density of 2.35 gm/cc were used for the analysis. However, after these calculations it was determined that much if not all the heavy concrete has a density of 4.0 gm/cc.
potential source that is directly struck by the beam there is no attenuation provided by the shield only collimation. Table 3 provides the peak dose rate though a 1cm seam for several distances from the shield. The width of the area to tally the dose is the same as the gap in the shield. The dose rate is approximately a factor of 500 higher and the dose rate persists for a substantial distance.

Table 3: Photon Dose through a 1cm Wide seam for 160 MeV Beam

<table>
<thead>
<tr>
<th>Distance from shield (cm)</th>
<th>Dose per electron (rads/e)</th>
<th>4 micro-amps lost (mrads/hr)</th>
<th>Bulk shield (mrads/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>2.54*10^{-16}</td>
<td>22,900</td>
<td>42</td>
</tr>
<tr>
<td>90</td>
<td>1.61*10^{-16}</td>
<td>14,500</td>
<td>32</td>
</tr>
<tr>
<td>300</td>
<td>5.41*10^{-17}</td>
<td>4,900</td>
<td>16</td>
</tr>
<tr>
<td>600</td>
<td>2.11*10^{-17}</td>
<td>1,900</td>
<td>8</td>
</tr>
</tbody>
</table>

The potential dose rate through seams in a single layer concrete shield made of blocks was the main motivation for a second layer of shielding, allowing the seams to be covered.

The end walls of the Linac shown on the layouts are not based on radiological design. End walls of the facility need to reduce the forward radiation to acceptable levels for routine and fault conditions. The project in conjunction with the RSC needs to determine the approach to apply for these walls. Some options are:

1. Make the end wall thick enough for direct hits of the electron beam. (about 400-500 cm of light concrete)
2. Supplement the end wall with radiation detectors and determine the thickness for routine beam losses.
3. Place distributed shielding along the beam transport to reduce the radiation that shines on the end-wall. This method requires more configuration management than methods 1 and 2.
4. Combination of the above.
5. Placement of Pb, Steel, and heavy concrete can reduce the dimensions of the required shielding.

The interface walls between the Linac and the EHs have not been designed. These transition walls fall between forward walls and side wall shielding depending on the angle relative to the electron beam.

Fault modes, interlocks and shielding for the horizontal chicane have not been analyzed.

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6 The collimation selects a portion of the target. The calculation includes dose that transverse a small portion of the shield to enter the crack.
7 The results were obtained from Table II and scaled with (1/r)^2.
**Beam Switches**

The beam switches for ATFII EH1&2 are not designed. The last known request was that if someone entered EH1 that the Linac beam would be turned off. The request may need to be reconsidered. At present there are no approved critical devices for EH1 or EH2. Two typical critical devices are beam plugs and turning off an appropriate bending magnet(s).

**Beam Plug (shutter)**-The beam plug needs to be a combination of a movable plug and shadow shielding to prevent scattered radiation from being transported through the beam port to the EH. The power of 110W probably does not require cooling to prevent unsafe failures but the increased temperature may cause vacuum issues. A beam shutter for 450 W will become hot based on an old estimate and cooling would be necessary.

If the beam is not intended to strike the shutter for any real length of time then the cooling can be eliminated. For example if the shutter is the second critical device and would only see beam if the first device fails then the vacuum issue is probably no a problem.

An initial length was given for a beam plug based on the shutters used for NSLSII. It can be recalculated based on new beam parameters and the old estimate is provided in Appendix I.

**Bending Magnet**-Another popular option is to turn off an upstream beam that removes the beam from the acceptance of the beam line. After the magnet is turned off the beam must be transported to an approved beam dump. The problem with this technique is that the beam optics can change and the beam hit an area in the vacuum system which allows radiation into the acceptance of the beam line. One might argue that a downstream shutter would take care of the radiation, but the usual acceptance criterion for a critical device design is that each critical device is capable of removing the radiation hazard. The RSC uses a slightly modified version, which is based on the fact that a single device is required to remove dose rates below 50 rem/hr. The RSC accepts pairs of devices where each device reduces the radiation hazard to less than 50 rem/hr and both must eliminate the radiation to acceptable levels. The RSC’s preference is for each device to eliminate the radiation as much as possible and to acceptable levels.

The elimination of scattered radiation from being a problem can be eliminated by removing vacuum box surfaces out of the acceptance of the downstream beam line and preventing radiation from hitting the surfaces. Apertures upstream of the magnet can be placed to prevent miss-tuned beam from striking the surfaces. Distributing the bend over several distributed magnets can also be used.

The beam dump associated with the bending magnet or the shutters will require shielding to reduce the radiation from challenging the shielding walls and roof. Typically the local shielding should reduce the radiation to less that the routine local loss used in the design of the shielding.
**Options/combinations**

The design can employ any combination of devices. There should be different designs for the devices to avoid common mode failures. For example, two identical beam shutters should be avoided if possible. Other options include the use of alternate critical devices. During some periods it may not be necessary to operate the Linac with the EH occupied and then the critical devices could stop the gun beam and close the beam plug as an example.

**Beam Dumps**

The Linac is expected to have at least one beam dump and the EHs are expected to have two. The project has expressed interest in using beam stops that have been recovered from SDL. Analysis of an SDL beam stop was conducted\(^9\) by H. Seymour and K. Yip.

**Experimental Halls**

The experimental halls have essentially the same issues as the Linac tunnel. Initial discussion for EH1 was to have the shield walls designed for routine losses of 1% and if an experiment created increased beam losses that local shielding would be added to reduce the radiation. I would suggest that this should be reconsidered carefully. Experiments that can disrupt beam transport to the final beam dump may become problematic.

The upstream labyrinth and CO2 laser penetration were designed for the original beam parameters but present layouts seem to suggest that the layout has changed. This should be resolved. Other penetrations and labyrinths for EH1 have not been designed. Some layouts have shown three labyrinths for EH1. I would discourage more than two as they represent potential weaknesses to the shield design, add to the interlock design, and consume floor area. However, if the Project has a good need for three labyrinths then they can be designed and reviewed.

The experimental halls are likely to have conditions that change more frequently than the Linac tunnel. The EH will have experimenters installing and changing experimental equipment with time. The users are not expected to be less familiar with all the potential safety issues as the ATFII personnel. Thus the layout designs should take this into account.

**Other Radiological Issues**

There are a series of radiological issues that will need to be considered for the designs. These include air activation, soil activation, residual activity, water activation, ozone concentration, tritium concentration and hydrogen generation in cooling water. Some of these issues were examined for the use of an SDL beam dump (see Footnote 9). Conditions in the EH are expected to change with time (due to changes in experiments) and it is likely these possible issues will need to be examined and potentially mitigated for the changing conditions.

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Appendix I.

ATFII Beam Shutters/Plugs
D. Beavis
March 11, 2015 (as distributed to ATFII personnel)

This note is to provide some simple and crude guidance for beam shutters to be used at ATFII. The primary purpose is for people to understand the space requirements for shutters and other limitations but without a detailed design for layout planning.

The report\textsuperscript{10} of P.K. Job et. al. provides analysis of NSLS-II shutters made of Tungsten alloy\textsuperscript{11}. The shutter has transverse dimension of 12 cm and a length of 20 and 30 cm. A 1.5 meter thick shielding wall is downstream of the shutter with a 4cm beam tube through it. There is a Pb insert in the wall near the beam pipe. The dose is scored as at the exit of the beam tube from the shielding 2 meters from the end of the shutter. A plot of the geometry is copied from their report and shown below.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{geometry.png}
\caption{Schematic Geometry for FLUKA Simulation}
\end{figure}

\textsuperscript{10} P.K. Job, A. Hussain, and R. Popescu; “Validation of Analytical Calculations of the NSLS-II Injection Shutters with FLUKA Monte Carlo Program”, NSLS-II Technical Note 132, July 17, 2014

\textsuperscript{11} Density is 18 g/cm\textsuperscript{3} which is typical of non-magnetic tungsten alloys.
The dose tallied on the exterior wall is shown in the figure below for a 20 tungsten shutter, which again has been copied directly from their report.

![Figure 4 Dose Rates at the Exterior of the Linac Forward Wall with 200 MeV Electrons at the rate of 15 nC/s, Incident on the W Shutter Block of Thickness 20 cm.](image)

The neutron leakage is 24.5 mrem/hr and the photon leakage is 2.0 mrem/hr. Examination of the 30 cm shutter results shows that the gamma peak from the beam pipe is absent with an overall photon wall dose rate of approximately 0.05 mrad/hr.

The results can be scaled for ATFII at 160 MeV by using \((160\text{MeV}/200\text{MeV})^2 \times 4,000\text{nA/(15 nA)}\) which provides a scaling factor of 171. This would mean that a 20 cm tungsten alloy shutter would leak 342 mrad of photons and 4190 mrem of neutrons out the beam pipe two meters away from the end of the shutter. If the beam dump is made 25 cm long then the photon peak is removed to the baseline dose of 10 mrad/hr. The shield wall would be required to be thicker. A shutter 28 cm of tungsten alloy would reduce the direct punch-through of the shutter to 1 mrad/hr. Since this radiation is within the beam pipe this is probably acceptable. Note that it would take approximately 85 cm of copper to provide the same protection. Initially, it was assumed that the beam shutter would be a disk of water cooled copper approximately 5 cm long followed by a non-cooled disk of tungsten alloy. If space in the beam line is not at a premium then the shutter can be all copper.

Heavy materials are not efficient at attenuating low energy neutrons. A block of polyethylene encased in stainless should be placed in a separate vacuum box to attenuate the neutrons. A few TVLs will reduce\(^{12}\) the dose rate substantially.

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\(^{12}\) In this case two TVLs of polyethylene should reduce the neutron dose by far more than a factor of 100, since the neutrons will be scattered to a much larger area. The TLV is based on a broad beam and we do not have that condition here. A TVL is for polyethylene is 15 cm.
Space is needed for the shutter vacuum box and probably one shadow shield at both ends of the shutter to reduce dose on equipment if the shutter is intended to be struck with beam. Local shielding on the sides of the shutter may be useful.

The large diameter of the beam shutter is to provide sufficient electromagnetic shower containment in transverse direction such that the uncontained radiation does not scatter off surfaces and into the beam aperture. To optimize the size of the shutter will require specific calculations rather than the scaling conducted here. This is one reason the shutter from APS will