LA-UR-15-29675
Approved for public release; distribution is unlimited.

Title: Moly99 Production Facility: Report on Beamline Components, Requirements, Costs

Author(s): Bishofberger, Kip A.

Intended for: Report

Issued: 2015-12-23

Disclaimer:
Los Alamos National Laboratory, an affirmative action/equal opportunity employer,is operated by the Los Alamos National Security, LLC for the National NuclearSecurity Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Departmentof Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Moly99 Production Facility:
Report on Beamline Components, Requirements, Costs

Kip Bishofberger
Version 6: September 2015

Introduction

In FY14 we completed the design of the beam line for the linear accelerator production design concept. This design included a set of three bending magnets, quadrupole focusing magnets, and octopoles to flatten the beam on target. This design was generic and applicable to multiple different accelerators if necessary. In FY15 we built on that work to create specifications for the individual beam optic elements, including power supply requirements. This report captures the specification of beam line components with initial cost estimates for the NorthStar production facility.

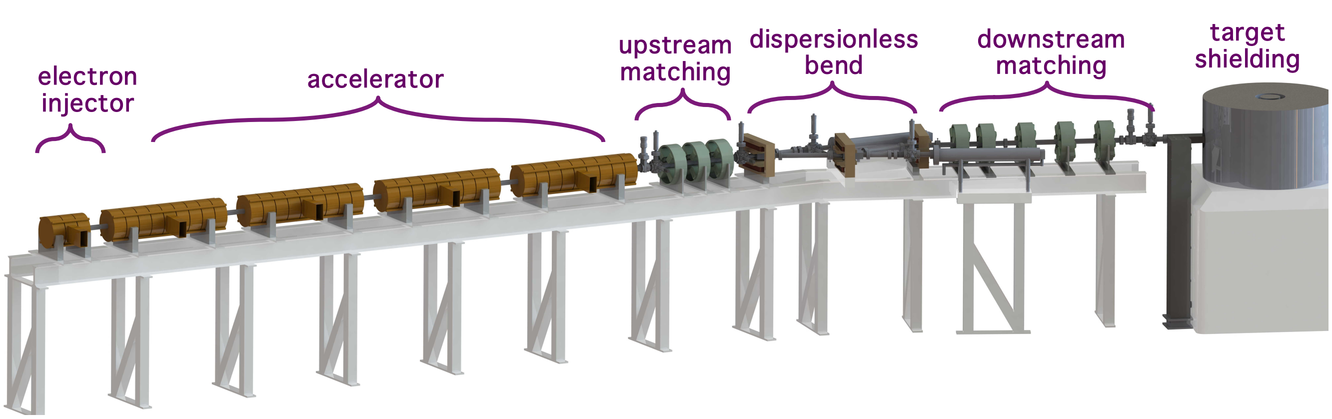
This report is organized as follows: The motivation of the beamline design is introduced briefly, along with renderings of the design. After that, a specific list is provided, which accounts for each beamline component, including part numbers and costs, to construct the beamline. After that, this report details the important sections of the beamline and individual components. A final summary and list of follow-on activities completes this report.

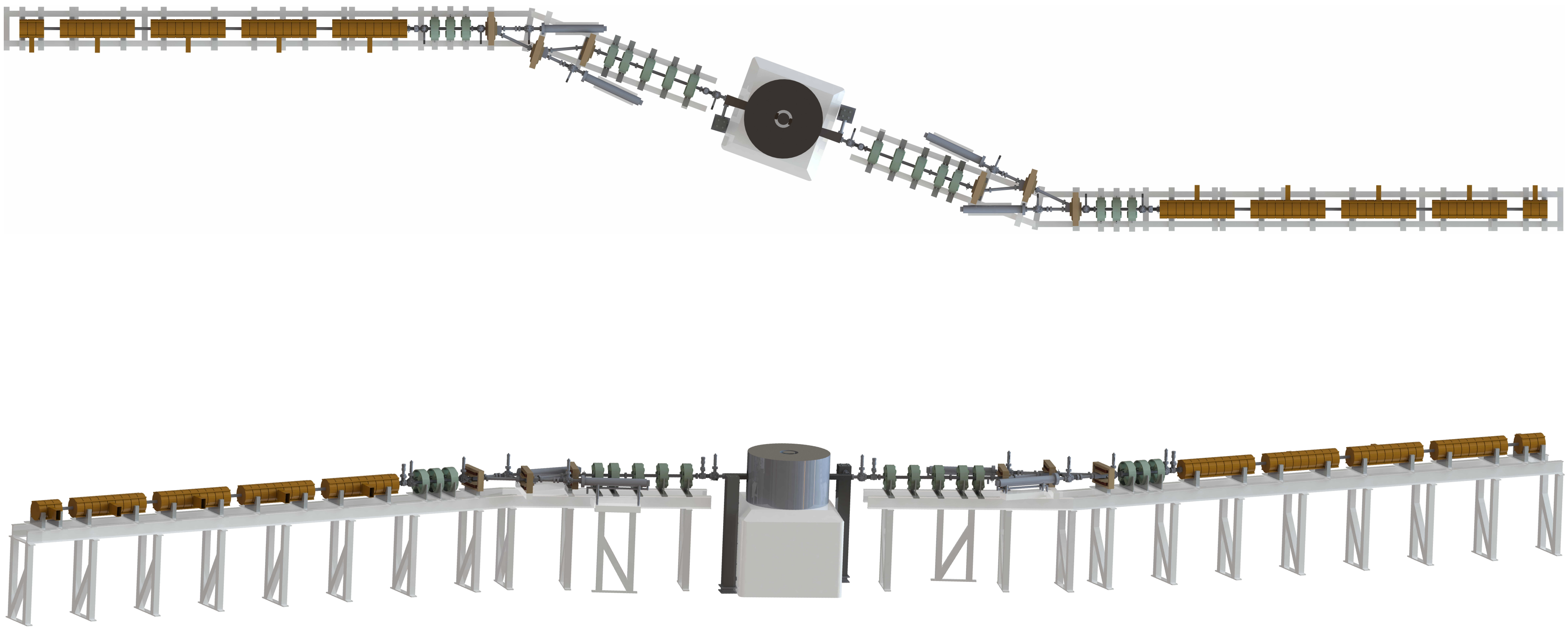
Conceptual Approach

The goal of this task is to design a beamline that begins at the exit of the linear accelerator, where the nominal beam energy has reached 42 MeV, and "match" the beam to the target dimensions. The overall requirements include:

1) Optimize beam size and profile to the desired distribution at the target.
2) Minimize adverse effects of equipment and beam-parameter fluctuations.
3) Provide radiation shielding opportunities to avoid activation complications.
4) Identify all diagnostics and components necessary to commission and maintain beam operation.
5) Locate all components to avoid diagnostic overlaps.

The above constraints, along with an overall minimization of cost and space, developed into the beamline design illustrated below, with the entire two-sided production facility illustrated on the next page.





The above beamlines design of the entire dual-sided Molybdenum-99 production facility beamline. The entire length, as drawn, is approximately 20 meters in length. The injector and accelerator is based on other high-current production-beamline designs, but are not studied in detail in this report.

The previous page illustrates what a two-sided production-facility beamline will look like. Each beamline consists of an electron injector followed by an accelerator to an energy of 42 MeV (represented by the copper-colored linac modules). The subsequent beamline to the target is the matching beamline that is the subject of this report. As designed, it succeeds in meeting the goals listed in the previous section.

The entire matching section, approximately 4 meters in length, can be subdivided in three parts. While these are discussed in detail later, the center section uses a three-dipole design, which enables radiation protection, commissioning optimization, and near elimination of energy-dependent complications. Upstream of the bends, a matching section provides a "large acceptance" of linear-accelerator beam parameters. Downstream of the bends is another matching section; in addition to maintaining the optimal spot size, it utilizes nonlinear optics to develop a flattop profile for maximum conversion efficiency with a more uniform target heating profile. A uniform beam profile does not have the complications associated with rastering or pulsed beam optics.

Cost Analysis

The table on the next page details the cost breakdown of the designed production beamline, including beam optics, diagnostics, power supplies, and "local control" equipment. Part numbers, whenever possible, are included, and other costs are generated from quotes or prior similar purchase experience. Estimates are rounded up to k$ in the table, but the entire system (in FY15 dollars without taxes, burdens, or labor) adds to about $520k. Purchasing for multiple beamlines simultaneously would reduce many of the costs somewhat.

In the table, each item's cost also shows a small gray number, which indicates the level of certainty of each cost estimate:

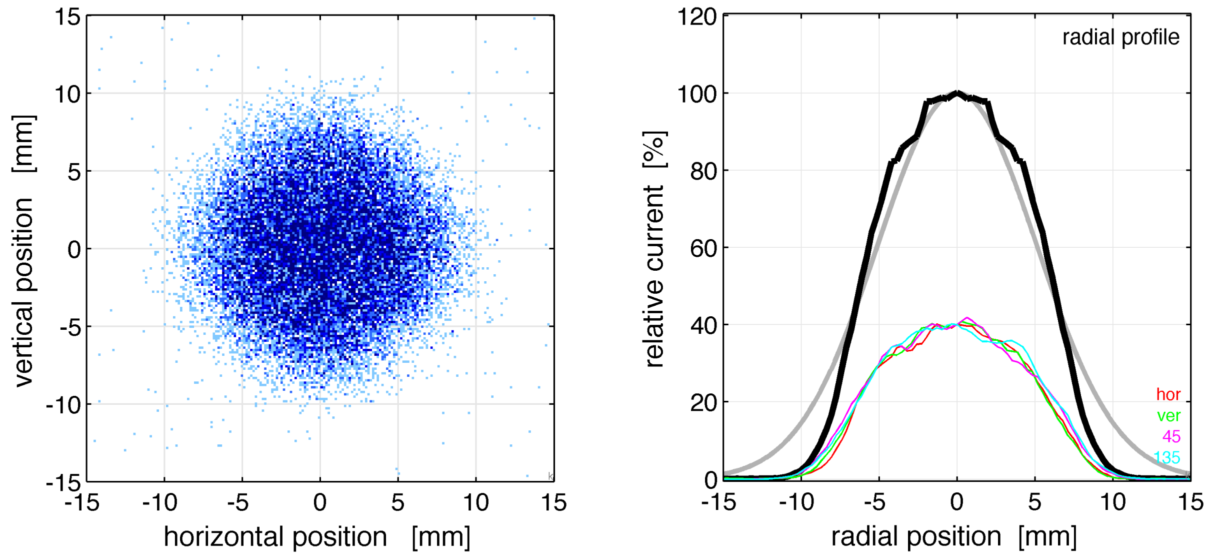
'1'	10%	Actual quote or recent purchase of item.
'2'	20%	Small scaling from actual quote or purchase.
'3'	40%	More general scaling (e.g. magnet design scaling).
'4'	300%	Subsystem not fully defined within this report.

The last category typically involves custom design, labor, or infrastructure. Experience at LANL still enables reasonable estimates of the level of involvement and assumes leveraging on-site expertise.

	count	*cost*	*specifications*	*vendor*	*support system (PS, local ctrls, cables)*	
MAGNETS		[each]	(4-cm bore)		[each]	
quadrupole	5	$4 k [3]	L=4cm; B'=3.5 T/m	Radiabeam	$2 k [2]	PS: 5V,10A
octopole	3	$10 k [3]	L=4cm; B'''=8.8 T/m3	Radiabeam	$2 k [2]	PS: 5V,10A
dipole	3	$8 k [3]	L=15cm; B=.6T	Radiabeam	$2 k [2]	PS: 10V,20A
corrector	6	$3 k [1]	L=1cm; BL=14Gm	Radiabeam #STM01-340	$6 k [2]	+/-5V,10A, per pair
VACUUM						
pipe, custom	9	$1 k [2]		MDC #402002	$7 k [3]	hardware, consumables
bend, custom	1	$3 k [3]	30-degree	MDC		
splitter, custom	2	$6 k [3]	25-degree	MDC		
bellows	4	$1 k [1]		MDC #470016		
ion pumps	3	$2 k [1]	30 l/s	Duniway #DSD-030-5125	$3 k [1]	ctrl:T-752A-F+cables
ion gauges	3	$1 k [1]		Duniway #T-NUDE-BAC	$3 k [1]	ctrl:T934-TC110+cables
gate valve	2	$3 k [1]	pneumatic	MDC #301014	$3 k [4]	pneumatics
fast gate valve	1	$10 k [1]	pneumatic	Midwest #75232-CE44-0006	$1 k [1]	cable: #770CV-79LX-ABB1
FV sensor	1	$2 k [1]		Midwest #770SF-99NN-003	$1 k [1]	cable: 770CS-99LX-ACW1
FV module	1	$8 k [1]		Midwest #770VF-16NN-AA4		
beam stop	2	$3 k [4]		Radiabeam		
DIAGNOSTICS						
OTR screen	3	$1 k [2]	uses 'OTR camera' setups		$3 k [1]	MDC cube
actuator	3	$2 k [1]	pneumatic		$1 k [3]	pneumatics, cabling
OTR camera	4	$1 k [1]	3 screens + 1 target	Basler Ace acA640-120g	$2 k [2]	power-over-ethernet, trigger
lens	4	$1 k [1]	f/2.8D	B&H Nikon AF 180mm		
mirror	1	$1 k [1]	75-mm square (only target)	Edmund #4-416	$1 k [1]	mount: Newport #U200-P3K
OTR viewport	4	$1 k [1]		MDC #9712002	$2 k [2]	support attachment
IR camera	1	$24 k [1]		FLIR #A655sc		
lens	1	$12 k [1]	88.9-mm lens option	FLIR #88.9mm	$2 k [2]	high-temp calibration
mirror	1	$1 k [1]	gold, 75-mm square	Edmund #84-436	$1 k [1]	Newport #U200-P3K
IR window	1	$2 k [1]	ZnSe 75-mm 3-12micron	Edmund #48-855		
IR viewport	1	$2 k [2]	custom for window	MDC #9712002-cust		
BPM	6	$3 k [1]	button	MDC/ISI	$8 k [4]	processing electronics
aperture	3	$12 k [4]	adjustable?	?		
BCM	2	$3 k [2]	average current	Bergoz #MPCT-S113	$4 k [3]	processing electronics
INFRASTRUCTURE			*(assume controls network exist; assume main rails exist)*			
image analysis	2	$4 k [4]	cRIO, FPGA, or computer	National Instruments	$2 k [4]	processing software
interlocks	1	$10 k [3]	software alarm monitoring			
feedback system	2	$4 k [4]	position, possibly 6D		$2 k [4]	PID software
heavy supports	7	$3 k [3]	dipoles, pumps, stops			
small supports	13	$2 k [3]	quads, octs, pipe			

Physics Design Review

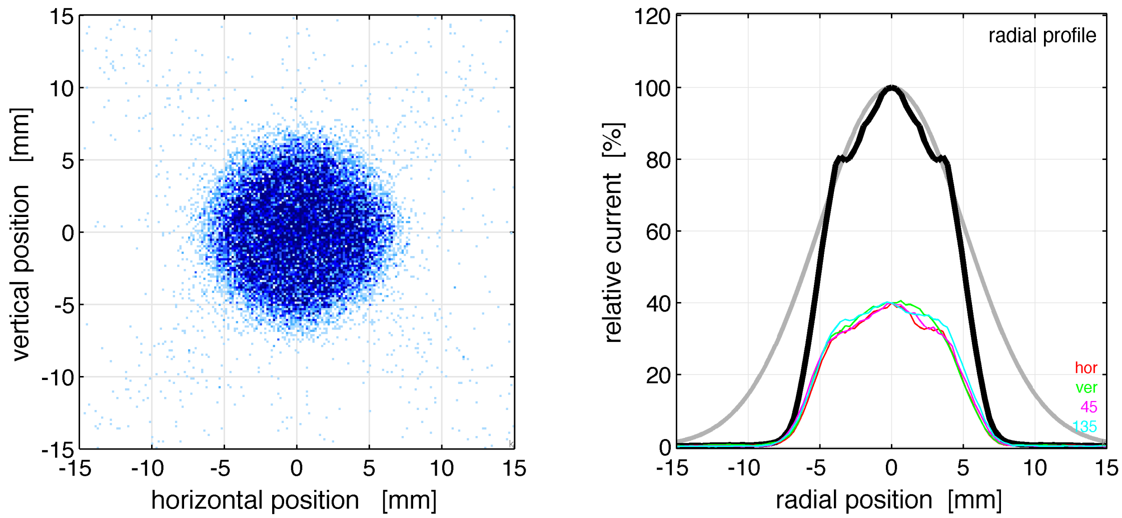
A prior report from Fall of 2014, detailed the optimization of the beamline for the goals listed in the Conceptual Approach. The plots on the next page summarize the "nominal spot profile" for this beamline design. The beamline assumes several key beam parameters, such as a 9-um emittance, and its spot size is optimized for 12-mm diameter on target.



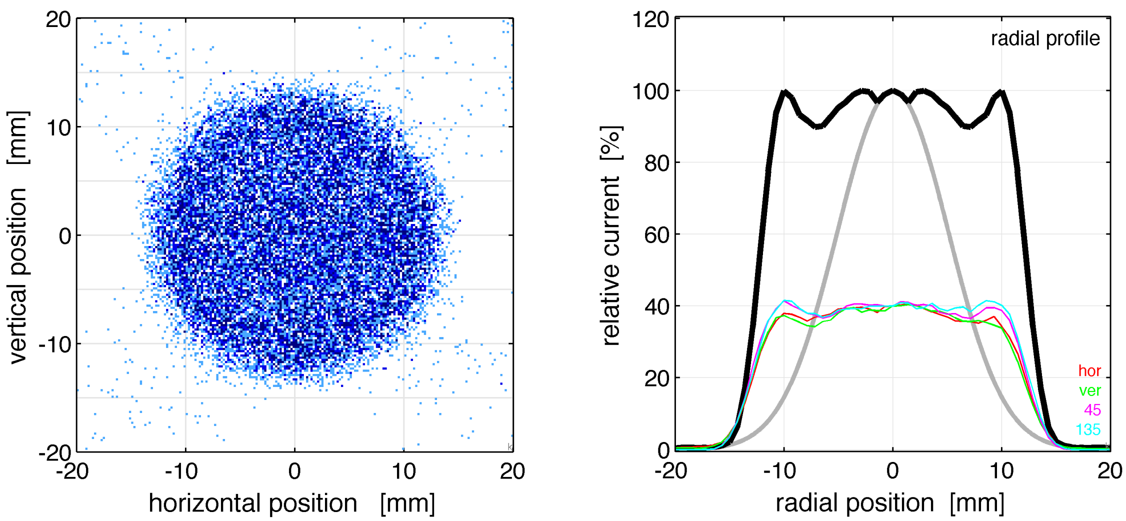
The left plot shows the particle distribution, while the black line on the right shows the radial profile. A grey Gaussian curve is shown with the same FWHM as the actual distribution. Two important differences exist between the two curves. First, the black distribution has wider "shoulders" than the Gaussian distribution, where additional particles are able to increase molybdenum production toward the edge of the target, increasing production efficiency. Second, and perhaps more importantly, the black distribution drastically reduces the "tails" of particles outside the target dimensions. These particles do nothing for production, yet generate significant thermal heating around the target and bremsstrahlung x-rays that activate beamline components. In a production facility, component heating and activation significantly decrease reliability and increase replacement cost.

This semi-flattop beam profile in these simulations includes zero collimation; 100% of the accelerated particles are utilized for production, and negligible activation x-rays are produced either. A later section of this report will discuss collimators for the very small fraction (under 1%) of particles that are outside of the desired target diameter.

Studies of different beam parameters were also conducted, including emittance changes, increased energy spread, etc. As an example, the following two plots show the beam profile when the beam emittance is reduced to 9-um. The profile is even more flat, with very sharp edges. This profile is even more suited to efficient production without beam-halo heating and activation issues. This simulation is an example of how the beam profile sets a requirement on the emittance capability of the accelerator section.



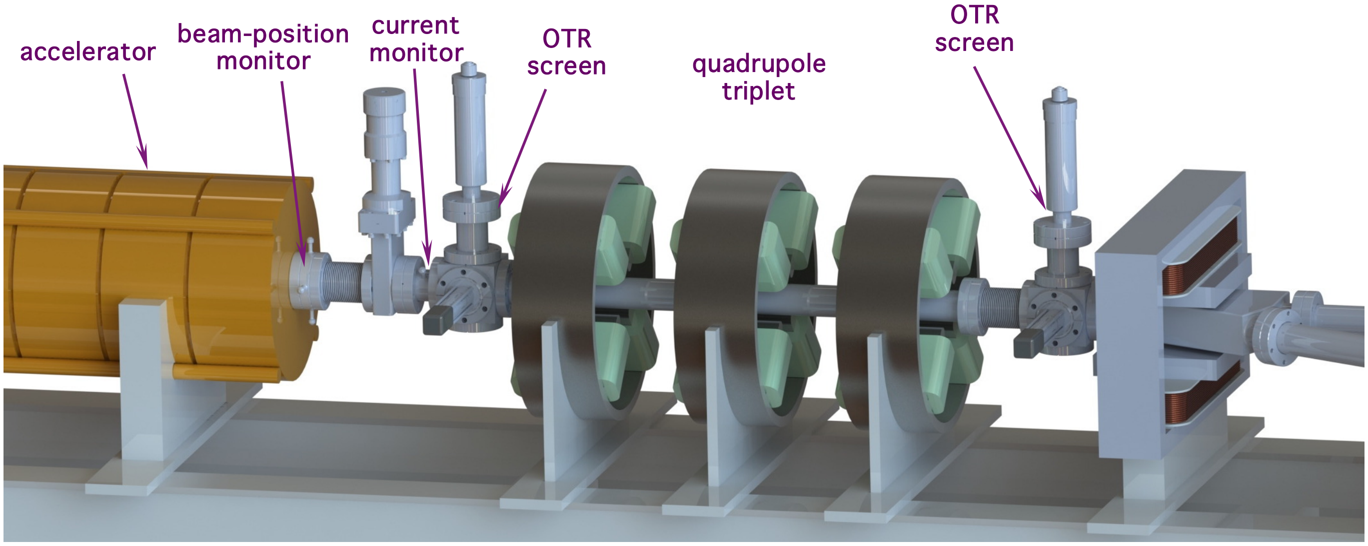
Similar to the reduced-emittance example above, a larger target diameter also enables an extremely flat beam profile, with sharp edges and negligible current outside the target diameter.



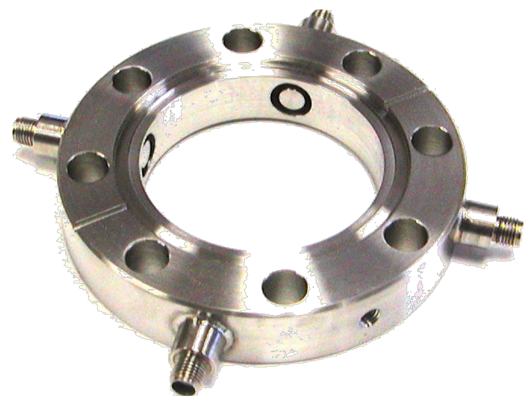
The two plots above show a well-shaped flattop, which has a lower peak-to-average heat flux. All of the above scenarios use the exact same beamline optics and dimensions; only the power-supply settings were adjusted. This means that after the production facility is operational, the target design could be changed significantly without forcing the beamlines to be rebuilt. The flexibility of the beamline design not only maximizes production efficiency for the current target design, but also allows future modifications if the target needs modification or a new application emerges. Again, there are no collimators in these simulations; over 99% of all particles fall within the above profile shapes.

Initial Matching Section

The first portion of the designed beamline is shown below. The beam exits the copper-colored linear accelerator on the left, passes through some diagnostics before reaching a quadrupole triplet. This triplet provides the large acceptance of beam parameters that the linear accelerator may provide.



Immediately after the linear accelerator is a beam-position monitor (BPM), the first of several along the beamline to maintain beam stability and performance. The BPM was designed at LANL and optimized for the production-facility beam parameters. Significantly more compact and robust than other BPM designs, LANL has already constructed several prototypes, several of which are currently installed at several accelerator facilities for calibration.



After the BPM, a bellows and gate valve provide flexibility during construction, commissioning, and maintenance (a fast gate valve, for machine protection, is provided further downstream). A dedicated current monitor is located after the gate valve, which verifies the peak and average current exiting the linear accelerator.

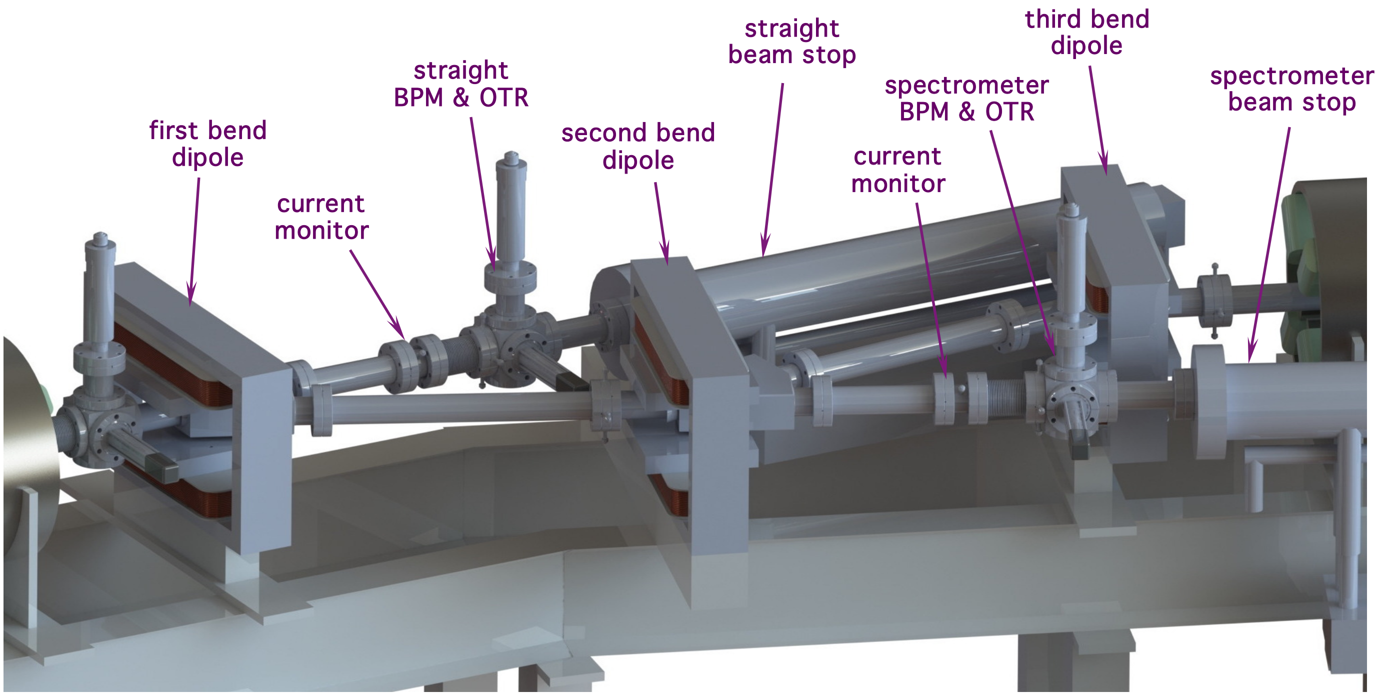
An "OTR screen" is provided after the current monitor, just before the first quadrupole. This setup consists of a vertical actuator from the top, based on a pneumatic piston, to temporarily push a screen into the path of the electron beam. This screen, oriented at 45-degrees to the beam direction, produces Optical-Transition Radiation perpendicular to the beamline. On the side, a camera is positioned that images this radiation. This apparatus is used during commissioning to verify the beam size, shape, and position (calibrating the upstream BPM). The screen is drawn up by the actuator when the production run is in progress.

The concept of OTR imaging is well-established for many beamlines around the world. The entire apparatus for beam commissioning, as illustrated here, has been designed, built, and tested at LANL with the exact cameras and supporting electronics needed for the production beamline. The apparatus again is arranged for maximum compactness and reliability for production facility requirements. A similar OTR system for monitoring the target itself is discussed later in this report.

The quadrupole triplet provides strong focusing in the horizontal and vertical dimensions that are needed to minimize unwanted nonlinear effects through the bending section. After the triplet, another bellows and another OTR screen is provided to monitor beam parameters. Finally, another BPM (somewhat concealed in the picture) provides in-situ monitoring of beam position entering the bend.

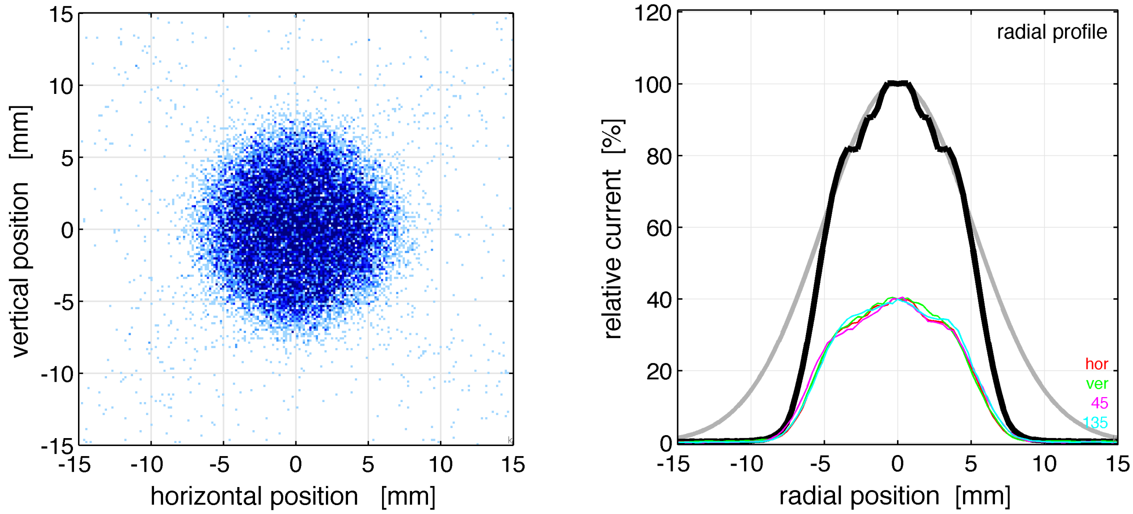
Dispersionless Bend Section

The following illustration shows the dispersionless bend section, including three dipoles with diagnostics designed to ensure reliability and optimization. A "straight" section (in the back of the illustration) is capable of verifying beam current and accelerator performance, while the spectrometer leg (in the front, far right) can measure beam energy and energy spread.

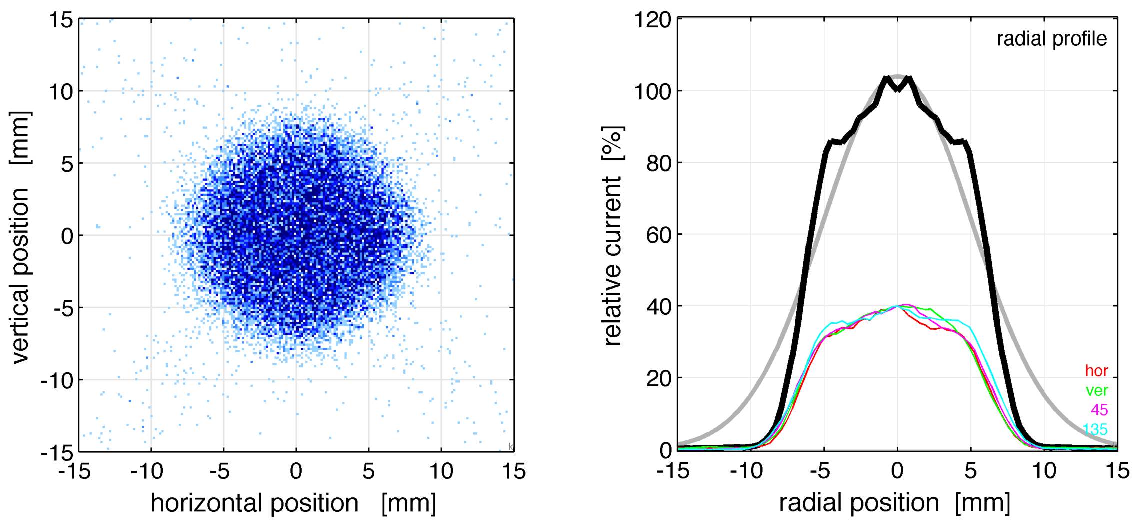


These legs are important during beam commissioning and performance verification. However, during standard production, the three bend dipoles steers the beam through the main beamline toward the final matching section. While a single dipole would be sufficient for simply bending a beam, the three-bend design provides several key advantages.

Most importantly, this design is "dispersionless," meaning it bends a beam with a large range of particle energies by the same angle. With typical energy spreads of 0.5%, plus another average fluctuating offset of maybe 0.2%, a beam will spread significantly through a non-dispersionless bend, and will change position with each pulse. The 2014 physics report of this design carefully studied the on-target beam spread due to energy spread and energy drift. A simulation to verify the beamline's insensitivity to beam fluctuations generated the beam profile shown below.



These plots show the effect of a significant reduction in beam energy, without changing any optical positions or strengths. Specifically, the average beam energy was decreased to 41 MeV (–2.4% from 42 MeV). A small difference in spot size has occurred (mitigated by the nonlinear optics), but more importantly, the center of the beam has not changed. This is the goal of a dispersionless beamline. The following plots show a 43-MeV beam (+2.4%), with again a small change to spot size, but no shift in position.



Both of the above scenarios are testing energy fluctuations far larger than typical accelerator performance. The beamline design has proven to be very robust with respect to energy changes. In addition, simulations with large energy spreads were also conducted, which showed similarly negligible effects on beam position, and even less changes to spot size than the above example.

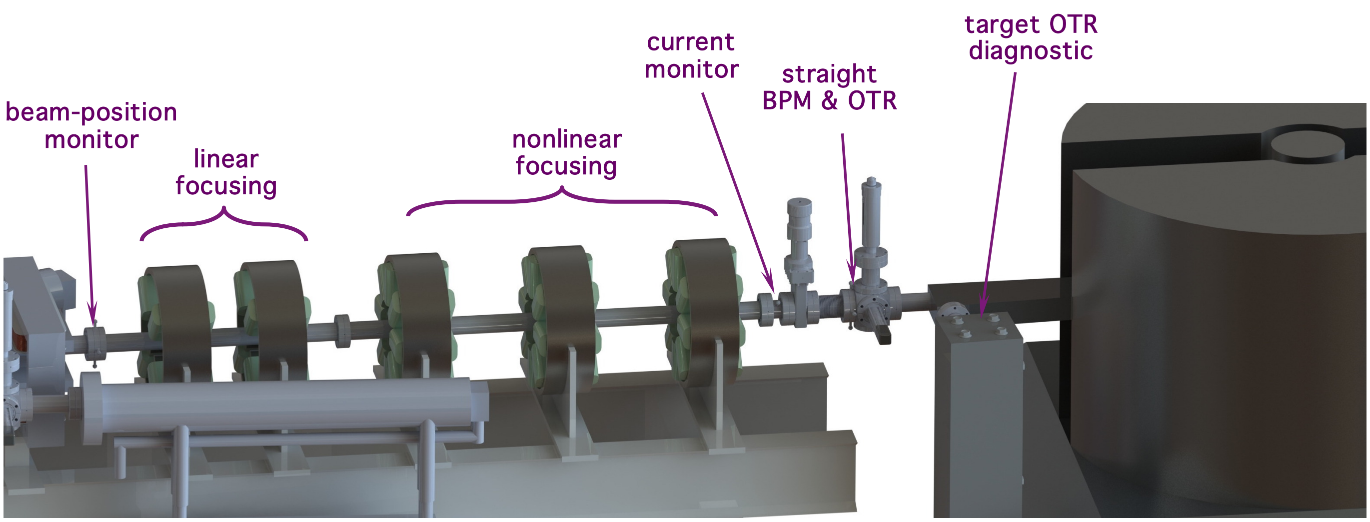
In the beamline design above, two cylindrical beam stops are also provided. The first one, partially concealed behind the dipoles, allows the beam to pass in a straight line, with the bend magnets turned off. This allows linear-accelerator operation or testing while the target is being constructed or repaired. A dedicated current monitor, BPM, and OTR screen ensure the beam is fully centered on the collector to avoid unwanted interception or activation.

The second cylindrical beam stop, in front of the last dipole and only partially in the image, is a stand-alone spectrometer. The first dipole is turned on, thereby bending the beam, but the second dipole is off, so the beam travels straight toward this collector. Again, a dedicated current monitor, BPM, and screen are able to measure average beam energy in addition to energy spread. This measurement is key to maintaining linear-accelerator performance and moly-99 production.

However, another BPM is located just next to the second dipole. This BPM (after calibration to the spectrometer), can measure average energy during a production run, and it is the most accurate noninvasive energy diagnostic to monitor beam health.

Nonlinear Optics Section

The final portion of the beamline takes the beam exiting the last dipole and matches it to the target dimensions. Two quadrupoles provide linear focusing to fix the overall spot size. Three additional octopoles provide nonlinear focusing as well. It is these elements that produce the flattop shapes shown earlier in this report and in the 2014 physics summary.



Several key diagnostics monitor the final beam performance. A BPM is located just after the last dipole, which verifies the beam is centered in the beampipe. After the focusing optics, the beam passes through a final current monitor, BPM, and screen. Another gate valve and a fast-acting vacuum sensor provide necessary safety if the target itself malfunctions or requires maintenance.

Two very key diagnostics monitor the Inconel target itself, which is the most critical for monitoring production rate and target heating. The vertically mounted box close to the target shielding houses the OTR diagnostic. A camera, along with two mirrors and telescoping optics, images the final beam distribution. Safety interlocks will utilize this in-situ diagnostic to verify beam performance, and optimization of the beamline elements will also use this image as the key performance parameter. In order to get a near perpendicular view of the target, one mirror sits in a slightly wider vacuum vessel, near the beam path. LANL has developed this OTR diagnostic with nearly the same dimensions, and it has been demonstrated and optimized at ANL's LEAF beamline.

A second diagnostic profiles the Inconel target-window temperature, utilizing the FLIR model A655sc Infrared Camera with specific calibration options and lenses. This system is located further upstream, using an on-axis port in front of the third dipole. Due to radiation sensitivity of the camera, it is located near the floor in a similar vertical box as the OTR diagnostic. Specific optics are needed for infrared radiation: A ZnSe window is used for the vacuum envelope, and a single gold-coated mirror is necessary to cover the operational wavelengths of the camera. This system minimizes the number of optics, which can severely degrade the camera's temperature accuracy. Like the OTR target diagnostic, the LANL team has optimized this system, utilizing ANL's LEAF beamline for demonstration.

Additional Beamline Components

Several important components are included in the beamline design and costing, but were "suppressed" in the beamline renderings shown in this report to simplify the discussion. First, a vacuum station, consisting of a pump and gauge, is provided at three locations (with a pump-out port at two of them). These are joined to the OTR-screen diagnostic cubes, one in each of the three beamline sections.

Another component not discussed are dedicated steering correctors, of which six are sprinkled along the beamline. Ensuring the beam remains centered through key focusing elements, these correctors have been designed to mount directly to the standard vacuum flanges. This technique, common at LANL and other facilities, is more compact and less expensive than traditional support systems.

A final beamline component are three collimators. This beamline design provides a uniquely flattop profile with vastly reduced tails, which is optimal for maximum production with minimal residual activation or heating. Nonetheless, a small percentage of particles (about 1%) remains in the tails; collimating these further alleviates concerns about activation. Dedicated collimators are included in the design in three positions. Immediately after the linear accelerator, a collimator clears beam halo which would otherwise activate downstream components. A second collimator in the bend clears off-energy particles that would otherwise be poorly focused at the target. The third collimator, just before the target, clears the residual tails from the flattop distribution. Removing 1% of the current has minimal impact on production efficiency. In addition, monitoring the current deposited on the collimators provides a final verification of the beamline's performance.

Conclusions

This report completes a full engineering design of the matching beamline from the initial accelerator to the target. Building on the FY14 physics study, the design includes a component count, specifications, and costs for construction. Individual beamline optic elements have been detailed. Beam diagnostics are also specified, and in several cases, prototypes have already been built and successfully tested, at LANL, ANL, and other national laboratories. The design has already been proven to ideally shape a beam profile for the design target; however, the flexibility of the beamline design also enables future target modifications without modification to the beamline itself.

The beamline design, as finalized here, has been studied for beam size, shape, quality, and reliability for a variety of component and beam sensitivities. A full trade study is anticipated in FY16, which defines more specific requirements on the accelerator-section performance, along with more detailed fabrication and assembly tolerances.

This beamline design will also be compared to other accelerator architectures, which will determine the most reliable and efficient technology for a future isotope production facility.