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Beamline Design for High Power Radioisotope Production Facility

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ABSTRACT

Argonne National Laboratory (Argonne) is supporting NorthStar Medical Radioisotopes LLC (NorthStar) in their efforts to become domestic ^{99}Mo producers. NorthStar is utilizing the photonuclear reaction in an enriched ^{100}Mo target for the production of ^{99}Mo. In this approach, a high-power electron accelerator is used to produce the required flux of high-energy photons through the bremsstrahlung process inside the target. Argonne is assisting NorthStar in development and optimization of ^{99}Mo production technologies. In this manuscript, we will discuss beamline configuration for the production facility utilizing NorthStar technology for ^{99}Mo production.

1. Introduction

NorthStar Medical Isotope, LLC, is planning to produce ^{99}Mo through a γ,n reaction on ^{100}Mo. This pathway for ^{99}Mo production relies on the use of high-power electron accelerators, which are not currently commercially available. There are several potential producers of such accelerators, either based on conventional technology (MEVEX, IBA) or superconducting technology (NIOWAVE). Because of the high cost of enriched material, as high as possible power on the target is desired to increase production rates. Argonne National Laboratory, in collaboration with Los Alamos National Laboratory (LANL), has conducted several demonstrations of the technology that proved the feasibility of this approach [1, 2]. The target, designed by LANL, is composed of a series of ^{99}Mo disks held in a target holder with cooling gaps between the thin disks. Cooling of the target is provided by flowing helium gas under high pressure through the target holder [3, 4].

Handling of the high-power beam requires a carefully designed beam transport system because of likely vacuum failure if the beam strikes an uncooled part of the system. This publication summarizes what has been done so far on the design of the beam transport line equipment and discusses the pros and cons of different approaches.

2. Beamline Requirements

The beamline provides a means to deliver the beam to the target. As discussed in previous publications [5], the highest ^{99}Mo yield per gram of ^{100}Mo is achieved by simultaneously irradiating the target from two opposite sides. Most of heat deposition in the target occurs from slowing down the electrons, which generates bremsstrahlung photons that, in turn, interact with the ^{100}Mo nucleus to knock out a neutron, thus generating ^{99}Mo. By irradiating from both sides, production of ^{99}Mo is distributed more evenly throughout the target. Because the front window of the target has high-pressure helium on one side and a vacuum on the other and significant heat deposition from slowing down the electrons in the beam, this window is the most stressed component of the target assembly. By irradiating the target from two sides, one can double the production of the ^{99}Mo isotope while keeping the same thermal load/stress on the target window.

Because the target will be irradiated from two sides by separate accelerators, one would want to eliminate line-of-sight for the two beams, so that each accelerator does not receive a large radiation dose from the opposing accelerator. This arrangement can be achieved by bending the electron beams with a magnet or a group of magnets. Any accelerator produces a beam with finite energy spread. When going through the magnet, a non-mono-energetic beam will disperse. To avoid this dispersion, one could use an achromatic (non-dispersing) bending system.

For efficient ^{99}Mo production, the accelerator facility is supposed to use a high intensity electron beam to irradiate the target. It leads to very high radiation levels inside the linac's vault during the process. It makes, in turn, specific requirements for the construction materials of the installation's components. They must withstand a high dose of radiation without degradation or decay. Use of any organic material should be avoided. Also, the vacuum chamber, collimators, and beam dump are under the highest stress of the radiation. They are supposed to be made from a material that produces the least radiation or activation isotopes that have a short half-life. Instead of common practice of using non-magnetic stainless steel, it would be preferable to build these components out of aluminum. It helps to sufficiently reduce the radiation cooldown time and allow quicker access to the vault for maintenance personnel.

Reasonable beamline requirements are:

- Deliver beam with desired intensity distribution to the target.
- Minimize effects of equipment and beam-parameter fluctuations.
- Allow efficient radiation shielding.
- Contain necessary diagnostics for commissioning and tuning.
- Contain sufficient diagnostics for beam monitoring during irradiation.
- Achieve reliable operations and long lifetime.
- Protect accelerator components and personnel from pressurized target cooling gas.
- Prevent accidental placement of electron beam on un-cooled parts of the target and beamline.
- Provide appropriate a vacuum in the beam pipes and accelerator.

Figure 1 depicts three beamline configurations discussed previously in several publications [6-8]. The bend in configuration B consists of a single magnet that does not meet criteria for achromat.

Variation of the beam energy will directly translate into a change of the position of the beam on the target, which is not desired for two reasons: deviation from the center of the target will decrease ^{99}Mo production rates, and beam deposition on the thicker or less cooled part of the target window can lead to catastrophic window failure. For those reasons, the single magnet configuration will not be discussed in detail in this paper.

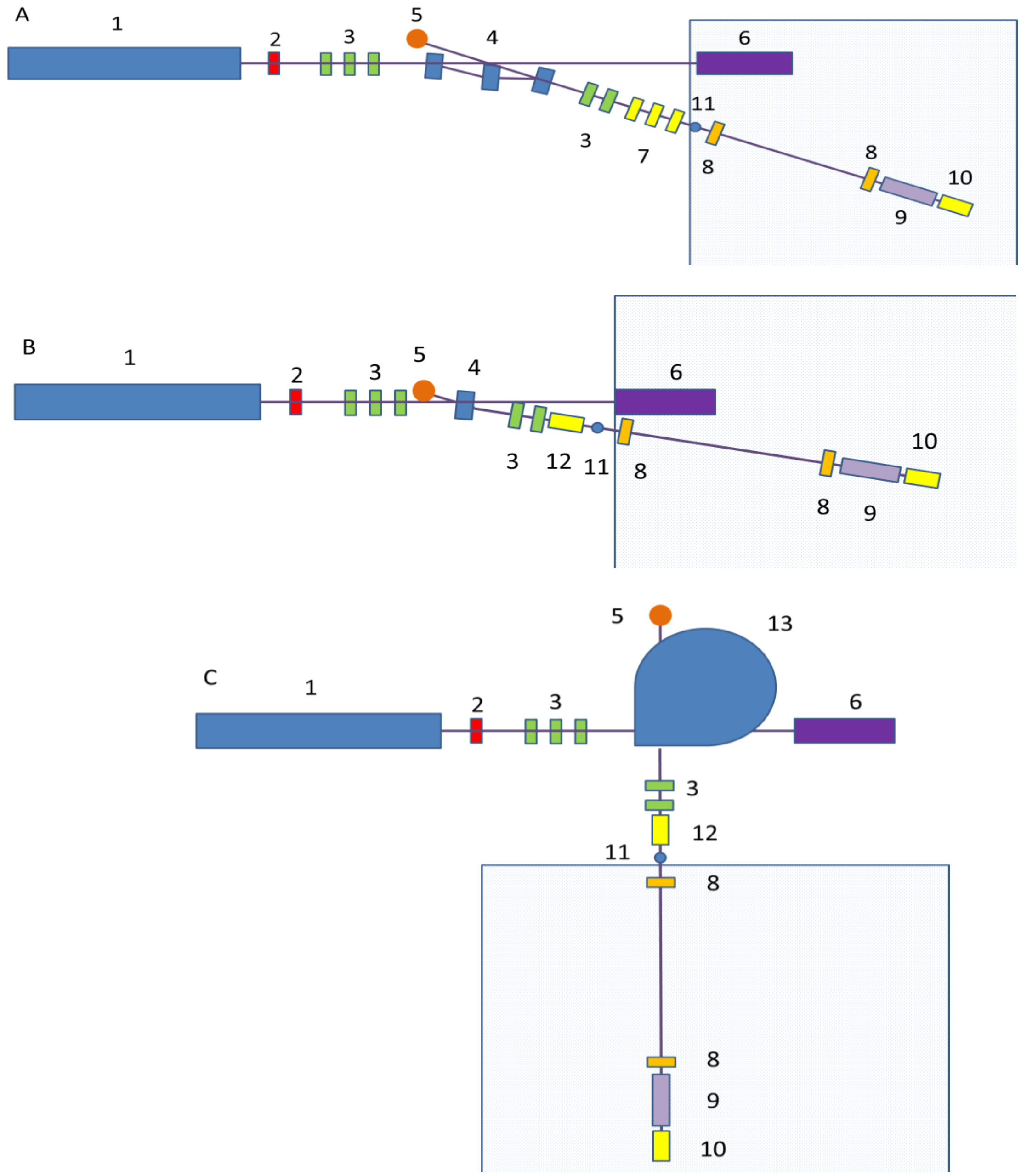

Figure 1. Beam line configurations: *A* was proposed by LANL; *B* and *C* were proposed by Argonne. Beam line elements are: 1- Linac, 2- Fast Acting Gate Valve, 3- Quad Magnets, 4- Bending Magnet, 5- Optical Transition Radiation Monitoring and Infrared Cameras, 6- Beam Stop, 7- Nonlinear Beam Optics, 8- Beam-Position Monitors, 9- Collimator, 10- Target, 11- Gate-Valve Vacuum Sensor, 12- Rastering Magnet, 13- Alpha Magnet. The beam line elements are not drawn to scale.

3. Beamline Components

3.1 Vacuum system

For efficient beam transport inside the accelerator and to the target, a high vacuum has to be maintained. To prevent electrical discharge and cathode degradation, a vacuum inside the accelerator has to be maintained to better than $1x10^{-7}$ torr. This level of vacuum is usually achieved by ion pumps. The beamline vacuum has to be maintained at the $1x10^{-6}$ torr level. The choice of the pumps for the beam transfer line is based on gas load. Gas load will mostly come from degassing of the beamline components when they interact with the beam, as well as gases from the target housing that are bombarded with the high power electron beam.

In our experience, the beamline vacuum can be kept below $1x10^{-7}$ torr with a properly sized single turbo-molecular pump. During irradiation, the vacuum will decrease to $1x10^{-6}$ torr. The lifetime of an ion pump providing $1x10^{-6}$ torr pressure is 3.5-4 years, and an equivalently performing ion pump is several times larger than a turbo pump. Based on these observations, the vacuum pump for the beamline should be a turbo-molecular pump backed by a rotary-vane fore-vacuum pump. This arrangement has a wide working pressure range, high pumping speed, and long maintenance intervals.

3.2 Bending magnet system

The earlier mentioned line-of-sight problem with the two accelerators would activate accelerator components and cause premature failure. To avoid this situation, one would bend the beam so that the bremsstrahlung photons would not hit the opposing accelerator. Because any accelerator will produce an electron beam with some energy spread as well as with beam energy instability, those bend magnet systems have to deliver a beam with different energies to the same position on the target. There are multiple configurations of the bending magnet systems that can accomplish this. Design of the system depends on the choice of accelerator for the production facility. So far, two accelerators have been considered by NorthStar: a linac from MEVEX Corporation and a pulsed Rhodotron from IBA. Those two accelerators have quite different beam parameters (emittance, energy spread, etc.), which will affect the design of the bending magnet system. In studies to date, we have been using beam parameters for the linac because we have significant operational experience with this accelerator. Based on our experience, a first-order dispersionless bend is considered sufficient for the application of target bombardment.

3.3 Focusing and correction magnets

To control the electron-beam size and shape, a set of optical elements has to be employed in the beam transport system. Beam-spot shaping on the target can be achieved by differing means. The LANL design employs nonlinear optics to manipulate the beam-intensity distribution, while the Argonne design employs rastering dipole magnets to achieve the desired beam-intensity distribution. So far, all experimental and design target work has been based on a Gaussian beam-intensity distribution, which naturally occurs in charge particle beams.

3.4 High-power beam dump

A beam dump capable of accommodating a full-power beam is desired during initial commissioning and tune-up and maintenance activities. It is also necessary to obtain the beam-intensity distribution at nominal beam power. In high energy accelerators, where average current is small, OTR (Optical Transition Radiation) screens are typically used for beam visualization. This would be impossible for a production accelerator because of its very high power. The only possibility for beam visualization in a production facility accelerator setting would be to image the beam on the target or high-power beam dump. A high-power beam dump capable of imaging a full power beam was designed at Argonne and is described in [9].

3.5 High-power beam collimator

During production runs and thermal testing of the helium-cooled 12-mm target conducted at Argonne [1-4], it became obvious that a production-scale beam-line configuration would need a collimator to protect the target from accidental beam misplacement or beam-profile change. The prototype of a high-power collimator was designed and fabricated at Argonne. The design and operating parameters of the beam collimator are discussed in [9].

3.6 Beam diagnostics

For destructive beam diagnostics, the whole or part of the beam is intercepted to produce an electrical or optical signal proportional to the current density. Most destructive diagnostic components can be used only during the tune-up operation, because they disturb the beam profile. The only notable exception is an OTR monitoring system, which uses light emitted by high-energy electrons impacting a target window. Because the window separates the vacuum and coolant sides of the target, it is in place during normal operation. While OTR cameras will be used for the beam imaging on the target window, they have a limitation on repetition rate and provide monitoring of only a single-point position of the beam. For tune-up and high repetition rate operation, OTR cameras should be supplemented by other non-destructive methods for beam position monitoring capable of operation at the full repetition rate of the accelerator. An infrared camera will be used for monitoring of the window temperature.

Beam position monitors (BPMs) are widely used for non-destructive diagnostics by nearly all accelerators in the world. They estimate the center of mass of the beam and can be used to measure the total beam current and longitudinal bunch shape. The control electronics measure the charge induced by the electric field of the charged-particle beam on an insulated metal plate. To determine the beam position, four plates are installed crosswise at the beam pipe. The displacement is measured directly by calculation of

$$dX = Kx \cdot \log(U1/U2)$$

where dX is the beam displacement from the center of the BPM, Kx is a multiplication factor that depends on BPM geometry, and U1 and U2 are the signal amplitudes from the opposite pairs of plates.

Signals from separate channels are processed simultaneously by electronics synchronized with the beam pulse. Each channel has an input band-pass filter, followed by an amplification chain.

A system of three BPMs was installed and tested at the Low Energy Linac Facility at Argonne with assistance from LANL [10]. The system consists of pickups, control electronics, and signal cables. The four-plated pickup is incorporated into a standard 4.5-in. CF flange (Figure 2). These pickups were designed and provided for our tests by LANL. Each pickup is installed in a 45°-rotated position (Figure 3). In this setup, the beam displacement is calculated according to the following equations:

$$dX = Kx \bullet (\log(U1/U2) - \log(U3/U4)) \cos(45°)$$
$$dY = Ky \bullet (\log(U1/U2) + \log(U3/U4)) \sin(45°)$$

The signal cable is a radio-frequency (RF) cable with low damping in the RF frequency range. Since the signals on each channel are processed independently but triggered synchronously, the electrical length of the RF cables must be equal within ±20 cm (±1 ns delay).

The BPM electronic module S-BPM-111.3.2 (Figure 4) was designed and manufactured by BERGOZ Instrumentation (http://www.bergoz.com). The module reads the raw signal from the BPM sensor, processes it, and sets up output voltage, which is proportional to the beam deviation from the central point. The output signal is processed by the analog-to-digital convertor and translates to the operator's control screen. The system was tested with the accelerator at up to a 35 MeV beam with a pulse lengths of 5.5 μs. The amplitude of the signal was about 0.5 V per 6 mm of beam displacement from the center of the pickup. Noise levels of the processed signal did not exceed 0.005 V.

Figure 2. Pickup with standard 4.5-in. CF flanges provided by LANL and installed and tested at Argonne linac.

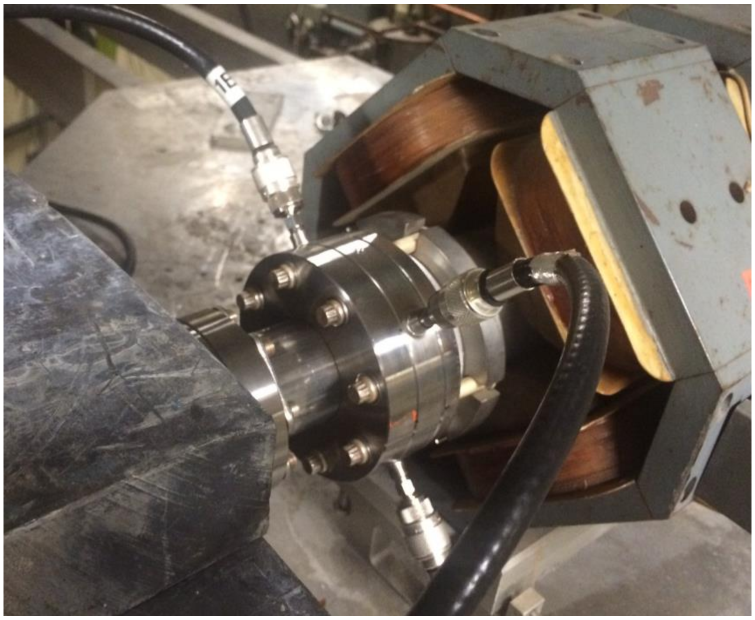

Figure 3. Pickup installed at the beam transport channel and connected with signal cables to the controlled electronic.

Figure 4. BPM’s control electronics installed in 19 in. standard rack (front view).

3.7 Accelerator protection

Proposed parameters for a production-scale accelerator is 100 kW beam power at 42 MeV. Misplacement of such a high-power beam will lead to catastrophic failure of the beam transport line. Beam position on the target window will be monitored by observing the OTR signal from the electron beam striking the target. This image can be used to interlock the accelerator, but depending on the repetition rate of the beam pulses, images will not be acquired continuously, which could lead to significant energy deposition in undesired locations. For the optimal interlock system performance it is desired to be able to interrupt the beam based on single pulse variation. This can be achieved by monitoring the beam current loss in a couple of critical places--e.g., the entrance to a magnet and /or the target collimator. The hardware electronic principal design was proposed in [9].The prototype of the electronic interlock circuit was tested at the linac with the real beam. The interlock trip delay was in range of 1 microsecond in case of deviation of the beam current out of the desired range.

Another area extremely important for accelerator protection is vacuum protection from a target window failure. The molybdenum target is cooled by a flow of high-pressure helium gas. The target window is exposed to high mechanical and thermal stresses, and its failure would result in inrush of high-pressure helium gas into the beamline and accelerator. To protect the accelerator, the beamline must be equipped with a Fast Acting Gate Valve system. This system is installed and is operational at Argonne. Recently, we have conducted a series of tests to quantify the effectiveness of such a system. The results of the tests are reported in [10].

4. Proposed Beamline Configuration and Discussion

As mentioned above, there were several configurations of the beamline proposed by LANL and Argonne. Over the last couple years, details of both designs evolved significantly, but it looks like they have started to converging to a common configuration except some details. Argonne's design has replaced an alpha magnet (Figure 1-C) with a 90-degree two-bend achromat that will be discussed below in more detail.

4.1 Chromaticity of the 90° bend

The bend analyzed here is consists of two 45° dipoles separated by a drift with two quadrupoles located at one third and two thirds of the distance between the bends—Figure 5.

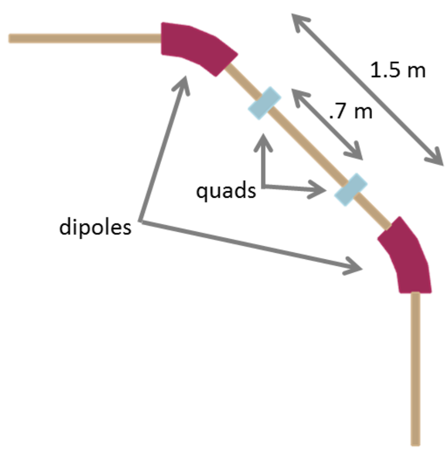

Figure 5. Diagram of 90° bend comprising two 45° magnets and two quadrupoles.

The design was suggested by David Douglas at Thomas Jefferson National Accelerator Facility [Personal Communication]. Suitable bend magnets were purchased from Buckley Systems. The indirectly cooled magnets are capable of producing a 3.3 kG field over a region $\pm$ 30 mm high and $\pm$ 40 mm wide. The design bend radius is 60 cm, implying a maximum beam energy of 60 MeV. Simulations were performed to determine the chromaticity of the bend design using LANL's Parmela particle tracking code [10] and ANL's elegant [11] beam dynamics code. By using the initial conditions to populate the transverse trace-space ellipsoids, it was clear from the Parmela results that, for monoenergetic slices of the energy distribution, the transport was essentially linear. The final distribution for a beam, including energy spread, could then be envisioned as a superposition of the ellipses representing each energy slice. The simulations were conducted for a nominal beam energy of 40 MeV and a spot size on target of approximately 7 mm. The results are summarized in Figure 6.

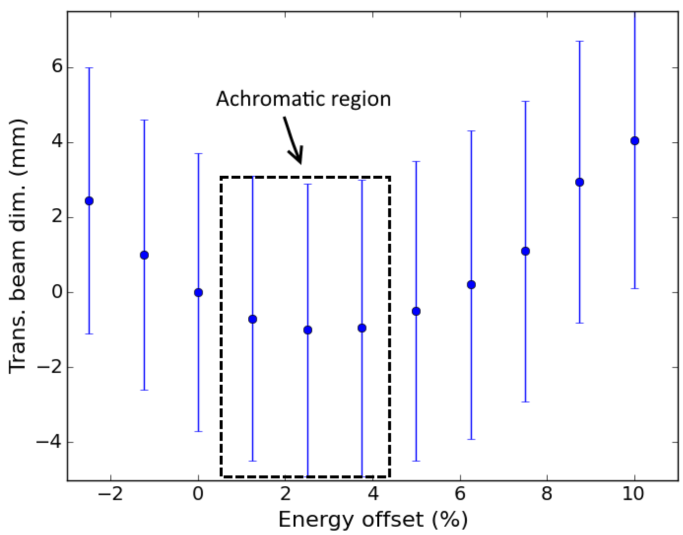

Figure 6. Effect of electron energy on beam spot. "Error" bars represent the beam size. Changing the electron energy affects the location the electron beam strikes the target, and, to a lesser extent, the beam's spot size. For a real beam with a finite energy spread, the observed beam spot is smeared out by contributions of various energies. For this design, an energy spread of $\pm$ 2%, covering the energy offset between roughly +1 and +5%, increases the spot size over that for an achromatic beam only slightly, from approximately 7 mm to 8 mm.

4.2 Cost estimates

Three of these magnets were purchased at a unit cost of $18,750. Because there is an existing stock of quadrupoles at the facility, no new quadrupoles were purchased. For this design, the required integrated field gradient is 0.26 T. Typically, a magnet with a magnetic length of 10 cm operated at 2.6 T/m field gradient has been assumed. To accommodate dispersion from the bending magnets, a bore greater than two inches in diameter is suggested. For the purpose of pricing, two quotes were obtained, the lower of which was for a quantity of six at a unit price of $5,200. Therefore, the price for the magnetic elements for each complete bend is expected to be approximately $48,000. For a larger quantity, the price might be somewhat reduced.

4.3 Importance of 90^o bend

A 90^o bend provides several important benefits for facility operations. The most important one is radiation protection. The radiation field in the 90^o direction to the beam is two orders of magnitude smaller than in the direction of the beam, so a 90^o bend configuration will allow a reduction for the shielding requirements and reduce activation of accelerator components, which will make maintenance work easier and will reduce the wait time required before vault access following an irradiation. Another important benefit of the 90^o bend is an ample space for OTR and IR camera installation and shielding.

5. Conclusion

We are proposing a double-bend achromat-based beam transport configuration for a production facility that will satisfy all requirements for the beam transport line: appropriate control and monitoring of beam parameters and comprehensive set of diagnostic tools. The right-angle configuration allows a reduction in shielding and a compact beamline with reduced activation of accelerator components. Beam interlocks and vacuum-system protection will ensure reliable and low maintenance operation of the production facility.

6. Acknowledgement

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7. References

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