Analysis of residual activity at the FRIB linear accelerator

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Abstract. The Facility for Rare Isotope Beams (FRIB) is an accelerator facility being established at Michigan State University (MSU). The facility will utilize a broad range of primary ion beams from $^{16}$O to $^{238}$U with a beam power of up to 400 kW and energy of 200 MeV/u for $^{238}$U in its baseline configuration to produce rare isotopes. A possible facility upgrade will include an increase of the beam energy up to 400 MeV/u for $^{238}$U and addition of new light ion beams down to $^3$He and protons for Isotope Separation Online (ISOL) operations. The FRIB double-folded linear accelerator will accommodate several high-rate beam loss devices. The residual activity of these devices were analysed and results are presented in this work.

1. Introduction

There are several segments in the FRIB linear accelerator (figure 1): front-end that delivers the primary beam from ion sources down to the accelerator tunnel; Linear Segment 1 (LS1) where the primary beam is accelerated up to an energy of 20 MeV/u (16.5 MeV/u for uranium); Folding Segment 1 (FS1) where the primary beam is stripped of electrons and proper ion charge states are selected for further acceleration; Linear Segment 2 (LS2) where the primary beam is further accelerated (up to 149 MeV/u for uranium); Folding Segment 2 (FS2); Linear Segment 3 (LS3) which brings the beam energy up to 200 MeV/u for uranium; and Beam Delivery Section (BDS) which delivers the primary beam to the target hall. A number of devices with the beam loss rate above 100 W are found across the accelerator. Induced radioactivity of each of these devices will be discussed in dedicated sections. Analysis of a few other devices such as collimators and chicanes where beam loss rates are either lower or devices that can only be used with a limited set of specific beam types was not included in this work. Induced radioactivity of various utilities such as water and nitrogen and helium in the cryogenic systems, the activation of air and condensates are outside of the scope of this work.

The FRIB facility is expected to start the physics program in 2022. This is followed by a 5 year plan to ramp up to the full power. During this time period, measurements will be taken to understand actual beam loss rates and activity levels of the linear accelerator components. Future updates were planned in the design of the facility. In the simplest scenario, Linac Segment 3 can accommodate more superconducting accelerating structures to bringing the beam energy up to 400 MeV/u for uranium while keeping the same power of 400 kW. Alternate scenarios may include construction of a new Isotope Separation Online (ISOL) target station and a light ion injector, or replacing the accelerating
structures with new more efficient ones. In that case, the devices considered in this work are expected to be re-evaluated or redesigned.

![Figure 1. Schematics of the FRIB linear accelerator. The arrows indicate high-rate loss beam devices.](image)

2. **Rationale for device local shielding**

Two main sources of irradiation inside the linac tunnel are normal operation uncontrolled beam losses and beam interactions with high-rate loss devices. A continuous beam loss rate of 1 W/m is assumed as baseline design input for the normal losses. In most cases, however, the activation of a beamline component is dominated by the local beam-device interactions if the loss rate in the device exceeds 100 W. The design goal is to provide enough local shielding for such a device so that the impact on the radiation environment from the local interactions would be comparable to that caused by the continuous 1 W/m beam losses. The three primary design considerations for the local shielding are the prompt dose to workers and public above the bulk tunnel shielding (6 m of concrete and soil), activation of the soil and the ground water around the tunnel, and the residual activation for the purpose of hands-on maintenance. Only the residual activity is of importance at Linac Segment 1 and Folding Segment 1 due to the low energy of the primary beam. The design goal for the local shielding from the standpoint of hands-on maintenance is to keep the dose rate from activated component below 5 mrem/h (50 μSv, 100 rem=1 Sv) whenever possible to prevent each area from being designated as a “Radiation Area” as specified by Nuclear Regulatory Commission (NRC) regulations [1] where additional controls are required to work in these areas. If the local shielding for a specific device is impractical due to the device size for example, then movable screens (temporary shielding) are considered to limit the exposure from the activated components to a manageable level.

3. **Charge stripping device**

The charge stripping device is located in Folding Segment 1. Its purpose is to strip the primary beam ions to higher charge states for more efficient acceleration in the downstream accelerating structures. All the beam types up to argon will be fully stripped. The uranium beam will have five charge states after the stripping device - 76, 77, 78, 79 and 80. A simple carbon foil-based device is considered for the initial operation while the beam intensities are still low. The baseline design will be based on liquid lithium curtain however.

A simplified model used in the calculation is shown in figure 2. There is a 1 mg/cm²-thick lithium curtain, lithium storage vessel, argon gas cover volume, external argon storage vessel, and a steel containment vessel with two wall thicknesses considered – 0.5 inch and 1 inch. The radiologically bounding beam in this case is $^{18}$O at 20 MeV/u. The full beam power at the stripping device is 40 kW. In addition, the contribution from the normal uncontrolled beam losses was evaluated. The activation of the device was calculated at a distance of 30 cm [1] from its walls assuming 30 y of irradiation and
4 h after shutdown. The programs PHITS Error! Reference source not found. and DCHAINSP-2001 [3] were used. The activities at other irradiation and decay times can be easily recalculated with existing tools based on known decay curves of common radionuclides. One of such tools is provided by MARS15 [4]-[7] in form of a matrix. Radionuclide production in argon and lithium were also evaluated as well as the consequences of the argon emissions, but these topics are outside of the scope of this work.

It was found that the induced radioactivity at the stripping device is dominated by the beam-stripper interactions over the normal beam losses in all the locations except for an area upstream of the external argon reservoir. A typical dose rate distribution is shown in figure 3. Table 1 shows that, depending on the location and the wall thickness, the maximum dose rate is reaching 99.8 mrem/h. The FRIB physics program will require a mixture of various beams, therefore there is a reduction factor for the dose rate due to the use of other beams which will produce less intense radiation fields. Nonetheless, the dose rate in the area around the unshielded stripping device is expected to be above 5 mrem/h, therefore the area will be controlled as “Radiation Area”. Using additional local shielding is impractical in this case because of the substantial device size and because the dose rate is not much higher than 5 mrem/h. Portable shielding screens will be utilized to keep doses as low as reasonably achievable.
Figure 3. Residual dose rate distribution upstream of the secondary containment vessel.

Table 1. Maximum and average residual dose rates at various locations of the charge stripping device.

| Location                        | Average dose rate (mrem/h), 0.5 inch vessel | Maximum dose rate (mrem/h), 0.5 inch vessel | Average dose rate (mrem/h), 1 inch vessel | Maximum dose rate (mrem/h), 1 inch vessel |
|---------------------------------|---------------------------------------------|---------------------------------------------|-------------------------------------------|-------------------------------------------|
| Right side of device            | 18.6                                        | 49.3                                        | 12.5                                      | 33.1                                      |
| Left side of containment vessel | 27.2                                        | 99.8                                        | 19.8                                      | 74.4                                      |
| Below containment vessel        | 13.6                                        | 34.5                                        | 9.3                                       | 21.8                                      |
| Above containment vessel        | 16.7                                        | 47.5                                        | 11.4                                      | 32.9                                      |
| Upstream of containment vessel  | 13.7                                        | 42.7                                        | 8.7                                       | 28.0                                      |
| Downstream of containment vessel| 20.5                                        | 75.3                                        | 17.0                                      | 72.5                                      |
| Upstream of argon storage vessel| 8.5                                         | 16.4                                        | 5.3                                       | 10.7                                      |
| Left of argon storage vessel    | 9.5                                         | 18.1                                        | 6.3                                       | 12.7                                      |

4. Charge selection device
The main function of the charge selection device is to remove unwanted charge states from the beam after the charge stripper. At the moment of writing this contribution, a design for device capable of handling the full beam power has not been developed yet. A temporary device will be used during the beam commissioning and the initial operation until 10% of the full power is reached. Since the initial beam power will be limited, the temporary device is much simpler than a concept for the full power device. The temporary device will be equipped with movable water-cooled jaws as opposed to rotating graphite disks. Final full power design will be based on operational experience during power ramp-up to 400 kW. The low power charge selector will be based on the existing hardware with cooper alloy jaws (see figure 4). The device will be enclosed in a 6 inch-thick steel box to mitigate the radiation streaming from the device (figure 5). Although the oxygen isotope beams are considered radiologically bounding, these beams will be fully stripped, and, therefore, the charge selection device will not be used with them. According to table 2, the lightest of the most commonly used beams will be $^{48}$Ca, with 135 W deposited in the jaws. The heavier beams will be producing less intense radiation fields than $^{48}$Ca (based on study of neutron fluxes and activation), even though the power deposited in the jaws may be higher. This makes the beam of $^{48}$Ca radiologically bounding for this device.

A typical distribution of the dose rate on-contact (0 cm) is shown in figure 6. The distribution was obtained with the MARS15 code assuming 30 days of irradiation and 1 day decay after beam shutdown (“30 d/1 d/0 cm” dose rate). Table 3 summarizes both the maximum and average dose rates at various surfaces of the device shielding. Since the shielding size is similar to that of a human
“phantom”, the average dose rate represents the actual “whole body” exposure more accurately. The average dose rate will stay below 1.7 mrem/h, and the maximum dose rate will be below 8.4 mrem/h.

The top portion of the shielding has a 14 inch diameter hole for the vacuum pump. This hole is substantial and will result in a streaming from the activated jaws. It was estimated that the dose rate above the hole 30 cm above the top shielding will be approximately 50 mrem/h. A barrier around the top device shielding is considered to limit the access.

![Figure 4. Temporary charge selection device.](image1)

![Figure 5. Shielding assembly of the temporary charge selection device.](image2)

**Table 2. Beam characteristics at the temporary charge selection device.**

| Beam  | Duration (week) | Energy after stripper (MeV/u) | Beam power on stripper (W) | Number of charge states | Fraction of beam to be accelerated (%) | Power loss on charge selection jaws (W) |
|-------|-----------------|-------------------------------|---------------------------|--------------------------|----------------------------------------|---------------------------------------|
| $^{238}$U | 12 | 16.5 | 1250 | 5 | 80 | 250 |
| $^{48}$Ca | 6.34 | 20 | 1135 | 1 | 90 | 135 |
| $^{78}$Kr | 2.21 | 20 | 1135 | 3 | 90 | 135 |
| $^{124}$Xe | 1.3 | 17.3 | 1250 | 3 | 80 | 250 |
| $^{18}$O | 0.86 | 20 | 1000 | 1 | 100 | 0 |
| $^{86}$Kr | 0.63 | 19.3 | 1130 | 3 | 90 | 130 |
| $^{16}$O | 0.44 | 20 | 1000 | 1 | 100 | 0 |
| $^{36}$Ar | 20 | 1000 | 1 | 100 | 0 |
Figure 6. Residual dose rate on-contact at the top shielding of the temporary charge selection device calculated after 30 days of irradiation and 1 day after shutdown. The circle indicates the 14 inch hole for the vacuum pump.

Table 3. Maximum and average residual dose rates on-contact at various shielding surfaces of the temporary charge selection device. The dose rates were calculated assuming 30 days of irradiation and 1 day after shutdown.

| Shielding Surface | Peak Dose Rate (mrem/h) | Average Dose Rate (mrem/h) |
|-------------------|-------------------------|---------------------------|
| Downstream        | 8.4                     | 1.7                       |
| Upstream          | 0.44                    | 0.15                      |
| Top               | 7.0                     | 0.59                      |
| Bottom            | 1.7                     | 0.41                      |
| Left              | 0.22                    | 0.068                     |
| Right             | 0.72                    | 0.35                      |

5. Beam dumps in Folding Segment 1
There are two small beam dumps in Folding Segment 1 (figure 7). The beam dump names are abbreviated FS1a and FS1b. The beam dump FS1a is intended for tuning up Linac Segment 1. We assumed that the operating duty will be limited to 5% of the operational time of 5556 h a year. The beam power at FS1a is 15 W. The second beam dump, FS1b, is purposed for the study of charge selection. It will be used for only a few days a year but at a higher beam power of up to 500 W. The designs of both dumps and their shielding are similar. Both are made of tungsten with brazed air-cooled copper fins. The dumps are enclosed in steel shielding with the top part (thinnest) to be 4 inches-thick and 6 inches-thick respectively (figure 8 and figure 9). Since the holes in the shielding are small, the direct streaming from the dump cores is relatively small, thus the dose rate at the dumps is driven by the activation of the shielding. The “30 d/1 d/30 cm” dose rate calculated at various
surfaces of the FS1a assembly for the bounding beam of $^{18}$O at 20 MeV/u is insignificant (table 4). For the FS1b dump, the dose rate is higher and reaches 8.12 mrem/h on average for the downstream surface of the shielding assembly (table 5). Radiation levels of bare dump cores are not yet determined. This will be relevant for dump maintenance operations.

![Figure 7. Schematics of Folding Segment 1.](image)

![Figure 8. Cut-through view of the FS1a shielding assembly.](image)

![Figure 9. Cut-through view of the FS1b shielding assembly.](image)

**Table 4.** Maximum and average residual dose rates at various surfaces of the FS1a shielding assembly.

| Shielding surface | Maximum dose rate (mrem/h) | Average dose rate (mrem/h) |
|-------------------|----------------------------|---------------------------|
| Top               | 1                          | 0.09                      |
| Bottom            | 0.5                        | 0.05                      |
| Upstream          | 0.1                        | 0.008                     |
| Downstream        | 1.4                        | 0.17                      |
| Side              | 0.15                       | 0.015                     |

**Table 5.** Maximum and average residual dose rates at various surfaces of the FS1b shielding assembly.
6. Beam dumps in high energy linac segments

The beam dumps in Folding Segment 2 and Beam Delivery Section have similar cores and shielding assemblies (figure 10). The cores are tungsten cylinders with air cooled copper fins. The shielding assemblies around the cores are composed of steel bricks 10 inches in height. An assumption was made that the steel blocks were constructed of A36 steel (type of construction steel). Other types of steel may be used for the construction. We currently consider either cast iron or ductile iron. The steel shielding rests on a concrete slab. The air cooling to the dump is provided through a channel that runs through the slab and steel assembly (figure 11). The shielding must be sufficient to provide protection against prompt exposure to the workers and public above the ground, residual exposure to the workers in the linac tunnel, and activation of the ground water and soil at the beam dumps. The shielding dimensions were verified against all three radiation sources. Note that different shielding dimensions are driven by different radiation sources. For example, the size of shielding above the dump core was determined by facility design goals to have the prompt dose to workers above the ground level below 0.1 mrem/h and the prompt dose rate to public below 0.001 mrem/h. The shielding below the dump core is validated against the design goals for ground water activation. The size of the assembly in the horizontal plane was estimated to meet the design goals for the residual exposure to workers in the linac tunnel.

Both the dumps are intended for tuning up the corresponding linac section – the FS2 dump will absorb beam passing through Linac Segment 2 while the BDS dump will be used to tune up Linac Segment 3. Although all the beam types can be used, the calculations presented in this section were carried out for the radiologically bounding beam of $^{18}$O. Both the dumps were designed to operate at a beam power of up to 135 W and a duty factor of 5%. The beam of $^{18}$O will be at 207 MeV/u at the FS2 dump, and at 278 MeV/u at the BDS dump.

| Shielding surface | Maximum dose rate (mrem/h) | Average dose rate (mrem/h) |
|-------------------|---------------------------|---------------------------|
| Top               | 9.07                      | 1.81                      |
| Bottom            | 10.2                      | 1.76                      |
| Upstream          | 0.93                      | 0.21                      |
| Downstream        | 29.9                      | 8.12                      |
| Side              | 4.30                      | 0.74                      |

Figure 10. 3-D rendering of the FS2 shielding assembly.

Figure 11. Cut-through view of the FS2 shielding. Air cooling channel is seen.
6.1. Residual activity of beam dump shielding in Folding Segment 2 and Beam Delivery Section

The residual dose on contact for the BDS dump shielding was calculated for 30 days of irradiation and 1 day after beam shutdown. Figure 12 shows a “30 d/1 d/0 cm” distribution in the horizontal plane cutting through the middle of the dump. The isocontours in the distribution indicate that the expected dose rate on the shielding surface will be at a level of a few mrem/h, which meets the design goal. The activation of the FS2 beam dump is expected to be even lower than that due to the lower beam energy.

![Image of residual dose distribution](image)

Figure 12. Residual dose rate (“30 d/1 d/30 cm”) in the BDS dump shielding at a level of the dump centre.

6.2. Activation of soil and ground water

There is a potential to activate the ground water and soil at the FS2 and BDS beam dumps above the FRIB design requirement to meet the drinking water criteria [8] due to relatively high beam energy. Ground water activation was evaluated based on the previously obtained results for continuous beam losses [9]. As it was found in [9], that the ground water activation approaches the limits for drinking water if the maximum star density immediately outside of the tunnel walls is $10^9$ 1/cm$^3$/y. For the beam dumps, the maximum level of activation is below $10^8$ 1/cm$^3$/y (figure 13), that is the expected activation level for the ground water should be 10 times below the regulatory limits. The drinking water limits were chosen to provide conservatism in design, even though there are no drinking water sources in the proximity to the facility.

An additional reduction factor is present. As described in [10], the beam dump geometry is typical for a target-like facility. An averaged ground water activation for a target-like facility is approximately 10 times lower than that for continuous losses in a beamline given the maximum star density is the same in both the cases. This was shown in [10] for a simple cylindrical tunnel. In our case, the tunnel geometry is not cylindrical but more complicated, but still some reduction factor is expected. Therefore we can conclude, that the activation of the ground water is expected to be more than 10 times below the regulatory limits for drinking water.
Figure 13. Star density distribution at the BDS beam dump.

6.3. Dose rate from bare dump cores
As figures 10 and 11 showed, the diameter of the penetrations in the dump shielding is relatively small compared to the shielding thickness. Therefore, it is expected that a contribution to the residual dose at the shielding from the dump cores will be relatively small compared to that from the shielding itself. However, the dose rate from the bare dump cores is needed in order to evaluate the worker exposure during the dump maintenance. Figure 14 shows a dose rate distribution at the bare BDS dump core obtained for 720 h of irradiation and 4 h of cooling time. The dose rate at 30 cm from the core reaches 500 mrem/h. An area where the dose rate exceeds 100 mrem/h at 30 cm from the source is designated a “High Radiation Area”. The high dose rate will severely limit maintenance activities. Placing an activated dump core in a 5 cm-thick steel casket will reduce the dose down to a more manageable level (figure 15). This calculation serves as a basis for understanding how to replace, handle, store and dispose the dumps.
Figure 14. Residual dose rate at bare BDS dump core after 720 h of irradiation and 4 h after shutdown. The dose rate at the location [A] is 498 mrem/h. The dose rate at the location [B] is 37 mrem/h.

Figure 15. The dose rate at FS2 dump core enclosed in a 5 cm-thick steel casket calculated after 100 h of irradiation and 24 h after shutdown. The dose rate at the location [A] is 12.5 mrem/h, and 13.3 mrem/h at the location [B].
7. Conclusions
The residual activation of high-rate beam loss devices at the FRIB linear accelerator was evaluated. These devices are the charge stripping device, two beam dumps in Folding Segment 1, beam dump in Folding Segment 2 and beam dump in Beam Delivery Section. The temporary charge selector designed to handle up to 10% of the facility full power was also evaluated. The full power charge selector is not yet designed. The residual activity for all the devices is understood, and the local shielding, if any, was evaluated. No local shielding is planned for the charge stripper. Movable shielding screens will be used where necessary to bring the dose rate to workers from several tens of mrem per hour down to levels that will facilitate operation. The activity of the bare cores of the beam dumps in Folding Segment 2 and Beam Delivery Section can be as high as several hundred mrem per hour depending on the irradiation time, cooldown time and beam type used. Specially designed caskets are considered to shield the bare dump cores for the purpose of maintenance, storage and disposal.

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