INDUSTRIAL BEAMLINE DESIGN FOR RADIOISOTOPE PRODUCTION

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Abstract

SPECT radioisotope producers generally utilize commercial cyclotrons which output proton beams in the 20 - 50 MeV range. To separate the target radiation environment from that of the cyclotron, beamlines are used to transport the extracted beams to one or more shielded target rooms. Industrial beamline systems pose an interesting engineering challenge. Such beamlines must focus the beam to customer dictated target specifications, often over a significant energy, and current range. Dual or single beam extracion may be required, and particles other than protons may also require transport to target. Beam spill in all primary and secondary lines must be kept low (usually less than 5%), and beam must be maximized to target. Industrial beamlines must be robust, reliable, and easy to maintain with consideration given to "rad hard" and low activation materials to minimize dose to maintenance personnel. This paper describes developments in these areas for beamline systems in radioisotope production facilities.

INTRODUCTION

This paper describes the process of designing a modern industrial beamline for radioisotope production. The process starts with the contract specifications, followed by initial layouts and ion-optical design work to meet the contract constraints. This is followed by the development of the overall assembly drawing, and the engineering, design and drafting of the various components that comprise the overall assembly. Lastly, a description of specifications for sub-system interfaces is given along with thoughts on factory testing, and user manuals.

BEAMLINE DESIGN

Contract Specifications

Beamline design starts with a thorough review of the contract specification. The contract for the beamlines at a cyclotron based radioistope production facility typically specifies, but is not limited to, the following [1]:

- particle type.
- range of particle kinetic energies.
- range of beam currents.
- maximum beam emittances in each phase-plane.
- number and length of primary lines.
- number and length of secondary lines.
- target spot size dimensions.
- permitted beam spills.
- nominal beam pipe diameter, flanging, and vacuum level.

The contract specifications are the constraints that must be met throughout the beamline design.

Beamline Layout

The next step in the design process is to develop a beamline layout. Often the client has an existing accelerator vault and target cave layout to adhere to. The number and length of primary and secondary beamlines specified in the contract must be accommodated as well as the prescribed target locations. In addition, the extracted beam trajectory orientation with respect to the accelerator must be taken into consideration. This can be particularly tricky for variable energy H^- cyclotrons, where the extracted beam trajectories have a common cross-over point through which the beamline centreline(s) must pass. Finding the accelerator orientation, and the crossover point locations, for the case of dual extraction, that permits secondary lines to intersect with prescribed target locations whilst not necessitating unmanageably large dipole magnet bend angles for all extraction trajectories requires an iterative approach involving a series of discussions between the client and the designer. Figure 1 shows a layout for beamlines on one side of the cyclotron at the INER TR30/15 facility.

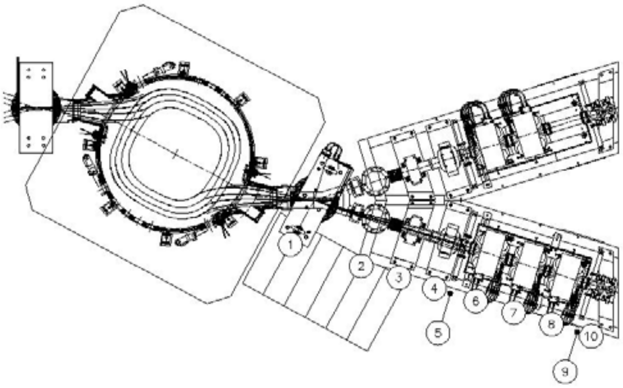

Figure 1: INER TR30/15 Beamline Layout. Numbers indicate residual radiation locations 0.5 m from the beamline. The upper beamline has a second quadrupole doublet in the target vault.

Ion-Optics

Once a layout has been reached that satisfies the geometrical constraints of the facility, and which minimizes power consumption in the main switching magnets through careful consideration of the bending angle requirements over all beam energies, the ion-optics study can begin. For initial design work to first-order the Beamline Simulator software is useful [2], and for higher-order corrections the PBOLab software suite is used [2].

A large number of ion-optics scenarios typically get generated. For example, for the case of 4 target locations, and 2 beam spot dimensions to be accommodated at each location (one rectangular, and one round for example), 2 emittance scenarios (one maximum, and another nominal), 4 beam energy cases (say 15, 20, 25 and 30 MeV), the total number of ion-optics cases to check becomes 4 x 2 x 2 x 4 for a total of 64 runs. Careful file management is required to keep track of all of the modeled scenarios.

The beamline designer first uses the worst case beam emittance scenario to guide the design. Major switching or bending magnets required for geometrical reasons are then inputted into the modeling codes. The next step is to determine the number and location of quadrupole magnets to easily achieve the required beam spots on target while at the same time keeping the transported beam sizes small in the optical element apertures to minimize aberrations and beam loss. Solutions tend to converge towards a quadrupole triplet for shorter lines, and sets of quadrupole doublets for longer lines.

The ion-optics solution must provide sufficient space for two point beam steering upstream of the quadrupole magnets, so that the beam is aligned prior to entry to the quadrupole magnets. In the horizontal plane this is typically achieved by the azimuthal adjustments on the extraction probe in conjunction with magnetic field adjustments on the upstream switching magnet (sometimes called a combination magnet). In the vertical plane this is achieved by two vertical steering magnets separated by a reasonable drift space, upstream of the quadrupole magnets. Space for beam diagnostic devices, vacuum pumping equipment, gauges, bellows, flanges, and supports is also required.

Overall Beamline Layout Drawing

Once all the ion-optics scenarios have been satisfied, such that a work-able layout of dipole and quadrupole magnets has been established, an overall beamline drawing is established similar to that shown in Figure 1, although at the beginning of the project the layout may be somewhat rudimentary. This drawing is continuously updated throughout the project as the detailed design of each component is completed. This ensures that any device interference issues are noted and dealt with as early as possible in the design process.

With the magnets laid in (such as major switching dipole magnets, small vertical steering dipole magnets, and quadrupole magnets) the remainder of the beamline devices can be laid in.

At the upstream end of the beamline it is traditional for this designer to connect the beamline to the cyclotron exit port with a large aperture set of bellows. The inner portion of the cyclotron main tank exit horn and bellows is protected with a beam current readback type water-cooled baffle to aid in beam centring and provide protection. This is usually followed by a large switching dipole magnet which in the case of Figure 1 directs the full range of extracted beam energies and particle types onto one of two primary beamlines. This magnet comes with an aluminum vacuum box to minimize residual radiation, with downstream graphite exit port monitors to ensure the beam is horizontally centred on the downstream beamlines. This magnet also comes with three point alignment. A gatevalve is also included at the upstream end of the beamline to separate the main tank vacuum region from that of the beamline.

Immediately following the switcher the first vertical steering magnet is located. This is followed by a second vertical steerer and a 4-way slits with beam current readbacks to ensure that the beam is centred upstream of the quadrupole magnets (if the beam is not centred through the quadrupole magnets they will steer the beam as well as focus it, which causes non-intuitive beam behaviour on target). The beamline pumping (typically cryo) is often situated in this region of the beamline along with a connection to the oil-less roughing system, high & low vacuum gauges, a leak detector port, and a set of bellows.

Between the quadrupole magnets and the vault wall is usually a Faraday cup with a set of 4-way slits for proper beam location and centring. All beamlines designed by this author have been successfully implemented with low current beam stops to minimize activation and residual radiation in the vault. The stops are capable of intercepting the full beam if required, for machine safety reasons, but are only used with beam current less than 30 micro-amperes during initial tune-up, with the final tune-up on target from 30 micro-amperes to full current (500 micro-ampere level) being achieved within a very short time frame (on the order of a minute or so). A bellows is also located in this region of the line. The last device before the vault wall is a neutron blocker. This device is a pneumatically operated stop composed of neutron shielding materials.

The beam pipe through the vault wall is surrounded with neutron shielding materials. The beamline connection to the target station may be as simple as a bellows, and a gate valve. The target station provides a target surface with beam current readback and usually a 4 way slit system with beam current readback, or a ring collimator with beam current readback. The target cave portion of the beamline may also be equipped with additional focusing quadrupole magnets [3]. These must utilize radiation resistant materials.

Beamline Component Detailed Design

The following guidelines developed in [1] by Stinson, Garner, Helmer and the TRIUMF Applied Program staff are followed during the detailed design of the beamline devices, these are:

- high beam transmission.
- use of low activation and low neutron producing materials.
- use of radiation resistant materials.
- use of industrial grade robust designs.
- minimize maintenance time in radiation areas.
- use of essential equipment only in radiation areas.

In terms of high transmission, a low emittance extracted beam is important. Device apertures at least twice as big as the nominal beam size are required. It is also important to have enough beam diagnostic information to enable operators to know where the beam is at all times. It is typical for our firm to employ 12 – 18 water-cooled graphite diagnostic readbacks between extraction and the target. For example, this could be (1) the stripper readback, (2) an exit horn baffle, (3, 4) a left and right spill monitor at the exit to the switching magnet, (5, 6, 7, 8) a top/bottom/left/right slit upstream of the quadrupoles, (9, 10, 11, 12) a top/bottom/left/right slit upstream of the Faraday cup, (13) the Faraday cup, (14, 15, 16, 17) the top/bottom/left/right target collimator, and (18) the target current readback.

With regards to low activation and low neutron production materials, there are three categories. First for vacuum box devices which may be struck by stripped neutral beam (in H^- machines) such as a main cyclotron vacuum tank, Thorson [4] shows that aluminum is the best choice over stainless steel. Second for the case of beam intercepting diagnostic devices, materials with a low neutron production rate are sought. Thorson [4] shows that for incident protons in the 0 – 32 MeV range, carbon yields the fewest neutrons by a factor of 5.5 lower than aluminum, a factor of 10.5 lower than iron, and a factor of 14.6 lower than copper. Third for achieving low residual activation after bombardment by protons, Thorson [4] shows that carbon is the best choice over copper. It is our experience that graphite beam intercepting devices have worked very well. The perceived problem that water absorption by graphite can be problematic to the vacuum system has not been seen in practice in the beamlines we have designed.

The INER TR30/15 (500 µA, extracted p+, 15 – 30 MeV; 150 µA, extracted d+, 7.5 – 15 MeV) beamline design followed the low activation principles. Radiation data was obtained June 14, 2004 after a 6.75 hour 29 MeV proton beam run of 305 µA [5]. The residual radiation levels at 0.5 metres from the beamline at the numbered locations in Figure 1 are given in the format (radiation level @ 2 hours, 4 hours, and 6 hours after beam off). The data is: Position 1 (0.350, 0.280, 0.256 mSv/hr), Position 2 (0.260, 0.190, 0.170 mSv/hr), Position 3 (0.135, 0.120, 0.105 mSv/hr), Position 4 (0.095, 0.067, 0.056 mSv/hr), Position 5 (0.055, 0.043, 0.040 mSv/hr), Position 6 (0.050, 0.034, 0.025 mSv/hr), Position 7 (0.027, 0.020, 0.016 mSv/hr), Position 8 (0.051, 0.019, 0.017 mSv/hr), Position 9 (0.038, 0.016, 0.014 mSv/hr), Position 10 (0.050, 0.015, 0.013 mSv/hr).

The radiation resistant materials Vespel™, Macor™, ceramic stand-offs, boron nitride, Kapton™, Tefzel™, melamine, and polyurethane materials are useful as are stainless steel cable ties. Nylon is avoided.

Industrial designs are utilized. This means simple, sturdy, and robust designs. Finicky break-able parts are avoided.

Minimization of maintenance time spent in a radiation environment can be attained through the use of quick disconnect vacuum, cable, and tubing connectors. This philosophy is very important in very high radiation areas. In low radiation areas, where device failure is uncommon it is sometimes prudent to avoid o-ring seals and to utilize Atlas Technology [6] bi-metal seals. These bi-metal seals permit a stainless steel knife-edge seal on the one side, and an aluminum weld-neck nipple on the other to weld to aluminum vacuum boxes and pipes.

Essential equipment in the vault means keeping all electronics equipment such as power supplies and logic controllers outside of the radiation environment of the cyclotron and target vaults.

Beamline Design Documentation

The engineering and drafting process for the various components and the overall layout together with the implementation of the bills of materials, and the scopes of work for machine shop production requires careful organization, and double-checking. Each new component requires a design note that must be presented to and critiqued by peers. The detailed drafting must be checked on an electronic basis first by an independent designer, and then by the engineer in charge. The complete beamline design is contained in a single multi-chapter document that contains the contract specifications, the ion-optics design note, the Engineer's detailed beamline specification, the overall beamline assembly, the design notes for major new components, all assembly and piece part drawings, a set of bills of materials for all parts, machine shop scopes of work for the manufacture of the entire beamline including machine shop specifications for painting, vacuum leak testing and the like. Interface specifications for power services, water services, air services, and controls sub-systems are provided. In addition, a beamline maintenance document, spare parts list, factory test results, and user manual completes the list of documentation required by the client.

CONCLUSIONS

An overview of beamline design for cyclotron based radioisotope production facilities is presented. These principles have successfully been implemented in a dozen beamlines to date.

REFERENCES

[1] M. Dehnel *et al*, "The Design and Operation of an Industrial Beam Transport System for 15-30 MeV Protons," IEEE Trans. Ind. App., Vol. 28, No. 6, Nov. 1992, p. 1384.

[2] http://www.ghga.com/accelsoft/

[3] N. van den Elzen, "Applications of Beam-Line Simulators," WAO'2001, Geneva, Feb. 2001, Switzerland.

[4] I.M. Thorson, "Shielding and Activation Estimates for the TRIUMF 42 MeV Cyclotron Facility", TRIUMF TSAC Document, TR-1982-01-04, 1982.

[5] M. Dehnel *et al*, "Beamline Developments in Commercial Cyclotron Facilities," CAARI'2004, Fort Worth, Oct. 2004, in print.

[6] http://www.atlasuhv.com/