ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK104

NEW PROTON DRIVER BEAMLINE DESIGN FOR THE ARIEL* PROJECT AT TRIUMF†

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Abstract

The new rare isotope beams facility at TRIUMF, ARIEL, under construction, comprises two primary driver beams: 50 MeV electrons from the SC linac and 480 MeV protons from the main TRIUMF cyclotron. A new 80 m long proton beam line will transport up to 100 μA of beam from the existing cyclotron extraction port to an ISOL target station. H^- cyclotron stripping foil extraction allows to feed this additional user simultaneously with 3 present different experimental programs. Distinctive features of the new beam line include: a) compensation of the cyclotron energy dispersion; b) low-loss (<1 nA/m) beam transport after a collimator dedicated to remove the beam halo produced by large-angle scattering in the extraction foil; c) a broad range of beam size variability at the production target by applying beam rastering at 400 Hz; d) sharing the same tunnel with the electron beam line that requires a unique beam loss protect system. Details of the beam optics design are discussed in the paper.

BL4N OVERVIEW

BL4N [1], a new proton beamline within the ARIEL project, will be delivering protons from the existing 500 MeV cyclotron to the ARIEL target to allow for an enhanced RIB physics program and therapeutic medical isotopes production at TRIUMF. Generally speaking, this beam-line has similarities with existing proton lines in terms of the beam energy, between 475 and 500 MeV, and maximum intensity of 100 μA. Specifically, it has been made mandatory that the beam-line design fulfills the following requirements which are distinctive from the existing proton lines:

- The layout must fit within the ARIEL building and be reconciled with the electron beam line layout through the North-South tunnel up to the proton target station.
- Shall be capable of transporting protons with a loss <1 nA/meter. Such a low beam loss will permit hands-on maintenance and prevent inordinate activation and damage to hardware components.
- Shall be designed to compensate the cyclotron's dispersion such that the beam centroid will no longer drift over time and will not need constant correction.
- Shall be designed to collimate large angle scattered particles from the stripping foil before they propagate down to the North-South tunnel. This will make the beam line cleaner.
- Shall provide a matching section after the last dipole to allow sufficient tunability for the instantaneous beam spot size at the target.
- Shall provide 20 mm×20 mm full width square/round spot on the target by means of rastering, while the instantaneous beam size shall be ≥2 mm (2rms) and flexible up to 8 mm at target.

DISPERSION COMPENSATION

The foil during use for the H^- stripping extraction may have uncontrolled motion due to curling and thermal distortion, causing beam centroid movement in the beam line. This is because the cyclotron is intrinsically dispersive; the beam dumped on the foil has energy and radial position correlated. The local dispersion values in position and angle turn out to be 3.4 cm/% and 3.4 mrad/% respectively at 480 MeV stripping azimuth. This means that a foil movement of 5 mm leads to a momentum shift of 0.15% or an energy shift of 1.2 MeV. These will be transported down to the beam line, represented as:

$$\begin{pmatrix} D \\ D' \\ 1 \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & R_{16} \\ R_{21} & R_{22} & R_{26} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} -3.4 \\ -3.4 \\ 1 \end{pmatrix} \tag{1}$$

where the initial values of D and D' are negative as in the `TRANSPORT` convention and $+x$ is opposite to the radial direction. The transfer matrix of 480 MeV for $(x, x', \Delta p/p)$ in units of cm,mrad,% from the foil to the combination magnet exit is:

$$\begin{pmatrix} R_{11} & R_{12} & R_{16} \\ R_{21} & R_{22} & R_{26} \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} -0.079 & 0.325 & 1.366 \\ -3.107 & 0.131 & 2.062 \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

Inserting Eq. (2) into Eq. (1) gives dispersion:

$$\begin{pmatrix} D \\ D' \\ 1 \end{pmatrix} = \begin{pmatrix} 0.53 \\ 12.18 \\ 1 \end{pmatrix} \tag{3}$$

This is not the same thing as the above elements R_{16} and R_{26}. It implies that the optics to cancel $D, D' = 0.53$ m, 12.18 mrad/% are very different from that needed to cancel $D, D' = 1.37$ m, 2.06 mrad/%. For the BL4N design, we will compensate the dispersion in the front-end (i.e. at the exit of the first bending magnet), otherwise it will propagate downstream with the beam centroid movement getting magnified, causing spills.

Besides canceling the dispersion, we also want to achieve in the front end a positional image of the stripping foil so that we can monitor the health of the foil to prevent failure. This requires $R_{12} = 0$ and $R_{34} = 0$.

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[*] Capital funding from CFI(Canada Foundation for Innovation)

[†] TRIUMF receives funding via a contribution agreement through the National Research Council of Canada.

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SPILLS FROM FOIL SCATTERING

We only permit a beam loss of <1 nA/m along the beam line. At full intensity of 100 μA, this is 10^{-5} level. For a 5 mg/cm^2 foil, 10^{-5} of particles are scattered beyond 7 mrad. See Fig. 1. These particles already run outside a nominal 4" beam pipe as the transfer matrix element R_{34} is ~1 cm/mrad along the line. Currently the foils in use are typically ~2 mg/cm^2. This produces an angle ≥ 3.3 mrad for 10^{-5} of particles.

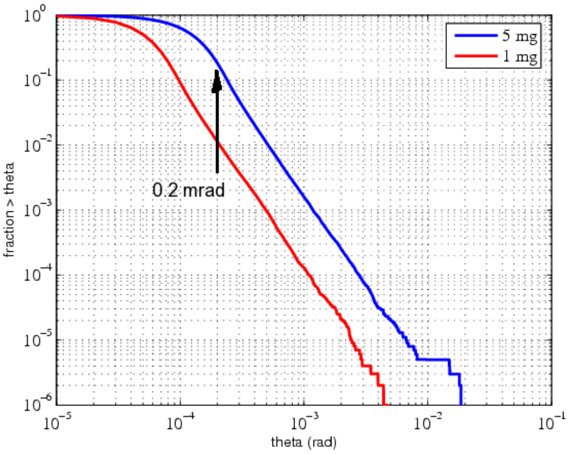


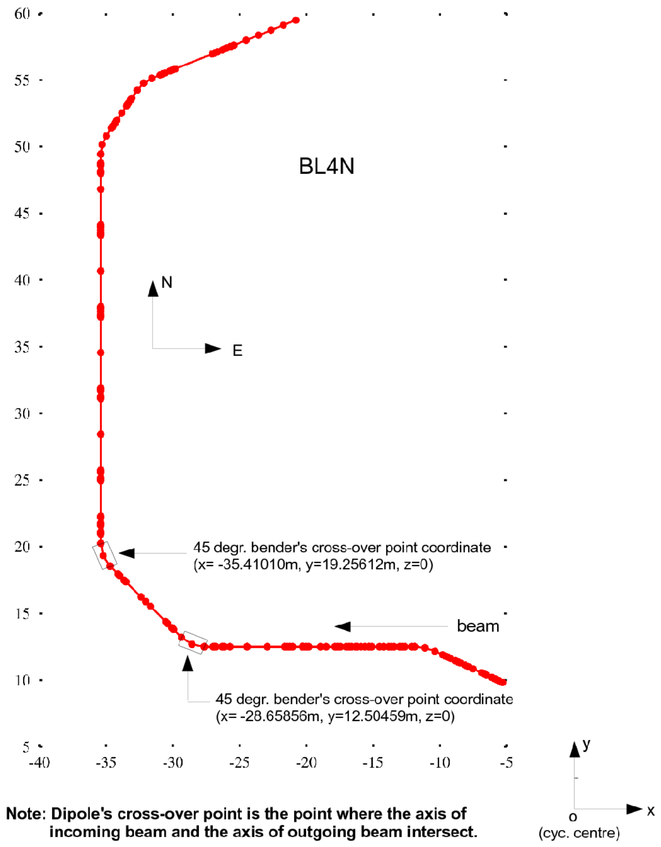
Figure 1: Log-log plot showing the fraction of particles scattered from stripping foil of an angle exceeding certain magnitude, calculated with `GEANT4`.

On the other hand, the cyclotron beam is intrinsically of high quality: the emittance is ~1.1 mm-mrad (2rms), and the angular spread is only ±0.3 mrad for the core of the beam. The solution is therefore to collimate the large angle scattered particles before they propagate down to the tunnel. We shall place a collimator in a dispersion-free region, where the particle's angles at stripping foil are mapped to transverse positions. This requires $R_{11} = 0$ and $R_{33} = 0$.

OPTICS LAYOUT

The resulting BL4N layout is illustrated in Fig. 2. It is composed of a front-end section, a collimator region, a 90° achromatic bend section with variable dispersion, a matching and periodic section, a 68° achromatic bend section, and a 4-quad matching section to the target with AC raster magnets placed.

In the front end section, we accomplish the dispersion compensation, foil imaging, followed by the beam collimation. The dispersion is canceled upon coming out of the 1st dipole magnet. The foil imaging is configured at a location ~20 cm outside the vault wall. This will allow easy access for repair, replacement or maintenance of the beam profile monitor. The collimation is realized by point-to-parallel focusing from the foil to the collimator, where the particle's transverse positions are dominated by their angles at the foil, thus large-angle protons can be collimated out. Further collimation in the 90° bend section of extreme energy particles is unlikely feasible as the shielding dimension required is likely too large to fit in locally. So, in both the 90° and 68° bend sections, we minimize the dispersion, aiming to minimize spills due to extreme energies. Over the periodic section, it is essential for the beam to get well matched through; once matched, the subsequent sections up to the target can always work out nicely without having to re-tune. To that end, we put a 4-quad matching section before the periodic channel. These 4 quads, plus the preceding doublet if needed, are the only tuning knobs to use. It is worth mentioning that we managed to reconcile the optical elements (particularly the large magnets) in the North-South tunnel in order to avoid interferences with the electron beamline which is sitting three feet below the BL4N.



Note: Dipole's cross-over point is the point where the axis of incoming beam and the axis of outgoing beam intersect.

Figure 2: Diagram of BL4N layout, where the red dots mark magnetic elements.

Fig. 3 shows the calculated beam envelope and dispersion, where the beam size displayed is 2 mm (2rms) at the target but this is changeable between 2 and 8 mm by simply tuning the last 2 quadrupole doublets.

COLLIMATION

To estimate the beam losses and their mitigation of the large-angle tails due to scattering, a simulation study [2] has been performed using the iterated single-scatter algorithm in ACCSIM [3] for the foil (2.5 mg/cm^2 proposed

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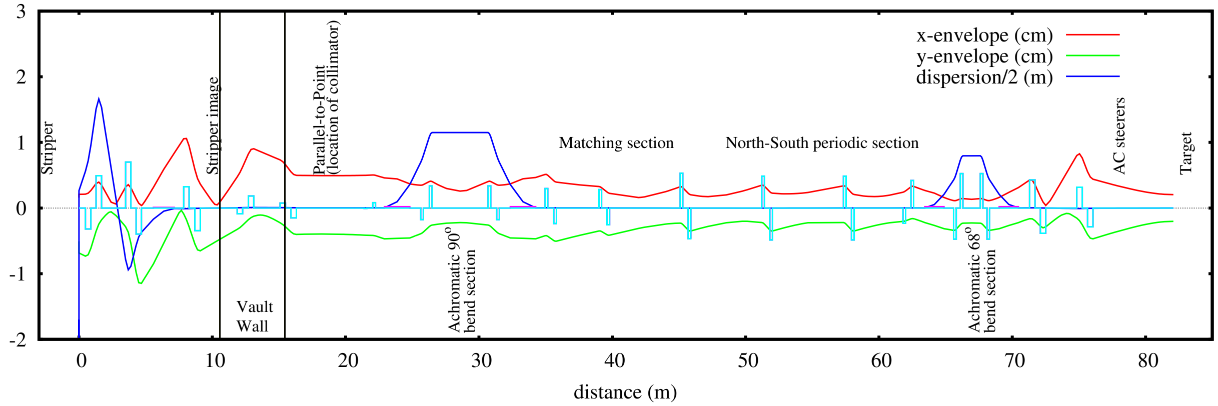

Figure 3: BL4N beam envelope (2rms) and dispersion. The instantaneous beam size as shown is 2 mm (2rms) at the target but is flexible up to 8 mm by tuning the last 2 quadrupole doublets.

thickness) followed by tracking through the 3D geometry of the beamline with G4beamline [4].

Without collimation, losses exceeding the desired limit of 1 nA/m are observed at several locations distributed along the beamline. With a copper collimator of circular cross section, having a 20 cm long conical section followed by a 1 m cylindrical section (to help clean up out-scattered protons) our simulations showed that effective loss control (limited to 1 nA/m everywhere) could be achieved, as seen in Fig. 4. Recently a second series of runs were performed for an elliptical aperture (~0.8 aspect ratio) which better matches with the beam-tail distributions, and showed a further improvement with total post-collimator losses of ~2 nA and peak losses of <1 nA/m. See Fig 5.

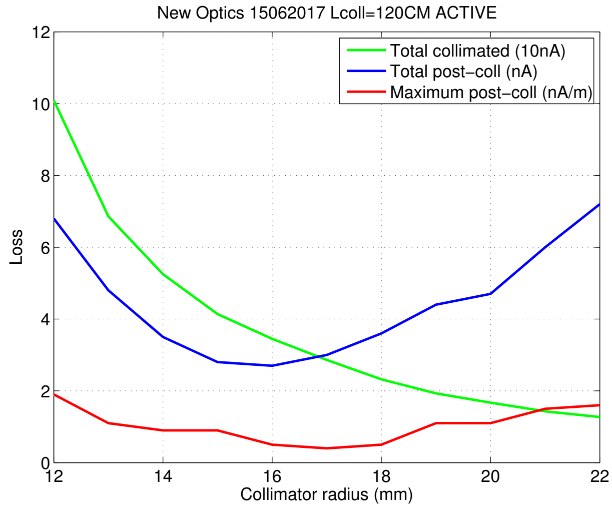

Figure 4: Loss control performance of 120 cm long collimators with elliptical aperture, as a function of aperture size.

BEAM RASTERING

Beam rastering with a frequency faster than 400 Hz is required to allow homogeneous surface power deposition in the target; a lower frequency could cause fatigue failure or aging of the target. We presume that we shall use LANL developed ferrite dipole magnet [5] which is 30 cm long and produces ±500 G peak field at 500 Hz. Such a magnet can generate a deflection of $\pm 500 \times 30/3545 = \pm 4.0$ mrad for the 480 MeV protons. To raster the beam over a 20 mm by 20 mm spot (full width) on the target, we shall need a lever arm of $R_{12}, R_{34} \geq 2.5$ m from the raster magnet centre to the target entrance. We put the raster magnet downstream instead of upstream from the last quadrupole doublet, so that the lever arm is independent of the instantaneous beam size. This way allows to simplify the tuning.

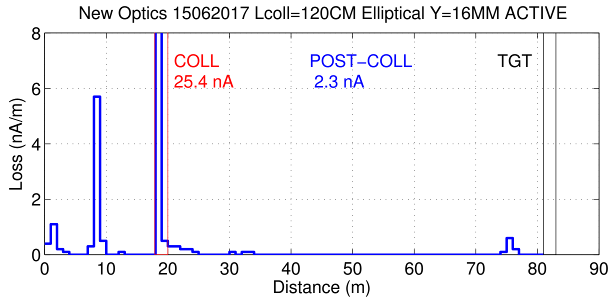

Figure 5: Distribution of losses along the beam-line.

SUMMARY

In summary, the optics design of BL4N accommodates all the known operational requirements and constraints: compensating the cyclotron's dispersion, collimating large angle scattered particles from the foil, matching beam onto the target, etc. All these are expected to make BL4N cleaner, more stable and more easily tunable than any of the existing TRIUMF primary beam lines.

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