TRI-DN-13-13: Beam Line 4 North (BL4N) Optics Design

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History of Changes

Release number	Date	Description of changes	Author(s)
01	2013-Jul-08	First release.	Y.-N. Rao R. Baartman
02	2013-Jul-19	Following I. Bylinskii's suggestion, I moved the 2 × 45° bend section towards North-East by 50 cm to allow additional shielding.	Y.-N. Rao
03	2014-Feb-12	Specified latitudes for quadrupoles tabulated under Section 6.	Y.-N. Rao
04	2014-Feb-27	Added up diagnostic elements and correctors.	Y.-N. Rao
05	2015-Feb-25	In terms of ARIEL 1.5 EHBT meeting Minutes and Actions dated in Feb. 2015 by S. Koscielniak, I made following changes: (1) relocated quadrupoles 4NQ11, 4NQ12, 4NQ13, 4NQ14, monitors 4NBPM20, 4NHARP16, 4NHARP18, 4NHARP20, and correctors 4NXYCB14 so that they do not interfere with the EHBT elements; (2) moved the raster magnet outside of the shielding wall; (3) added up the target entrance module assumptions. All these changes are reflected in the element tables under Sections 6 and 7. Besides, I added up some statements.	Y.-N. Rao
	2015-May-29	In terms of upper level requirements, made following changes: (1) adopted the agreed abbreviations for diagnostic devices; (2) eliminated the vertical steerer 4NYCB4 and relocated 4NBPM4 before the 4NHARP4B to prolong the collimator shielding to ∼3.3 m in the longitudinal direction. The steering function shall be accomplished with quadrupole 4NQ5 by asymmetrical excitation.	
	2015-Jun-30	(1) As per the request from M. Marchetto, I moved the proton target APTW eastward by 2 cm so that the separation becomes exactly 8.0 m between the APTW and AETE. This movement involves changes of coordinates for all the elements from 4NYCB22 onward to the end. (2) Replaced 4NHARP4A & 4NHARP4B with 4NWS4A & 4NWS4B respectively. (3) Changed/added up statements in terms of reviewers comments.	

History of Changes

Release number	Date	Description of changes	Author(s)
06	2019-Apr-18	(1) Updated quadrupoles in terms of their types that we know so far. (2) Discarded multi-wire ionization profile monitors and replaced them with wire scanners. (3) Added up two beam halo monitors, one BPM, and four correctors (one of them is combined with a beam blocker), according to the calculation & simulation results. Besides, added up a bunch time structure monitor and a time-of-flight monitor. (4) Adopted the newly-proposed terminology for the elements.	Y.-N. Rao
	2019-Jun-25	Updated element's coordinates to comply with the coordinate positions of the combination magnet cross-over point and the yoke edge point which were rectified by the DO and BL Group.	

1 Abstract

The Beam Line 4 North (BL4N) is defined in this document in terms of the magnetic optics design, geometrical layout and element coordinates, as well as element specifications.

2 Objective

The BL4N shall deliver proton beam from the 500 MeV cyclotron to the ARIEL west target. This note describes the design of BL4N magnetic optics, covering major element coordinates and performance specifications in sufficient details for proceeding to the mechanical/engineering design.

3 Definitions

- **Coordinate system:** The cyclotron Cartesian coordinate system defined herein is such that the origin is in the centre of cyclotron, $+x$ axis is at 91° w.r.t. the centre-line of valley #1, $+y$ axis is at 181° w.r.t. the centre-line of valley #1, and $+z$ axis points upward. The x-y-z is right-handed. The (x, y) plane is the geometrical median plane of the cyclotron. It's worthy to mention that $+x$ axis is approximately (instead of exactly) pointing to East, while $+y$ axis is approximately (instead of exactly) pointing to North.

- **Beam profile monitor :** The beam profile monitor herein is required to be the wire scanner (WS) which is capable of measuring x and y profiles of the 480 MeV proton beam with intensity ranging from 10 nA up to 100 μA with sufficiently good signal-to-noise ratio. The measurement for low intensity beam ($<$ 100 nA) is essential for the routine check of the beam-line tune, especially when the machine just starts up from shutdown or maintenance. Whereas the measurement for high intensity beam ($>$ 10 μA) is necessary for accurate characterization of the beam property under realistic operational condition of the machine. **It's worthy to emphasize that the multi-wire ionization chamber (i.e. the harp monitor) must be abandoned for the BL4N, because (1) the harp monitor has very poor signal-to-noise ratio, making it difficult to discern the beam tails and halos; and (2) different wires show different responses to the beam density, causing distortions to the beam profile and therefore completely screwing up the beam size**.

- **Bunch Time Structure Monitor (BTSM):** is meant the PSI type of monitor [12] which is capable of measuring both the longitudinal and transverse density distribution of bunch with intensity up to 100 μA. To date, we have no diagnostics to measure the longitudinal density distribution of the bunch. The existing LE and HE probes in the cyclotron do not have such a capability at all; while the notch monitor for BL1U can't measure the beam variation over a time scale shorter than 1 μs. But we wish to measure the distribution of individual bunch over a time scale of $\leq$ 5.0 ns ($\simeq$ 1/23.055 MHz/9.0), because this would allow us to investigate the beam behavior under the space charge force in the cyclotron.

- **Beam Position Monitor (BPM):** is the non-intercepting monitor based on 4 inductive pick-ups and tuned to the second harmonic (46 MHz) of the cyclotron fundamental frequency [13].

- **Knob:** By knob is meant settable optical parameter. Implementation may be either through one-to-one correspondence between set point and a single independent power supply, or multiple supplies under software control as a single set point.

- **Nominal beam size:** is defined as $\sqrt{\beta\epsilon}$, where β is the betatron amplitude function and ϵ is the beam emittance. On average $\beta \sim 5$ m. The nominal emittance is $\epsilon \simeq 1.2$ mm-mrad (4rms, normalized) coming out of the cyclotron. These give a nominal beam size of ~2.5 mm (2rms). The calculated beam envelopes (2rms) described in this design note were performed for the beam energy of 480 MeV. This is based on the fact that the existing primary beam lines 1A and 2A both have been running at 480 MeV for over 10 years and are still running at 480 MeV.

- **Beam line name prefix:** The beam line elements are named according to the newly-proposed terminology, that is, using a common prefix 4N. For example, the quadrupole magnets are named as 4NQx, where x is from 1 through 36. All the other elements are numbered accordingly.

4 Requirements and Constraints

4.1 Top Level Requirements [1]

- BL4N shall deliver proton beam from the extraction port #4 of the cyclotron to the ARIEL west target station, with energy between 475 and 500 MeV and power up to 50 kW (i.e. with intensity up to 100 μA).

- The layout shall be consistent with the site geometrical envelope and consistent with the electron beam line (EHBT) layout over the North-South tunnel up to the west target station.

- Shall minimize interference with the layout of EHBT [3], and also retain reasonable clearance from the wall in the tunnel north end to allow easy installation of and access to both beam lines.

4.2 General Requirements

- simple and robust.
- low loss.
- easy to tune.
- easy to maintain.

4.3 Specific Requirements [2]

- BL4N shall be capable of transporting protons with losses less than 1 nA/meter at any location, i.e. losses are sufficiently low to permit hands-on maintenance and prevent inordinate activation and damage to hardware components.
- shall be designed to compensate the cyclotron's periodic dispersion such that the beam centroid shall no longer drift over time and shall not need constant correction.
- Shall be designed to collimate large angle scattered particles from the stripping foil before they propagate into the North-South tunnel. This shall make the beam line cleaner.
- Shall displace, by rastering, the centroid of beam spot by ±8 mm with respect to the beam line axis [10], with an error of beam angle w.r.t. the beam line axis less than 0.25 mrad. The beam rastering shall be independent for the horizontal and vertical planes.
- Shall provide a matching section after the last dipole magnet to allow sufficient tunability for the instantaneous beam spot size [10] to be flexible between 2.0 mm (FWHM) and 4.0 mm (FWHM) at target.
- Target group must provide information such as the peak and average density permitted, beam distribution and halo permitted, etc.

4.4 General Constraints

- The layout shall fit within the ARIEL building and North-South tunnel civil construction footprint all the way to the west target station.
- The layout shall be consistent with the envelope of EHBT and shall minimize mechanical interference between these two lines.
- Shall enter the west target station at the same elevation as the EHBT.

- The layout shall be consistent with conventional electrical, air and water services envelopes.
- Shall stay within budget and schedule: where possible, the use of TRIUMF surplus magnets is preferred.

4.5 Specific Constraints

- The cyclotron has periodic dispersion [4], which is $D = 3.4\,\mathrm{m}$ and $D' = 0.34$ at 480 MeV stripping location. This means that a foil movement of 5 mm leads to a momentum shift of 0.15% or energy shift of 1.2 MeV. This needs to be compensated in the front-end of the beam line, otherwise it will propagate downstream, magnifying the beam centroid movement and causing spills.
- BL4N shall be using the existing extraction port #4 of the cyclotron. The beamline axis shall be started exactly along the exiting axis of the combination magnet with zero degree angle. The combination magnet exiting axis passes through its cross-over point and also is perpendicular to the yoke edge in the geometrical median plane. **The coordinates for the cross-over point and the yoke edge are respectively determined as [5] ($x = -4.69881\,\mathrm{m}$, $y = +9.63399\,\mathrm{m}$, $z = 0.00000\,\mathrm{m}$) and ($x = -5.12683\,\mathrm{m}$, $y = +9.79484\,\mathrm{m}$, $z = 0.00000\,\mathrm{m}$), defined in the cyclotron Cartesian system.**
- Around the collimator, sufficient radiation shielding [6] is required to reduce the dose rate to $\leq$10 mSv/hr in order to limit the activation of beam line components. The amount of beam to be collimated out shall be $\leq 1\,\mu\mathrm{A}$.
- Throughout the North-South tunnel, BL4N elements shall be reconciled properly with the EHBT elements to avoid mechanical conflicts.
- The initial condition of the beam at 480 MeV shall be: $\alpha_x = -0.69$, $\beta_x = 3.43\,\mathrm{m}$, ϵ_x=0.73 mm-mrad (4rms); $\alpha_y = 2.38$, $\beta_y = 27.39\,\mathrm{m}$, ϵ_x=0.94 mm-mrad (4rms); $\Delta p/p = 7.0 \times 10^{-4}$ (2rms). This refers to the condition of beam just dumped on the stripping foil when BL4N is alone taking all the circulating beam, obtained from `COMA` simulations. The foil to be used is a carbon foil of typical thickness of $1.65\,\mathrm{mg/cm^2}$. The scattering due to such foil is 0.21 mrad (2rms) in both x and y, and 4.0×10^{-4} (2rms) in $\Delta p/p$.
- The last magnetic element of BL4N shall stay $\geq 3.73\,\mathrm{m}$ from the target, upstream from the shielding wall.
- The raster magnets shall reach an integrated field strength of ≥ 60 G-m at maximum rastering frequency (e.g. 400 Hz). They may have different specifications than the existing BL2A raster magnets.

- The diagnostic elements 4NBPM36B, 4NWS36 and 4NPM36, plus a collimator 4NCOL36, shall be incorporated into the target entrance module. The collimator 4NCOL36 shall eliminate large amplitude particles thus help to protect the target.
- The BL4N terminus coordinate shall be ($x = -20.78000\,\mathrm{m}$, $y = 59.48100\,\mathrm{m}$, $z = 0.00000\,\mathrm{m}$), exactly 8.00000 m apart from the EHBT terminus in the (x, y) plane.

4.6 Working Assumptions

- The BL4N shall be reusing appropriate TRIUMF surplus magnets in terms of their integrated field strengths that are achievable to satisfy the optics requirements. The magnets shall be populated to avoid mechanical conflicts with the EHBT elements, and also to retain reasonable clearance from the west wall in the tunnel section to allow easy installation. Specifically, the two 34° dipole magnets shall be reusing the old 35° benders named 4AB2 and 4VB1 [7] (decommissioned from the old beam line) as they are close enough in the bend angles. The in-vault dipole magnet 4NMB4 shall be reusing the old 35° bender named 4BVB2 which was in fact making a 25° bend in the old BL4B, so the old vacuum chamber pertained to the 4BVB2 might be reusable too.
- The 45° dipole magnets are limited to a dimension of length $\leq 1.85\,\mathrm{m}$, width $\leq 1.27\,\mathrm{m}$, and height $\leq 1.30\,\mathrm{m}$ within a rectangular envelope including any overhang of the magnet windings along the beam direction. This suggests that a sector bender [8] rather than a rectangular bender should be adopted for the design in order to fulfill the requirement on the field quality (i.e. the width of the good field region and the field homogeneity over this region). Otherwise, it would result in an oversize magnet, causing collision with the west wall and/or with the EHBT quad sitting right underneath.
- TRIUMF existing primary beam lines 1A, 2A and 2C4 all possess 4.0 inch aperture for the quadrupole magnets all over. For the BL4N, with collimator to reduce spills in transportation, we could in principle use smaller quadrupoles e.g. Danfysik L5 type (of 20 cm effective length and 2.795 inch aperture) from 4NQ11 (inclusive) onward to the end. Thus, our primary selections are the surplus magnets with apertures larger than 2.795 inch.
- The correctors shall reach an integrated field strength up to 15 kG-cm. The insertion length shall be ≤65 cm for the paired XY-correctors, ≤30 cm for the single X- or single Y-corrector. These can be the same type of correctors currently employed in the BL2A, or those given by KEK if they are radiation hard.
- The BPM's, beam halo monitors (BHM), wire scan profile monitors (WS), toroidal non-intercepting monitor (TNIM), and target entrance collimator shall be the same/sim-

ilar type as/of those being used in the BL2A. The overall insertion length shall be $\leq$36 cm for the WS's, and $\leq$36 cm for the BPM's and TNIM as well. The BHM shall be assembled on a common structure with the BPM to which it's next.

- The raster magnets shall reach an integrated field strength of $\geq$60 G-m at the maximum rastering frequency (e.g. 400 Hz) and possess a total insertion length of $\leq$1.10 m. They could be the ACSI type ferrite AC raster magnets [9], designed for the BL2A.
- The instantaneous proton beam spot size shall be $\geq$2.0 mm (FWHM) at target, and flexible up to 4.0 mm [10]. This shall be achieved by tuning the last two quadrupole doublets.
- **The Target/Ion Source Group takes responsibility to produce the engineering specifications of and to implement the beam diagnostics located in the target entrance-module.**

5 Implementation and Optics Layout

5.1 Spills from Foil Scattering and Collimation

We tolerate a beam loss of about 1 nA/m at any location along the beam line. At full intensity, this is $\sim 10^{-5}$ level. For a 5 mg/cm^2 foil, 10^{-5} of particles are scattered beyond 7 mrad. Look at the log-log plot Fig.1. These particles already run outside the 4" beam pipe as the beam line transfer matrix element R_{34} is ∼1.0 cm/mrad. Currently the foils in use are typically ∼2 mg/cm^2. This produces an angle $\geq$ 3.3 mrad for 10^{-5} of particles.

On the other hand, the cyclotron beam is intrinsically of high quality: the emittance is ∼1.2 mm-mrad (4rms), and the angular spread for the core of beam is only ±0.3 mrad.

The solution is therefore to collimate the large angle scattered particles before they propagate to the North-South tunnel.

We shall place a collimator at a dispersionless location, where the particle's transverse positions are mapped from their angles at the stripping foil. This requires $R_{11} = 0$ and $R_{33} = 0$.

With copper as the collimator, a thickness of ∼30 cm is needed as the mean range in copper of 500 MeV proton is ∼20 cm, while the attenuation length (1/e) of high energy neutrons [6] in iron is 21 cm. So, the shielding thickness of iron around the collimator is determined by the dose rate to be acceptable and the amount of protons to be collimated out.

To permit hands-on maintenance and limit activation of beam line components, the dose rate is required to stay below 10 mSv/hr. Simulation result [6] shows that for 1 μA proton

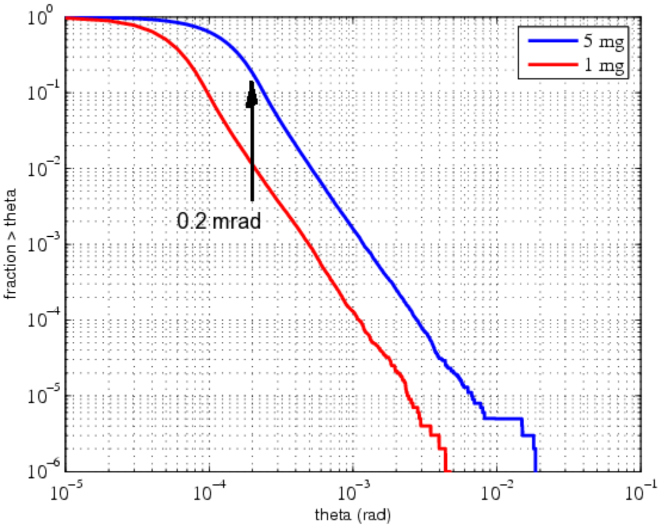

Figure 1: Log-log plot showing the fraction of particles scattered from stripping foil of angle exceeding certain magnitude, calculated with `GEANT4`.

beam collimation, the shielding block dimensions required are about 3.5 m long (out of which 2.2 m is in the forward direction), 3.0 m wide and 3.0 m high. But even if we drop the amount of collimated beam by a factor of 100 down to 10 nA, the shielding thickness can only reduce by about $0.21 \ln(100) = 1.0$ m in each dimension; we would still need about 2.0 to 2.5 m shielding thickness. Such a big size restrains us from putting the collimator inside the cyclotron vault because there is no adequate room available locally. Therefore, we shall put the collimator immediately after the vault wall before the 90° bend section.

The benefits of the collimation are two-fold: reduced spills in the transportation, and smaller apertures i.e. cheaper quads. We can use smaller aperture magnets downstream the collimator wherever appropriate except for the last four matching quads.

5.2 Dispersion Compensation and Foil Monitoring

The foil during use may have uncontrolled motion due to curling and other thermal distortions, causing beam centroid movement in the beam line. This is because particles at the stripping foil are already in a dispersive region where the energy and the radial position are correlated. This is understood as such that the initial dispersion is non-zero, it will therefore propagate downstream through the beam line unless we cancel it at some location.

Fig.2 shows the R and p_r/p_0 as a function of energy at the location of stripping foil, calculated with `STRIPUBC`. From these, we find accurate values of the positional and angular dispersion at 480 MeV, which are $D = \Delta R/(\Delta p/p) = x/(\Delta p/p) = 3.4\,\mathrm{m}{=}3.4\,\mathrm{cm}/\%$ and $D' = x'/(\Delta p/p) = 0.34 = 3.4\,\mathrm{mrad}/\%$.

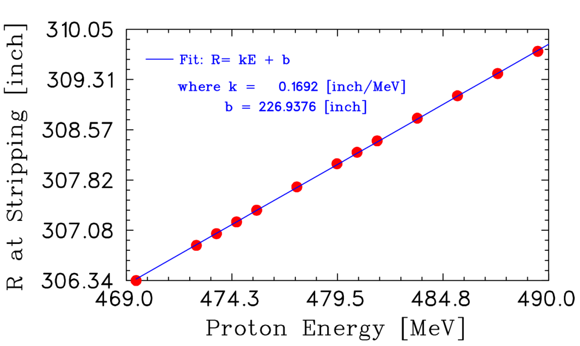

Figure 2: `STRIPUBC` calculated R and p_r/p_0 vs. energy at the azimuth of stripping foil, from which we find out the positional and angular dispersion values at 480 MeV.

These are transported towards the beam line through a transfer matrix:

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

Note that the D and D' are negative at start. This is because the proton beam is bent to the right-hand side (looking downstream) through the cyclotron fringe field region and in `TRANSPORT` convention $+x$ is opposite to the cyclotron's radial direction.

The transfer matrix of 480 MeV, calculated with `STRIPUBC`, for $(x, x', \Delta p/p)$ in units of (cm,mrad,%) around a reference trajectory from the foil to a location of ∼68 cm downstream the combination magnet cross-over point (along the combination magnet exiting axis) is

$$\begin{pmatrix} R_{11} & R_{12} & R_{16} \\ R_{21} & R_{22} & R_{26} \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} -0.078 & 0.329 & 1.302 \\ -3.067 & 0.128 & 1.062 \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

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

$$\begin{pmatrix} D \\ D' \\ 1 \end{pmatrix} = \begin{pmatrix} 0.45 \\ 11.05 \\ 1 \end{pmatrix} \tag{3}$$

This is not the same thing as the elements R_{16} and R_{26}, indicating that the optics to cancel (D, D')=(0.45 m, 11.05 mrad/%) is very different from that needed to cancel (R_{16}, R_{26})=(1.302 m, 1.062 mrad/%). Furthermore, should be aware that the beam particles have an energy-correlated position and angle in the radial direction when they're dumped on the foil. In other words, the beam itself has a radial dispersion, called beam's dispersion. The beam's dispersion in magnitude is smaller than the machine's value by a factor of ~ 2.6. This is because it's not single turn extraction in TRIUMF cyclotron. For the BL4N design, we shall aim to cancel the machine's dispersion (D, D') at the exit of the first dipole magnet 4NMB4. Nevertheless, our optics layout shall have good flexibility to cancel the beam's dispersion if this turns out to be even more helpful.

For instance, the BL1A was seemingly designed to be achromatic, but in fact when the cyclotron's dispersion is taken into account, it reaches as high as 12 cm/% at Q6, not really achromatic at all. This is mainly due to R_{11}, the x-magnification, reaching 3.1. The BL2A case is even worse, with a magnification of 6 throughout the line, the dispersion reaches 20 cm/%. This has the detrimental effect that the beam moves horizontally throughout the beam line as the foil curls and moves as it's aging.

Besides canceling the dispersion, we also desire to achieve 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 $R_{34} = 0$.

5.3 Optics Layout

Fig.3 shows the BL4N layout. It's composed of a vault section, a collimator section, a 90° achromatic bend section with variable dispersion value, a matching and periodic section, a 68° achromatic bend section, and 4-quad matching section to the target, including the AC raster magnets.

In the vault section, we realize the dispersion compensation and foil's positional imaging. The first 4 quads 4NQ1 to 4NQ4 are dominated by the requirement of canceling the dispersion (D, D'). The foil's positional image is formed at a location of ~20 cm outside the vault wall, allowing an easy access for the repair/maintenance of the wire monitor. The collimator section is placed after the vault wall and before the 90° bend section. The 6 quads 4NQ5 to 4NQ10 are bounded by the 3 dictations: (1) forming an angular image of the foil at collimator mid-point (i.e. $R_{11} = R_{33} = 0$); (2) forming a double waist at collimator mid-point (i.e. $\sigma_{11} = \sigma_{33} = 0$); (3) forming a positional image of the foil before entry into the vault wall (i.e. $R_{12} = R_{34} = 0$). The resulting optics appears to have enough flexibility to vary the beam envelope between 4.0 mm and 7.0 mm (2rms) in parallel throughout the collimator section. This is in favor of an efficient collimation. Further collimation inside the 90° bend section for extreme energy particles is impractical as the shielding block required would be too large to fit in locally. So, in both the 90° and 68° bend sections, we tend to minimize the dispersion value, aiming to minimize spills due to extreme energies. Throughout the periodic section, it is essential to get the beam well matched; once matched, the subsequent sections all the way 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.

The optical elements in the North-South tunnel have to be populated properly to avoid mechanical interference with the EHBT elements.

Fig.4 shows the resulting beam envelope and dispersion etc..

5.4 AC Rastering

The distance from the last dipole magnet to the target is ∼11.5 m, long enough to accommodate 4 quads and a pair of x,y AC raster magnets. The AC rastering must be fast enough; low frequency causes fatigue failure of the target. We could use the ACSI designed ferrite AC raster magnet [9] which is ∼1.10 m long in total and produces up to ±150 G-m integrated field at 400 Hz. Such a magnet can generate a deflection of $\pm 150/35450 = \pm 4.2$ mrad for the 480 MeV protons. To produce a raster radius of e.g. 8 mm on the target, we would need a "kick arm" $R_{12}, R_{34} \simeq 1.9$ m from the raster magnet centre-line to the target entrance. Whereas the space available is around 5.0 m from the raster magnet to the target. This suggests that we might use a weaker magnet (≥60 G-m) than the ACSI type. We shall place the raster magnets downstream instead of upstream from the last quadrupole doublet, so the lever arm is independent of the instantaneous beam spot size adjustment. This way allows to simplify the beam line tuning.

5.5 Beam Instrumentation and Correctors

We shall need to equip adequate diagnostic elements to facilitate the beam line tuning and also to investigate the beam properties. As a rule of thumb, we need one BPM plus one pair of X/Y-correctors per quadrupole doublet. (Likewise, their layouts and placement have to avoid conflicts with the EHBT elements throughout the North-South tunnel.) Detailed calculations were performed to look into the "orbit" correction, giving rise to an optimized configuration for the correctors and BPM's. In particular, **it's crucial to have a vertical corrector put in the beginning of the beam-line (i.e. upstream from the first quad 4NQ1)**, because the beam may be off-center coming out of the cyclotron. This has been the experience in the BL1A, 2A operations.

The front-end two profile monitors namely 4NWS2 and 4NWS4 are essential for catching sight of beam down to the beam line. The 4NWS6 is located to show the positional image of the stripping foil. The 4NWS10A and 4NWS10B are placed at both ends of the collimator 4NCOL10 to discern tails in the beam profiles before and after the collimation, plus the 4NBPM10A and 4NBPM10B to check whether the beam position is centering through the collimator. It has been verified with simulations that, with 2 pairs of steerers namely 4NCBX/Y6 and 4NCBX/Y8, the beam position can be corrected to center at 4NBPM10A and 4NBPM10B both. This is important for an efficient collimation. Note that 4NWS10A is put next to 4NBPM10A, and 4NWS10B is next to 4NBPM10B; these two devices together

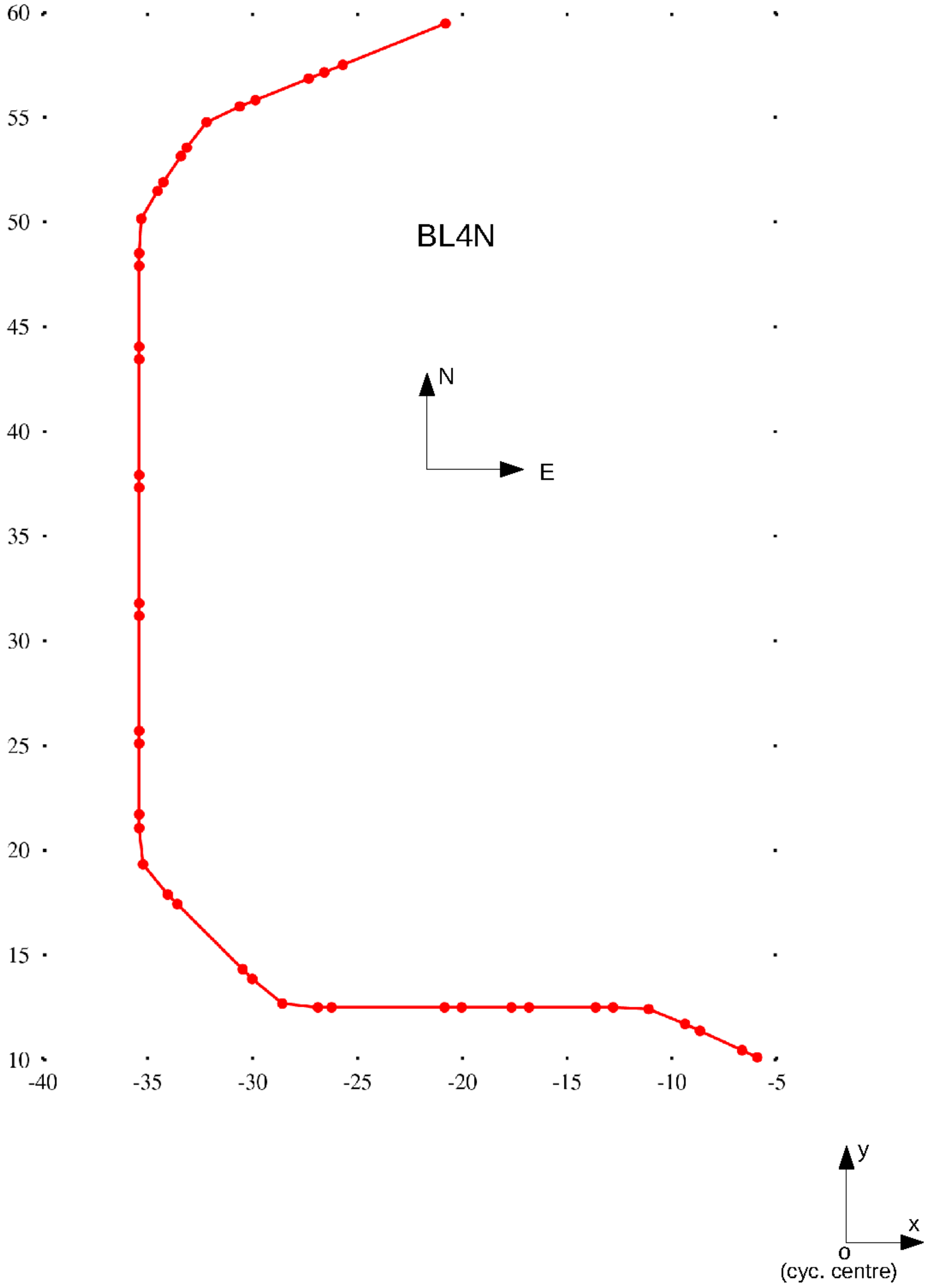

Figure 3: BL4N layout. The dots mark the magnets (except for the last one marking the target). This diagram is for illustrative purposes.

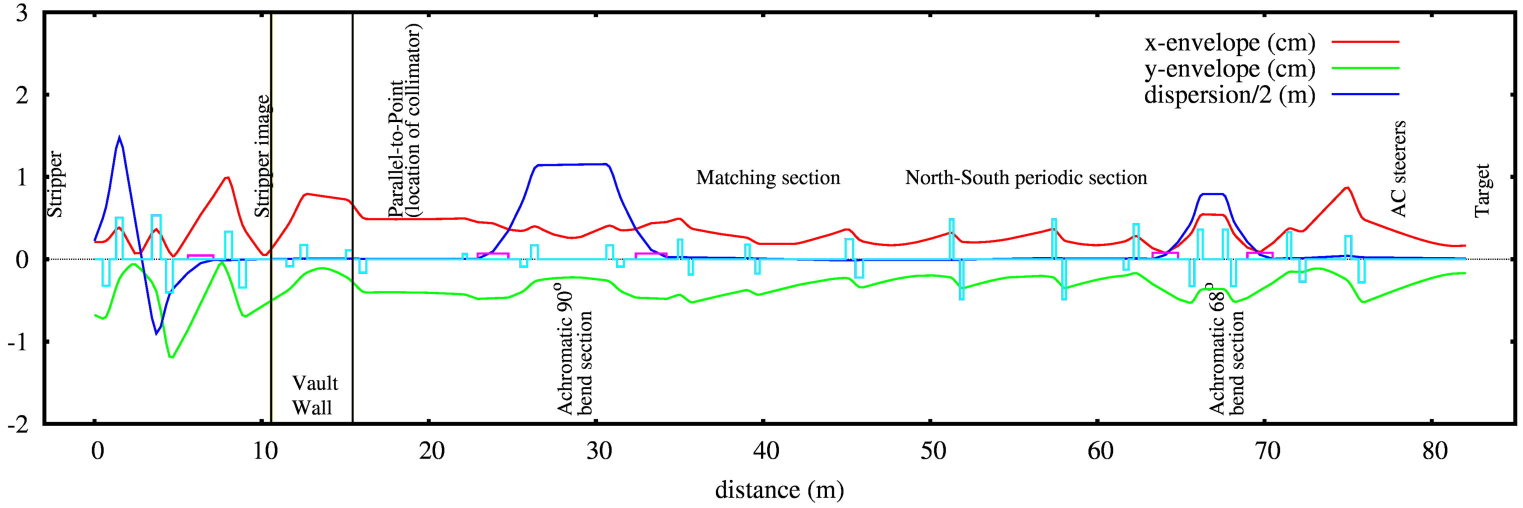

Figure 4: BL4N beam envelope (2rms) and dispersion. The instantaneous beam size is 2 mm (2rms) on the target.

may have to adopt the compact design as implemented in the UCN beam line final leg, so that they can fit in properly.

Two beam halo monitors i.e. 4NBHM10 and 4NBHM16 have been added in and placed exactly following F. Jones' suggestion [11], i.e. the 4NBHM10 is immediately before 4NQ11, while the 4NBHM16 is immediately before 4NMB16. At these 2 locations, the losses from halos due to the foil scattering are relatively high in terms of the simulation result. Note that these 2 BHM's are resp. put next to a BPM, very similar to the BL2A configuration where the BHM#8 and BPM#8 are assembled on a common structure. This shall facilitate the assembly.

The 4NBTSM14 and 4NWS30 are put in the mid-way of the achromatic bend sections to discern large energy tails of beam under dispersion. The 4NBTSM14 shall be a PSI-type of monitor [12], dedicated for the measurements of bunch longitudinal density distribution (and transverse distributions as well). The 4NWS18 plus 4NWS22, 4NWS24 and 4NWS26 are placed in the tunnel section to investigate beam matching through the periodic section; the latter three must be placed at exactly the same location of that cell in which they're located. The 4NWS36 shall be a 5-wire monitor to allow an accurate reconstruction of the beam density tomography near the target.

The 4NBPM36A and 4NBPM36B in pair shall be used to capture the beam position with sufficient precision so that we can predict the size of rastering beam at target. The 4NBPM36A shall be placed outside the shielding wall and downstream the raster magnets; while the 4NBPM36B, placed downstream from 4NBPM36A by $\geq$2.26 m, shall form part of the target entrance-module. With a separation $\geq$2.26 m between these two BPM's, we shall expect to predict the rastering radius on the target with an accuracy better than $\pm$0.30 mm, and predict the rastering angle (rel. to the beam line axis) with an error less than $\pm$0.10 mrad, given a resolution [13] of the BPM's better than $\pm 100\mu$m. These two BPM's shall resolve beam positions faster than the rastering speed to provide independent verification of beam rastering and potentially provide redundant protection for the target.

Besides, we shall need a protect monitor 4NPM36 placed near the target to measure the halo and/or transverse density distribution of the rastering beam. This 4NPM36 shall be incorporated into the target entrance-module along with 4NBPM36B, 4NWS36 and a collimator 4NCOL36, and placed as close as possible to the target. These element's locations are proposed and listed in the table below. **Nevertheless, the responsibility to produce the engineering specifications of and to implement the beam diagnostics in the target entrance-module lies with the Target/Ion Source Group. Also, the exact locations of 4NBPM36B, 4NWS36, 4NPM36 and 4NCOL36 shall be determined by the Target Group.**

A time-of-flight monitor 4NTOFM20 for monitoring the cyclotron isochronism, and a toroid [14] 4NTNIM22 for measuring the beam current, shall be placed in the periodic section (to allow easy access for service). Fig.5 shows the layout of the elements.

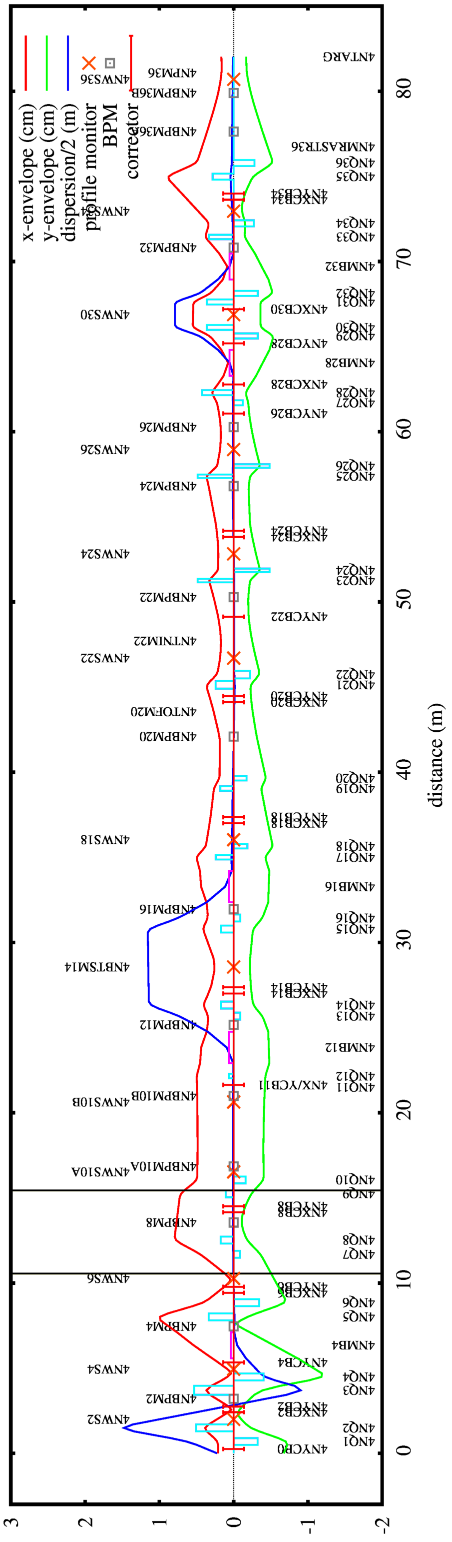

Figure 5: Layout of dipole and quadrupole magnets, correctors, BPM's, and profile monitors etc.

6 Magnetic Elements List

The table 1 lists, in sequence, the coordinates of dipole and quadrupole elements.

The edge is either the entrance or exit of a dipole (hard edge model). The 4NMBx means a dipole. For each dipole, I give the entrance, mid-point and exit along the reference trajectory; I also give the cross-over point (CoP). The cross-over point is the point where the axis of the incoming beam and the axis of outgoing beam intersect. Dipoles of the same bend angles are powered in series with a single power supply.

The 4NQx means a quadrupole. For each quadrupole, I give the mid-point. The quads powered in series with a single power supply are separately: 4NQ13 + 4NQ16; 4NQ14 + 4NQ15; 4NQ23 + 4NQ24 + 4NQ25 + 4NQ26; 4NQ29 + 4NQ32; 4NQ30 + 4NQ31. All the others are run as singlet. The 2nd column gives the polarity of each quadrupole, where F and D, respectively, indicate horizontal focusing and defocusing.

The 3rd column is the reference trajectory length in meter, measured from the combination magnet cross-over point along its exiting axis. The $x-y-z$ frame is the cyclotron Cartesian system where the origin is in cyclotron centre. The z coordinate is constantly 0, meaning in the cyclotron's geometrical median plane. The second-to-the-last column gives the nominal bend angles for the dipoles and integrated field strengths for the quads ($= B_{pol}\, L_{eff}/r_{aper}$). The last column designates the magnet type.

The latitude for each quadrupole on drawing is ±1 cm for 4NQ1, 4NQ2, 4NQ3, 4NQ4, 4NQ5, 4NQ6; ±2 cm for 4NQ7, 4NQ8, 4NQ9, 4NQ10; −8 cm for 4NQ11 and +8 cm for 4NQ12 (movement must be symmetrical); and ±5 cm for the others but the movement must be symmetrical wherever the optics dictates. Note that the + means downstream while − means upstream. These tweak ranges are not given arbitrarily; the basis is coming from the fore-mentioned optics requirements, which are, collimating beam halos due to large angle scattering, imaging the foil, cancelling the cyclotron dispersion, minimizing dispersion in the bend sections, matching the periodic section, and enabling to vary the instantaneous beam spot size on the target.

Table 1 Coordinates of Dipoles and Quadrupoles

Name	Pol.	s[m]	x[m]	y[m]	Int. Strength[T] or Bend Angle[degr]	Designated Mag. Type
4NQ1	D	1.36892	-5.96069	10.16225	3.8797	4Q14/8
4NQ2	F	2.16797	-6.68598	10.49758	6.0523	4Q14/8
4NQ3	F	4.37688	-8.69097	11.42455	8.2936	4Q19/8
4NQ4	D	5.16408	-9.40550	11.75490	4.8399	4Q14/8

edge		6.26112	-10.40127	12.21527		
4NMB4		7.02339	-11.12228	12.45805	24.8126	4BVB2 (NO.02)
CoP			-11.10419	12.54026		
edge		7.78567	-11.87861	12.54026		
4NQ5	F	8.69207	-12.78501	12.54026	4.0238	4Q14/8
4NQ6	D	9.52847	-13.62141	12.54026	4.1357	4Q14/8
4NQ7	D	12.36487	-16.45781	12.54026	1.0178	4Q14/8
4NQ8	F	13.20127	-17.29421	12.54026	2.0915	4Q14/8
4NQ9	F	15.91767	-20.01061	12.54026	1.2888	4Q14/8
4NQ10	D	16.73407	-20.82701	12.54026	1.9513	4Q14/8
4NQ11	D	22.18016	-26.27310	12.54026	0.0116	4Q10/3.6
4NQ12	F	22.83016	-26.92310	12.54026	0.4819	4Q10/3.6
edge		23.59723	-27.69016	12.54026		
4NMB12		24.51653	-28.58602	12.71846	45.0	
CoP			-28.65984	12.54026		
edge		25.43584	-29.34550	13.22592		
4NQ13	D	26.35584	-29.99604	13.87646	1.0682	4Q14/8
4NQ14	F	27.00584	-30.45566	14.33608	2.0466	4Q14/8
4NQ15	F	31.47278	-33.61426	17.49468	2.0466	4Q14/8
4NQ16	D	32.12278	-34.07388	17.95430	1.0682	4Q14/8
edge		33.04278	-34.72442	18.60484		
4NMB16		33.96209	-35.23188	19.36431	45.0	
CoP			-35.41008	19.29050		
edge		34.88139	-35.41008	20.26018		
4NQ17	F	35.68639	-35.41008	21.06517	1.8614	4Q8.5/8.5
4NQ18	D	36.33640	-35.41008	21.71517	1.4321	4Q8.5/8.5
4NQ19	F	39.72499	-35.41008	25.10377	1.3930	4Q8.5/8.5
4NQ20	D	40.32499	-35.41008	25.70377	1.3514	4Q8.5/8.5
4NQ21	F	45.81499	-35.41008	31.19377	3.3018	KEK QA-I
4NQ22	D	46.41499	-35.41008	31.79377	3.0028	KEK QA-I
4NQ23	F	51.93999	-35.41008	37.31877	2.9469	DanFysika L5
4NQ24	D	52.53999	-35.41008	37.91877	2.9469	DanFysika L5
4NQ25	F	58.06499	-35.41008	43.44377	2.9469	DanFysika L5
4NQ26	D	58.66499	-35.41008	44.04377	2.9469	DanFysika L5
4NQ27	D	62.37565	-35.41008	47.75443	1.0905	TUDA-S
4NQ28	F	62.97565	-35.41008	48.35443	3.7232	TUDA-S
edge		63.96565	-35.41008	49.34443		
4NMB28		64.72611	-35.29809	50.09378	34.0	4AB2 (NO.03)
CoP			-35.41008	50.12802		
edge		65.48656	-34.97190	50.77764		
4NQ29	D	66.30656	-34.51337	51.45745	2.8491	TUDA-S
4NQ30	F	66.80656	-34.23377	51.87197	3.1654	TUDA-S

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4NQ31     F      68.30656   -33.39498  53.11552     3.1654         TUDA-S
4NQ32     D      68.80656   -33.11538  53.53004     2.8491         TUDA-S
edge             69.62656   -32.65684  54.20985
4NMB32           70.38702   -32.14497  54.76847      34.0      4VB1  (NO.01)
CoP                         -32.21867  54.85948
edge             71.14748   -31.49214  55.15302
4NQ33     F      72.11849   -30.59183  55.51676     2.5617         4Q8.5/8.5
4NQ34     D      72.92489   -29.84415  55.81885     2.8720         4Q12/6
4NQ35     F      75.66129   -27.30700  56.84392     2.9774         4Q12/6
4NQ36     D      76.46769   -26.55932  57.14600     2.9595         4Q12/6
4NMRSTR36        77.42089   -25.67553  57.50308
4NTARG           82.70089   -20.78000  59.48100
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7 Diagnostic Elements and Correctors List

The table 2 lists, in sequence, the coordinates of BPM's, wire scan profile monitors (WS), beam halo monitors (BHM), bunch time structure monitor (BTSM), time-of-flight monitor (TOFM), XY-correctors (XCB & YCB), toroid (TNIM), target protect monitor (PM) and collimators (COL). For each element, I give the mid-point coordinate. The 2nd column s is the reference trajectory length in meter, measured from the combination magnet cross-over point along its exiting axis. The x and y coordinates are in meter.

The last column designates the element type, where the 4VSM3/BB1 refers to an old vertical steering magnet combined with a beam blocker. It was decommissioned from the old BL4V. **Should be stressed that for the purpose of extraction probe commissioning and extracted beam characterization, we shall need at least these elements to be installed, namely 4NYCB0, 4NQ1, 4NQ2, 4NWS2 and 4NYCB2 (combined with the beam blocker)**.

Note that the 4NX/YCB11 is a pair of in-quad corrector, by means of powering the quad 4NQ11 asymmetrically.

The longitudinal positioning latitudes on drawing are as follows: 0 mm for the 4NWS6, 4NBTSM14 and 4NWS30; ±20 cm for the other WS's (but any movements must be symmetrical wherever the optical symmetry dictates), for the BPM's as well as for the BHM's; ±40 cm for the correctors; and ±100 cm for the TOFM and TNIM.

Table 2 Coordinates of Diagnostic Elements and Correctors etc.

Name	s[m]	x[m]	y[m]	Designated Type
4NYCB0	0.93072	-5.56294	9.97836	
4NWS2	2.66872	-7.14050	10.70772	
4NXCB2	3.09332	-7.52590	10.88590	
4NYCB2	3.42332	-7.82544	11.02439	4VSM3/BB1
4NBPM2	3.88332	-8.24297	11.21743	
4NWS4	5.61603	-9.81573	11.94456	
4NYCB4	6.01603	-10.17880	12.11242	
4NBPM4	8.13447	-12.22741	12.54026	
4NXCB6	10.10167	-14.19461	12.54026	
4NYCB6	10.46167	-14.55461	12.54026	
4NWS6	10.94667	-15.03961	12.54026	
4NBPM8	14.23447	-18.32741	12.54026	
4NXCB8	14.83447	-18.92741	12.54026	
4NYCB8	15.19447	-19.28741	12.54026	
4NWS10A	17.20727	-21.30021	12.54026	
4NBPM10A	17.52727	-21.62021	12.54026	
4NCOL10	18.68727	-22.78021	12.54026	
4NWS10B	21.30727	-25.40021	12.54026	
4NBPM10B	21.66727	-25.76021	12.54026	
4NBHM10	21.90727	-26.00021	12.54026	
4NYCB11	22.31033	-26.40327	12.54026	
4NXCB11	22.31033	-26.40327	12.54026	
4NBPM12	25.84584	-29.63541	13.51584	
4NXCB14	27.68584	-30.93649	14.81691	
4NYCB14	28.04584	-31.19105	15.07147	
4NBTSM14	29.23931	-32.03496	15.91538	
4NBPM16	32.63278	-34.43450	18.31492	
4NBHM16	32.87278	-34.60421	18.48463	
4NWS18	36.71428	-35.41008	22.09306	
4NXCB18	37.68749	-35.41008	23.06627	
4NYCB18	38.04749	-35.41008	23.42627	
4NBPM20	42.77249	-35.41008	28.15127	
4NTOFM20	44.23499	-35.41008	29.61377	
4NXCB20	44.79499	-35.41008	30.17377	
4NYCB20	45.15499	-35.41008	30.53377	
4NWS22	47.38499	-35.41008	32.76377	
4NTNIM22	48.39499	-35.41008	33.77377	

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  4NYCB22        49.81999   -35.41008  35.19877
  4NBPM22        50.95999   -35.41008  36.33877
  4NWS24         53.50999   -35.41008  38.88877
  4NXCB24        54.49999   -35.41008  39.87877
  4NYCB24        54.85999   -35.41008  40.23877
  4NBPM24        57.48499   -35.41008  42.86377
  4NWS26         59.63499   -35.41008  45.01377
  4NBPM26        60.95499   -35.41008  46.33377
  4NYCB26        61.74749   -35.41008  47.12627
  4NXCB28        63.46565   -35.41008  48.84443
  4NYCB28        65.86656   -34.75941  51.09267
  4NWS30         67.55656   -33.81437  52.49375
  4NXCB30        67.87656   -33.63543  52.75904
  4NBPM32        71.49529   -31.16965  55.28331
  4NWS34         73.62809   -29.19215  56.08227
  4NXCB34        74.30809   -28.56167  56.33700
  4NYCB34        74.66809   -28.22788  56.47186
  4NBPM36A       78.31089   -24.85034  57.83648
  4NBPM36B       80.57089   -22.75490  58.68309
  4NWS36         81.38089   -22.00388  58.98652
  4NPM36         81.75089   -21.66082  59.12512
  4NCOL36        81.92589   -21.49857  59.19068
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8 Summary

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

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