HIGH ENERGY BEAM DUMP AND COLLIMATOR FOR NORTHSTAR

R. Gromov, J. Bailey, S. Chemerisov, R. Kmak, V. Makarashvili, G.F. Vandegrift, and M. Virgo
Argonne National Laboratory
9700 South Cass Avenue, Lemont, IL, USA

gromovr@anl.gov, jbailey@anl.gov, Chemerisov@anl.gov, rtkmak@anl.gov, Makarashvili@anl.gov,
Vandegrift@anl.gov, mvirgo@anl.gov

ABSTRACT

Argonne National Laboratory is funded by the National Nuclear Security Administration’s (NNSA’s) Office of Material Management and Minimization (M3) to assist NorthStar Medical Technologies in developing an electron accelerator-based system that produces Mo-99 by a (γ,n) reaction on a Mo-100 target. The NorthStar production facility will require a high energy beam dump system and a collimator to provide safe beam tuning and delivery to the production area. The projected beam parameters are as follows: energy 40–42 MeV, average power 120 kW, and repletion rate 800 Hz. The beam collimator is to be installed upstream of the target to protect the target holder and the surrounding area from excessive power deposition from the beam. The beam dump is to be used like a beam stop for tuning the accelerator for nominal power before putting it directly on the target. This beam-dump system must include the capability for beam profile measurements. For these measurements, we have designed a system that combines a water-cooled set of aluminum plates and an optical transitional radiation camera looking at the beam dump at a 45° angle. Two water loops are used to minimize the thermal stress. The beam collimator consists of a water-cooled aluminum cylinder. It is electrically insulated from the vacuum chamber by ceramic holders.

KEYWORDS

Beam dump, collimator, high power beam

1. INTRODUCTION

Argonne National Laboratory, in cooperation with NorthStar Medical Technologies and Los Alamos National Laboratory, is developing a technology for the production of a Mo-99 from irradiation of a Mo-100 target [1, 2]. The new facility will be composed of an electron linear accelerator with high average beam energy, a Mo-100 target, and a Mo recovery system. At the end of the linac, the electron beam is defocused to irradiate a large target area of about 5 cm in diameter. Initially, the defocused and tuned beam is directed to a beam-dump system. An optical transitional radiation (OTR) camera looks at the 45° face of the beam dump. The image is used to tune the beam shape and monitor its stability. When a stable beam with the required parameters has been produced, the beam is directed onto the target face. A water-cooled collimator is placed upstream of the target to protect the surrounding area from excessive power deposition during irradiation. The collimator is electrically insulated, and the electrical current from the collimator is monitored by electronics. In the case that the beam position deviates significantly, which consequently leads to a rise in the current, the electronics immediately trip the system.

2. CONSTRUCTION MATERIALS

Considering the properties of the construction materials, only copper, aluminum, beryllium, and pyrolytic graphite are possible candidates based on their critical thermal properties (Table I). Beryllium and pyrolytic graphite are expensive and are not easily machinable. Furthermore, beryllium has special
requirements for safe handling. Copper and aluminum are very good in machinability, are inexpensive, and have good thermal conductivities. The density of copper is three times higher than that of aluminum. Consequently, the power deposition per unit volume for copper would be much higher than that for aluminum. Additionally, the lifetimes of activation products for aluminum are much shorter than those for copper (Al-25: 7 s; Al-24: 2 s; Cu-62: 9.7 min; Cu-61: 3.3 hr; Cu-60: 23 min) allowing quicker access to the target room following irradiation. The thickness of the beam dump and the collimator must be greater than the electron stopping distance. This corresponds to 83.5 mm for a 42 MeV electron beam. The final thickness of the metal parts of the elements was chosen to be 100 mm.

Table I. Properties of potential construction materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Melting Point</th>
<th>Density (g/cm²)</th>
<th>Thermal Conductivity (W/m-K)</th>
<th>Machinability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1083°C</td>
<td>8.9</td>
<td>385</td>
<td>Good</td>
</tr>
<tr>
<td>Aluminum</td>
<td>659°C</td>
<td>2.7</td>
<td>205</td>
<td>Good</td>
</tr>
<tr>
<td>Beryllium</td>
<td>1287°C</td>
<td>1.85</td>
<td>216</td>
<td>Poor</td>
</tr>
<tr>
<td>Pyrolytic graphite</td>
<td>3650°C</td>
<td>2.2</td>
<td>3.5(c) or 300(a,b)</td>
<td>Poor</td>
</tr>
</tbody>
</table>

3. POWER DEPOSITION SIMULATION

Prior to the principal design of the high-power beam dump and the collimator, computer simulations for power absorption versus thickness were performed. For these simulations, the electron beam was assumed to be Gaussian with a FWHM diameter of 5 cm and a total average power of 120 kW. All simulations were performed using MCNP6 (Monte-Carlo N-Particle) code [3]. According to the results (Figure 1, left), the highest thermal stress on the beam dump is at the center point, where the power deposition is about 4.5 W/cm³ per kW of beam power. Further calculations have shown that for a set of water-cooled plates of this geometry, the water flow rate is expected to be about 49 GPM (185 L/min), and the temperature rise is expected to be 7.6°C.

![Figure 1. Power deposition in kW/cc per kW of beam power simulated by MCNP6 for beam dump (left) and collimator (right).](image-url)
The thermal stresses in the collimator are significantly lower because of the geometry and the lower power dissipation compared to the beam dump (Figure 1, right). Therefore, cooling water supply requirements are also considerably lower. The estimated flow rate is 4 GPM (15 L/min), the flow velocity in the collimator channel is 20 ft/s, and the temperature difference from inlet to outlet is about 3.4°C.

4. PRINCIPAL DESIGN OF THE BEAM BUMP

Figure 2 is a 3D illustration of the beam dump. The beam dump is to be used to stop the beam and dissipate its energy during the accelerator tune-up process. Although it is not designed to be under high-power stress for long periods of time without interruption, it should still be capable of dissipating the full beam power during long-term operation. It would be difficult to transport an electron beam with such high current through a metal window, so the beam dump must be installed inside the vacuum chamber or be a part of it. To remove the excess heat, convective water cooling is to be used. Because the water flow and, consequently, the pressure are significantly elevated, special requirements are required for the front-surface plate.

Based on computer simulations, the thickness of the front plate should be kept small. The maximum allowable thickness of the plate is determined by the heat generation rate, thermal conductivity, and the Al-water heat transfer coefficient:

\[ L = \frac{h}{q} \cdot (T_{\text{MAX}} - T_{\text{water}}) \]  

(1)

In this case, the front-plate thickness is specified to be no thicker than 6.4 mm. Because there is a large pressure drop across the front plate between external vacuum conditions and the internal high-pressure cooling water, parallel ribs support the internal face of the front plate. Because the aluminum plates beneath the front plate will experience much less thermal stress, it was possible to increase the thickness of the last two plates to 12.7 mm.

Figure 2. 3D view of beam dump (left) and cross section of beam dump (right).

The cooling plate assembly is covered by an aluminum enclosure. The vacuum chamber has two input ports, one for beam delivery and one for beam profile monitoring by the OTR camera (Figure 2). The water supply and return fittings are located on the horizontally opposing walls of the beam dump. Thermocouple wires exit through a separate port distanced from the radiation generation area, and they are connected to the instrumentation via a multi-connection electrical feedthrough.
5. OPTICAL TRANSITIONAL RADIATION (OTR) CAMERA

A camera will be used to monitor the beam profile. This will be a standard CCD camera manufactured by Basler. It will be positioned to look at the face of the 45° front plate of the beam dump through the optical port. This camera is sensitive to γ- and n- radiation, so proper shielding is required for protection. Preliminary tests of OTR camera shielding requirements were performed with a 10 kW electron beam during Mo-99 experimental production runs. For these runs, the camera was placed behind a lead and borated polyethylene wall, looking at the beam spot via a mirror. Radiation doses were measured using nanoDoT™ ASLD dosimeters [4]. The observed doses ranged from 10 µGy to >10 Gy. The OTR camera successfully survived several 18-24 hour experimental runs where the average beam current was 86-221 µA. The accumulated dose is presented in Figure 3.

![Figure 3. Radiation dose accumulated by the shielded OTR camera in four different runs.](image)

6. HIGH-POWER COLLIMATOR

Figure 4 is a cross-sectional representation of the high-power collimator. The purpose of the high-power collimator is to protect the area surrounding the target from high-power deposition and to trip the interlock system, if the beam position deviates from safe conditions during the course of a run. It must be capable of dissipating both a fraction of the beam power during long runs as well as full beam power for short time periods, if beam control is lost. The collimator is to be installed inside the vacuum chamber. Heat will be removed by water cooling. It will be electrically insulated from ground in order to use electric current to monitor the correct position of the beam inside the vacuum chamber. Because the target and collimator area is the source of a significant radiation field, all electrical and water feedthroughs will be located as far as possible from this area. There are two different electrical insulation types for water and electrical penetrations into vacuum – ribbon and ceramic. Ceramic has better vacuum insulation quality and radiation resistance, although it is very sensitive to stress and tension in the material.

Initially, we discussed the idea of using a 4-sector collimator in order to monitor the deviation of the beam direction from the reference trajectory, but this approach appeared to require significant complexity and may not have been reliable. Each sector would have to be electrically insulated from ground and the other sectors, and separate water-cooled pipes would have made the design bulky and inconvenient. It would have been necessary to insulate each water line from ground, and because ribbon insulation cannot be used due to the high radiation conditions, ceramic insulation would be the only possible approach for water delivery.
In the final design, the collimator was chosen to be a single-body device, which will be installed inside the vacuum chamber. Water-cooled 3/8-inch pipes pass through the ceramic brake at a distance of one meter from the collimator. This distance is used to decrease the radiation stress on the ceramic brake. The cooling water lines inside the collimator form a double-helix. Cooling water pipes penetrate the vacuum chamber, and additional ceramic spacers along the length of the collimator prevent electrical contact with the vacuum chamber wall.

7. TARGET INTERLOCK PROTECTION

The target interlock protection system is intended to trip the accelerator, if the beam deviates from the reference trajectory. The protection mechanism is implemented in hardware (Figure 5). It uses the collimator current to analyze the beam delivery parameters. If the collimator current exceeds the maximum tripping level, it means the beam has deviated too far from the axis or has been defocused. If the collimator current drops down to the minimum trip level, one of the following conditions has been encountered: the beam is completely lost on its way to the target (malfunction of the bending magnet, etc.); the beam has been over-focused, resulting in a significant increase in power deposition over a small region on the target; or the collimator connection has been lost. In any of these cases, the high-power electron beam must be tripped immediately.
8. CONCLUSIONS

The high-power beam dump and collimator described here are important parts of the future Mo-99 production facility. High power density and radiation conditions demand particular approaches to component design. The main challenge was to dissipate the high power of the 120 kW electron beam. A secondary challenge was to provide a mechanism for monitoring beam shape and position. The radiation conditions create restrictions on the materials that can be used for the devices. We successfully combined these requirements in our design, and these components are being manufactured. In the beginning of 2016, they will be tested at the Argonne Low Energy Accelerator Facility using an electron beam having an energy of 42 MeV and an average power up to 20 kW.

ACKNOWLEDGEMENTS

Work supported by the U.S. Department of Energy, National Nuclear Security Administration’s (NNSA’s) Office of Defense Nuclear Nonproliferation, under Contract DE-AC02-06CH11357. Argonne National Laboratory is operated for the U.S. Department of Energy by UChicago Argonne, LLC.

REFERENCES


Government License Notice

The submitted manuscript has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory (“Argonne”). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.