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Design of High Power Beam Dump and Collimator

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ABSTRACT

Argonne National Laboratory is funded by the National Nuclear Security Administration's Office of Material Management and Minimization to assist NorthStar Medical Technologies in developing an electron-accelerator-based system that produces ^{99}Mo by a γ,n reaction on a ^{100}Mo target. This 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, repetition rate 800 Hz. The beam collimator is to be installed before 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 and beam shape before putting the beam directly on the target. For these purposes, we designed a system that combines a water-cooled set of aluminum plates with ribs. To minimize the thermal stress, two separate water loops were used. The beam collimator is composed of a water-cooled aluminum cylinder. It is electrically insulated from the vacuum chamber by ceramic holders.

1. Introduction

Argonne National Laboratory, in cooperation with NorthStar Medical Technologies, is developing technology for the production of Mo-99 by irradiation of a Mo-100 target [1, 2]. The new facility will be composed of electron linear accelerators with high average beam power, a Mo-100 target system, and a Mo-99 recovery system. In order to achieve a manageable power density, the electron beam is defocused to a diameter of approximately 5 cm before it reaches the beam dump. In order to protect the target from unnecessary activation and heating during acceleration and electron beam tune-up procedures, the beam is directed to the beam stop, which is installed on a separate beam transport arm. Continuous beam transverse profile monitoring is performed by an Optical Transitional Radiation (OTR) camera looking at the 45-degree face of the beam dump. In this configuration, the electron beam is tuned to its required power and profile. After that, the beam is directed to the face of the production target.

The enriched-Mo target is designed to dissipate high average power in the central area, but the surrounding area has less cooling capacity and requires an additional shielding from excessive power deposition. A water-cooled collimator has been designed to protect the edges of the target. The collimator is electrically insulated from the beam line and ground, and electrical current generated in the collimator is used to monitor the irradiation process. Deviation of the beam from the reference trajectory can cause serious damage to the vacuum chamber and other elements of the system. In the case that the collimator current changes significantly from the normal operation value, the interlock system immediately trips the machine.

2. Power deposition simulation

Considering the critical properties of thermal conductivity, possible activation-product generation, melting temperature, machinability, and vacuum stability, only two metals (copper and aluminum) can be considered as practical materials for the beam stop and collimator. We chose aluminum as the construction material for these components for two reasons. First, its lower density one-third that of copper decreases power deposition per unit volume of material and allows the plates to be thicker, making for easier construction. Second, the (γ,n) reaction isotopes of aluminum are less abundant and have shorter half-lives time than those of copper (Al-25 ÷ 7 s; Al-24 ÷ 2 s; Cu-62 ÷ 9.7 m; Cu-61 ÷ 3.3 h; Cu-60 ÷ 23 m) allowing quicker access to the target room following irradiation. The thickness of the beam stop and the collimator must be greater that the electron stopping distance, which is 83.5 mm at 42 MeV. Therefore, the thickness of the elements was designed to be 100 mm.

Prior to the design of the high power beam dump and the collimator, computer simulations of power deposition and absorption versus thickness were performed. For these investigations, the electron beam was assumed to be Gaussian, the full width at half maximum (FWHM) of the beam was assumed to be 5 cm, and the total average power was assumed to be 120 kW. All simulations were performed with the MCNP6 (Monte-Carlo N-Particle) code [3]. According to the results (Fig.1), the highest energy stress on the beam dump is at the middle point, with power deposition of about $4.5x10^{-3}$ kW/cm^3 per kW of beam power. On the basis of on the simulation results, the FATHOM hydraulic model for cooling water loops has shown that for a set of water cooled plates, the water flow rate is required to be about 49 GPM (185 L/min) and the water temperature difference is expected to be 7.6°C.

Because of its geometry and the low power levels to which it is subjected compared to the beam dump, the collimator experiences considerably lower thermal stress (Fig.2). Therefore, the cooling water supply requirements are considerably lower. The estimated flow rate is 4 GPM (15 L/min), the flow velocity in the collimator channel is 20 ft/s (6.6 m/c), and the temperature difference from inlet to outlet is about 3.4°C.

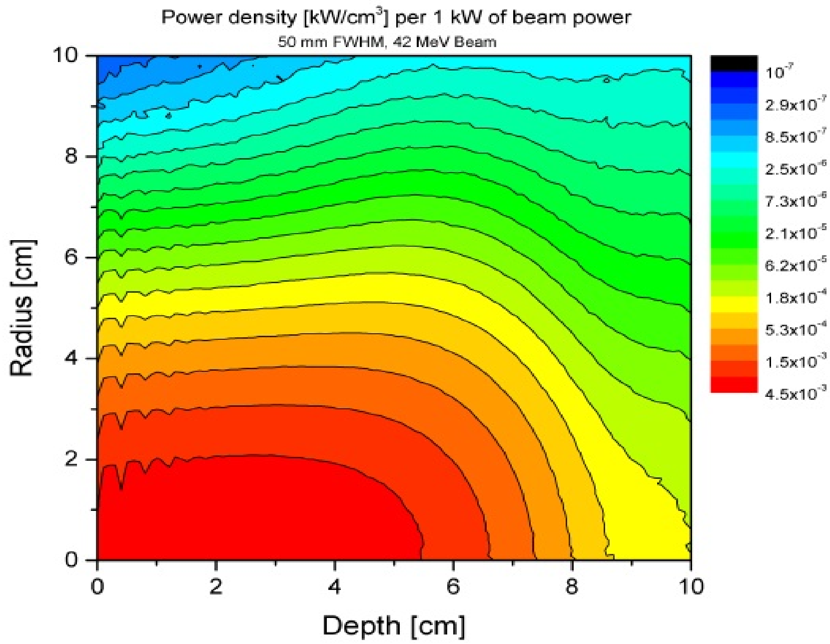


Figure 1. Power deposition in beam dump in kW/cm^3 per kW of beam power, simulated by the MCNP6 code.

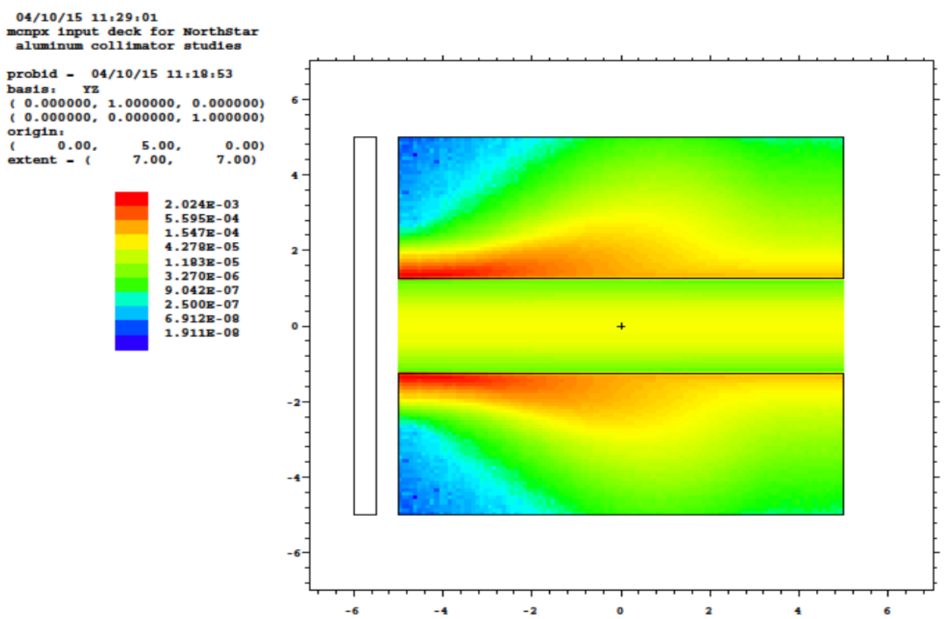


Figure 2. Power deposition in collimator in kW/cm^3 per kW of beam power, simulated by the MCNP6 code

3. Principal design 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 a long time without an interruption, it needs to be reliable when absorbing the full power during long periods operation. It would be difficult to transport an electron beam with such a high level of current through the metal window, so the beam dump has to be installed in the vacuum chamber or be a part of it. To remove the excess heat, convective water cooling is to be used.

The beam dump is composed of a vacuum elbow with an attached set of parallel aluminum plates. One port of the vacuum chamber is attached to the beam transport channel and another port is used for the OTR-camera (Fig.3). The aluminum plates are separated by gaps for cooling water flow. Two water loops are present to provide more uniform cooling. Six thermocouples are inserted into the plates to monitor the actual temperature of the beam dump. Because the water flow and, consequently, the pressure are considerable, special requirements are applied to the front surface plate.

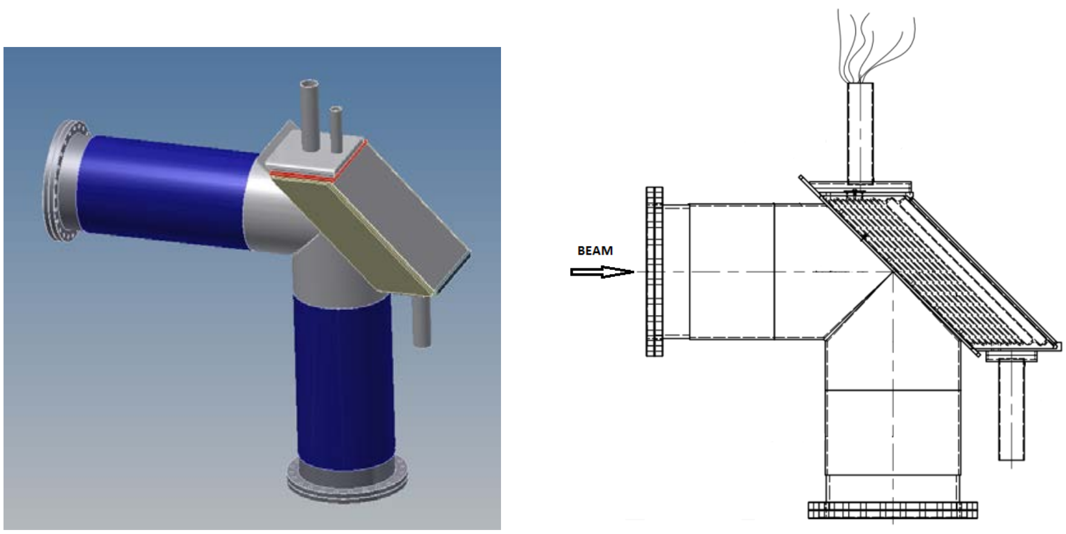


Figure 3. Beam dump: 3D view (left) and internal view (right).

On the basis of the computer simulation, the thickness of the front plate of the beam dump is supposed to be small, i.e., < 2.5 mm (Fig.4). The maximum allowable thickness of the plate is defined by the heat generation rate, thermal conductivity, and Al-water heat transfer coefficient: $L=h/q\cdot(T_{MAX} - T_{water})$. The front plate of the beam dump experiences a high pressure drop between the external vacuum condition and the high pressure of the internal cooling water. To withstand this pressure drop, parallel ribs are applied to the internal face of the plate. The back aluminum plates are supposed to be under much lower thermal stress. The thickness is set at up to 12.5 mm for the last two back plates.

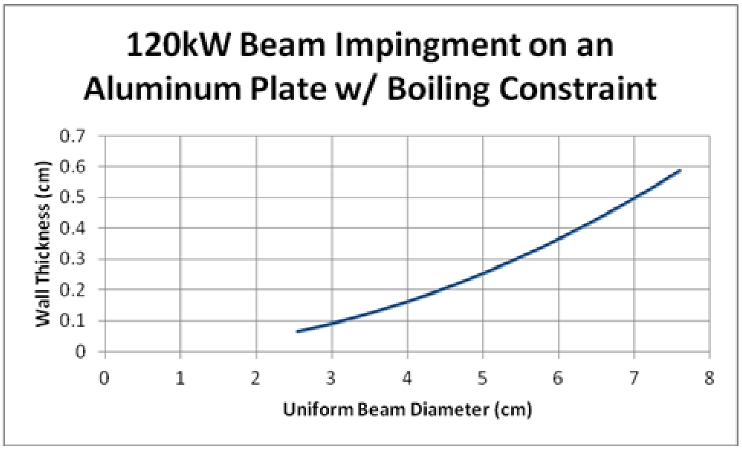


Figure.4. Acceptable plate thickness dependence on the diameter of the defocused beam.

The cooling plate assembly is covered by an aluminum enclosure. The water supply and return fittings are located on the opposite horizontal walls of the beam dump. Thermocouple wires go through a separate port to a distance of 1 meter from the radiation generation area and connected to the reader through a multi-connection port.

4. Optical Transitional Radiation Camera

An OTR camera, i.e. a BALSER CCD camera with small-angle long-focus optics is used to observe the beam profile image on the face of the beam dump. The camera faces toward the 45-degree front plate of the beam dump. Since the camera is sensitive to radiation, shielding of the camera is required. To protect the camera from the straight gamma radiation, it is placed behind a corner and looks toward the front plate via a mirror. Heavy shielding is applied around the camera to protect the electronics from gamma and neutron fluxes.

The OTR camera has already been tested in high radiation areas. Preliminary tests with a 10 kW beam were performed during experimental Mo-99 production runs (Fig.5).

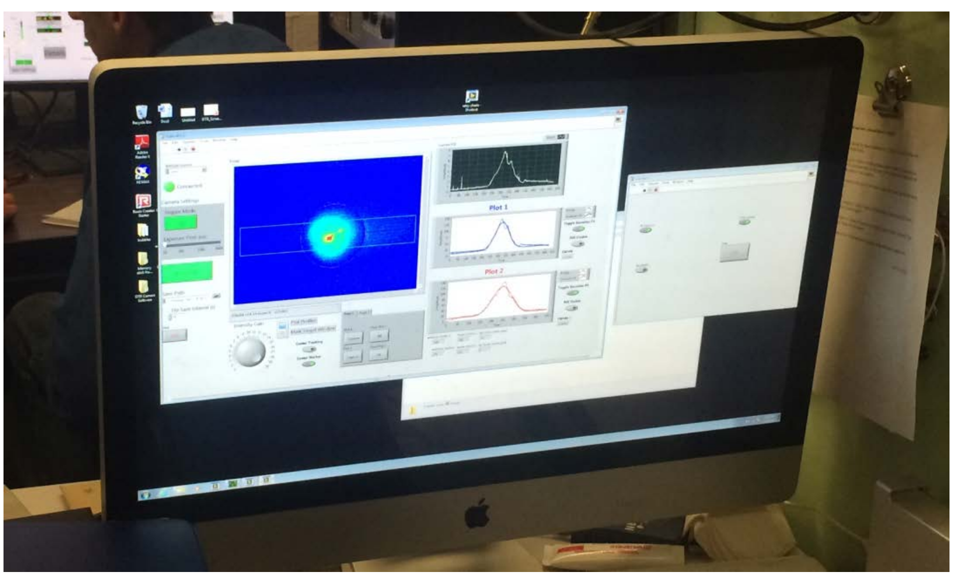


Figure.5. OTR camera control screen during a Mo-99 experimental production run.

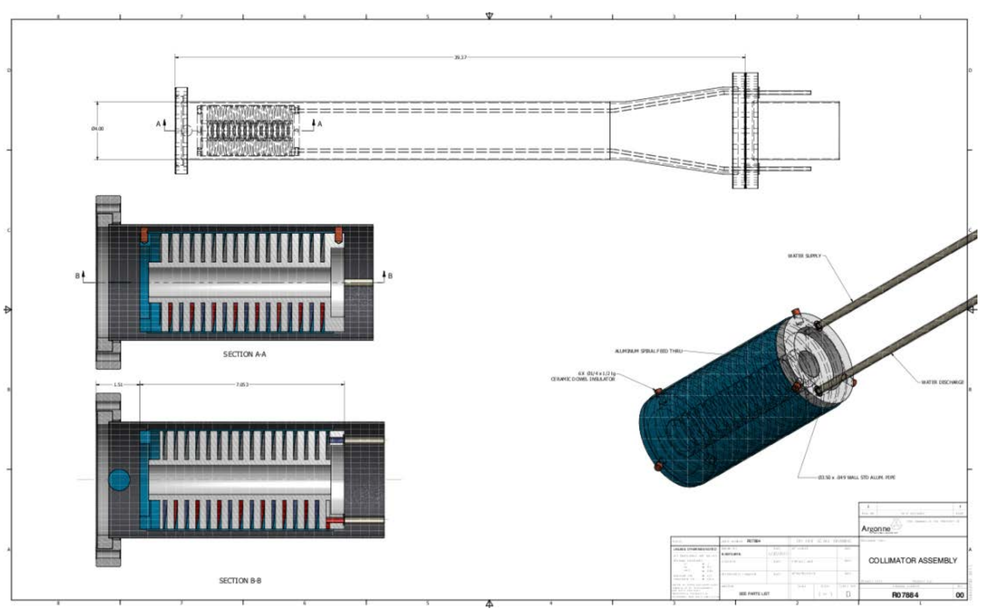
For these runs, the OTR-camera was shielded by led bricks and polyethylene plates for radiation protection. Radiation sensitive Au-samples were placed around cameras to verify the damage dependency from the gamma and neutron radiation. These experiments have shown what CCD-cameras performed successfully throughout a 24-hours non-stop run with an average beam power of 10 kW. The normalized doze at the camera was $4.23 \pm 0.33 \cdot 10^{-3}$ [uCi/g-uA-h].

5. High Power Collimator

The high power collimator is used to protect the surrounding target area from high power deposition and to trip the interlock system in case the beam position deviates from the safe condition during an experimental run. It is supposed to be able to dissipate part of the beam power during long runs and keep the short sharp increasing of the power deposition in case of damping of the sufficient part of beam on it. The collimator is to be installed inside the vacuum chamber. It should be water cooled for heat removal. It should also be electrically insulated from the ground, in order to use electric current to monitor the position of the beam inside the vacuum chamber. The target and collimator area is a source of a high radiation field. Any electrical trough and water in/out ports should be as far as possible from this area.

Initially, we discussed the idea of using a 4-sector collimator in order to monitor the direction of the beam deviation from the reference trajectory. But this approach looked very complex and not reliable. Each sector has to be electrically insulated from the ground and other sectors; separate water cooled pipes also make the design bulky and inconvenient. Each water line should also be insulated from the ground. Since ribbon insulation cannot be used because of the hard radiation condition, ceramic insulation is the only applicable for water through delivery.

The final design of the collimator is the whole-body device, which is installed in the vacuum chamber. Two water cooled 3/8” pipes go through the ceramic feedthrough at one meter distance out of the collimator. This solution is used to decrease the radiation stress on the ceramic. A drawing of the collimator is shown in Fig.5.



Pict.5. High power collimator assembly.

The cooling water lines inside the collimator are in a double-helix shape. Cooling water pipes extend inside the vacuum chamber and use additional ceramic spacers along the length of the collimator to prevent electrical contact with the vacuum chamber.

6. Conclusions

The high power beam dump and collimator described here are important parts of the future Mo-99 production facility. High power density and hard radiation conditions demand a specific approach to the component design. The primary problem is to dissipate the high power from the 120 kW electron beam. The secondary problem is the monitoring of the beam shape and position. The hard radiation conditions restrict the applicable materials for these devices. We successfully combined these requirements in our design. These components are now being manufactured. In a short period of time, we are going to test them at the Argonne Low Energy Accelerator Facility in an electron beam with 42 MeV of energy and 20 kW of average power.

7. Acknowledgments

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