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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)
2	July 19, 2013	In response to I. Bylinskii's suggestion, I moved the 2×45^{o} bend section towards North-East by 50cm for additional shielding.	Y.-N. Rao
3	Feb.12, 2014	Specified latitudes for quadrupoles as tabulated under Section 6.	Y.-N. Rao
4	Feb.27, 2014	Added up diagnostic elements and correctors.	Y.-N. Rao
5	Feb.25, 2015	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 some statements.	Y.-N. Rao
	May 29,2015	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 right upstream the 4NHARP4B to extend the collimator shielding to ~3.3m in total in longitudinal direction. The steering function shall be accomplished with quadrupole 4NQ5 by asymmetrical excitation.	

1 Abstract

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

2 Objective

The BL4N shall deliver proton beam from the 500 MeV cyclotron to the ARIEL target. This note describes the design of BL4N magnetic optics, covering major element coordinates and performance specifications.

3 Definitions

- **Coordinate system:** The Cartesian coordinate system defined herein is such that the origin is in the centre of cyclotron, $+x$ points to East, $+y$ points to North, and $+z$ points upward.
- **Beam profile monitor:** The beam profile monitor herein is meant a wire scanner (WS) or multi-wire ionization chamber (HARP), measuring both x and y profiles.
- **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 $\epsilon \simeq 1.2\,\pi$mm-mrad (2rms, normalized) after 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 beam energy of 480 MeV. This is considering the fact that currently the existing primary beamlines 1A and 2A both are running at 480 MeV.

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 450 and 500 MeV and power up to

50 kW (i.e. 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 beamlines.

4.2 General Requirements

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

4.3 Specific Requirements [2]

- BL4N shall be capable to transport protons with loss less than 1 nA/meter.
- shall be designed to compensate the cyclotron's periodic 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 into the North-South tunnel. This will make the beam line cleaner.
- Shall displace, by rastering, the centre of beam spot by ± 8 mm with respect to the beam line axis [8], and the error of beam angle w.r.t. the beam line axis shall be smaller 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 to allow sufficient tunability for the instantaneous beam spot size [8] to be flexible between 2 mm (FWHM) and 4 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 up to the west target station.
- The layout shall be consistent with the envelope of electron line EHBT and minimize interference between these two lines.
- Shall enter the west target station at the same elevation as EHBT.
- The layout shall be consistent with conventional electrical, air and water services envelopes.
- Shall stay within budget and schedule: where possible, the number of magnet types shall be minimized. The use of old TRIUMF magnets is acceptable.

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 and the beam centroid movement will be magnified, causing spills.
- BL4N shall use the existing BL4 front end channel and start at the exit of combination magnet where the coordinate is ($x = -5.3110\,\mathrm{m}$, $y = +9.8296\,\mathrm{m}$, $z = 0\,\mathrm{m}$) as defined in the global Cartesian system.
- Around the collimator, sufficient radiation shielding [5] is required to reduce the dose rate to 10 mSv/hr to limit activation of beam line components.
- Through the North-South tunnel, BL4N elements shall be placed to avoid interferences with the electron beamline EHBT elements.
- The initial beam condition at 480 MeV shall be: $\alpha_x = -0.69$, $\beta_x = 3.43\,\mathrm{m}$, ϵ_x=0.55 πmm-mrad (2rms); $\alpha_y = 2.38$, $\beta_y = 27.39\,\mathrm{m}$, ϵ_x=1.10 πmm-mrad (2rms); $\Delta p/p = 7.0 \times 10^{-4}$ (2rms). These refer to the condition of beam just dumped on a stripping foil when BL4N is alone taking the 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 from 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 ≥ 150 G-m at frequency of 400 Hz.

- The 4NBPM30B and 4NWS30 and 4NPM30 and collimator 4NCOL30 shall be incorporated into the target entrance module.

4.6 Working Assumptions

- Assume the dipole magnets can reach a field strength up to 1.46 Tesla with a sufficiently good field region. This implies a bend radius (hard edge model) of 2.424 m at 480 MeV. For the 34° dipoles, they shall be the same type of 35° bending magnets [6] as used at 4VB1, 4VB2 and 4AB2 in the past; while the 45° dipoles shall be about 28% longer in the effective length, perhaps shall be a different type.
- With collimator to reduce spills in transportation, we therefore can and shall use smaller quadrupoles e.g. Danfysik "L5"s type (200 mm effective length and 71 mm aperture) instead of our own 4Q8.5/8.5 type (400 mm effective length and 100 mm aperture), everywhere except before the collimator 4NCOL4.
- The raster magnet shall reach an integrated field strength up to 150 G-m at frequency of 400 Hz and a total insertion length of ∼1.10 m. This can be the ACSI type ferrite AC raster magnet [7], designed for BL2A.
- The correctors, BPMs, multi-wire ionization profile monitors, wire scan profile monitors, target entrance module collimator, and toroid non-intercepting monitor (NIM) shall be the same type as those being used in the BL2A; the overall insertion length shall be 65 cm for the paired XY-correctors, 30 cm for the single X- or single Y-correctors, 36 cm for the multi-wire ionization profile monitors and wire scan profile monitors, and 36 cm for the BPMs and toroid NIM as well.
- The instantaneous proton beam size shall be ≥2 mm (2rms) at target, and flexible up to 4 mm. 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 can only tolerate a beam loss of about 1 nA/m 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 $\sim$1 cm/mrad. Currently the foils in use are typically $\sim$2 mg/cm^2. This produces an angle ≥ 3.3 mrad for 10^{-5} of particles.

On the other hand, the cyclotron beam is intrinsically of high quality: the emittance is $\sim 1.1\pi$mm-mrad (2rms), 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 down to the North-South tunnel.

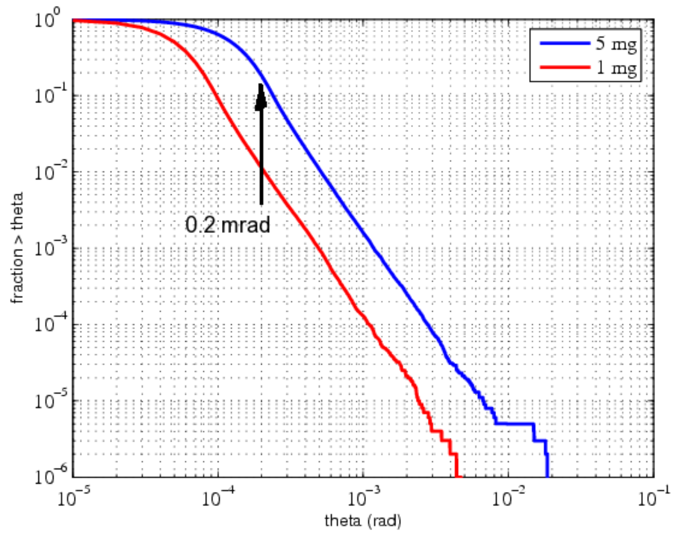

Figure 1: Log-log plot showing the fraction of particles scattered from stripping foil of angle exceeding certain magnitude, calculated with `GEANT4`.

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

With copper as collimator, a thickness of $\sim$30 cm is needed as the mean range in copper of 500 MeV proton is $\sim$20 cm, while the attenuation length (1/e) of high energy neutrons [5] in iron is 21 cm. So, the shielding thickness of iron around the collimator is determined by the dose rate that is acceptable and the amount of beam to be collimated.

To limit activation of beam line components, the dose rate has to be kept below 10 mSv/hr. Simulation result [5] shows that for 1 μA proton beam collimation, the shielding block dimensions required are about 3.5 m long (in which 2.2 m is in the forward direction), 3.0 m wide and 3.0 m high. Even if we drop the amount of beam collimated 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 to 2.5 m shielding thickness. Such a big dimension restrains us from placing the collimator inside the cyclotron vault as there is no adequate room available locally. Instead, we shall put the collimator immediately after the vault wall before the 90° bend section.

The benefits of collimation are two-fold: reduced spills in the transportation, and smaller apertures i.e. cheaper quads and dipoles. We can use smaller aperture magnets everywhere downstream the collimator except 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 radial position are correlated. This can be understood as such that the initial dispersion is not zero, it will therefore propagate downstream through the beam line unless we cancel it at some location.

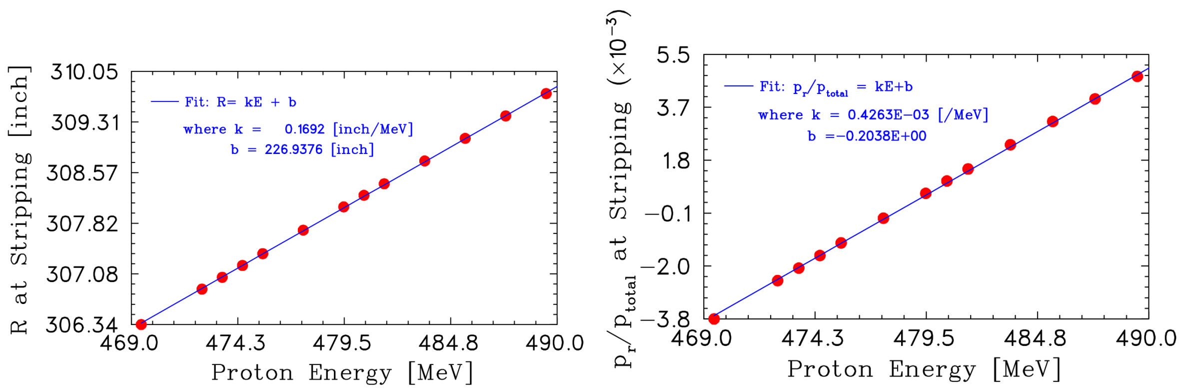

Figure 2: STRIPUBC calculated R and p_r/p_0 vs. energy at the azimuth of stripping foil, from which we find out the positional and angular dispersion values at 480 MeV.

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

These are transported towards the beam line through 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 D and D' are negative at start. This is because in TRANSPORT convention $+x$ is opposite to the radial direction.

The transfer matrix, calculated with STRIPUBC, of 480 MeV for $(x, x', \Delta p/p)$ in units of cm,mrad,% from the foil to the conventional location about 68 cm beyond the combination magnet centre 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 matrix (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 elements R_{16} and R_{26}. This means that optics to cancel $D, D' = 0.53\,\mathrm{m}$, $12.18\,\mathrm{mrad/\%}$ is very different from that needed to cancel $D, D' = 1.37\,\mathrm{m}$, $2.06\,\mathrm{mrad/\%}$. For BL4N design, we shall compensate the dispersion at the exit of the first bending magnet.

For example, BL1A was designed to be achromatic, but in fact when the cyclotron dispersion is included, it reaches as high as $12\,\mathrm{cm/\%}$ at Q6. This is mainly due to R_{11}, the x-magnification, reaching 3.1. BL2A is even worse, with a magnification of 6 throughout most of the line, dispersion reaches $20\,\mathrm{cm/\%}$. This has the detrimental effect that the beam moves horizontally throughout the beam line as the foil curls and moves as it is aging.

Besides canceling the dispersion, we also desire to achieve in the front end a positional image of 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 consists of a front end section, a 90° achromatic bend section with variable dispersion, matching and periodic section, a 68° achromatic bend section, and 4-quad matching section to the target, including AC raster magnets.

In the front end section, we realize the dispersion compensation, foil imaging and beam collimation. The foil imaging is formed at a location of $\sim$20 cm upstream the vault wall. This shall allow easy access for repair, replacement or maintenance of beam profile monitor. Further collimation in the 90° bend section of extreme energy particles is unlikely feasible as the shielding dimension required is perhaps too big to fit in locally. So, in both the 90° and 68° bend sections, we tend to minimize the dispersion, aiming to minimize spills due to extreme energies. Over the periodic section, it is essential that beam gets 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.

It's worth mentioning that the optical elements in the North-South tunnel have to be placed properly to avoid interferences with the electron beamline EHBT elements.

Fig.4 shows the beam envelope and dispersion.

5.4 AC Rastering

The distance from the last dipole to the target is $\sim$11.4 m, long enough to accommodate 4 quads and a pair of x,y AC raster magnets. The AC steering must be fast enough; low frequency causes fatigue failure of the target. We can use the ACSI designed ferrite AC raster magnet [7] which is $\sim$ 1.10 m long in total and produces up to $\pm$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 8 mm on the target, we would need a "kick arm" $R_{12}, R_{34} \geq 1.9$ m from the raster magnet centre to the target entrance. Whereas the available distance is $\sim$ 5.0 m between the raster magnet and the target. This suggests that perhaps we can use a much weaker magnet than the ACSI type. We shall place the raster magnet downstream instead of upstream from the last quadrupole doublet, so the lever arm is independent of the instantaneous beam spot size. This way allows to simplify the tuning.

5.5 Beam Instrumentation and Correctors

We shall need to equip adequate diagnostics in the front end 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 XY-correctors per two quadrupoles. (likewise, their placements have to avoid interferences with the electron line EHBT elements throughout the North-South tunnel.) As per our experience with BL1A and 2A tuning, the very front end two profile monitors namely 4VHARP2 and 4VHARP4 are essential for catching sight of beam down to the beam line. The 4VWS6 is located to monitor the image of the stripping foil. 4NHARP4A and 4NHARP4B are placed at both ends of the collimator. 4NWS8 and 4NWS24 are put in the mid-way of the achromatic bend sections respectively. 4NHARP12 plus 4NHARP16, 4NHARP18 and 4NHARP20 are placed in the North-South tunnel to investigate beam matching through the periodic channel (the latter three shall be placed at exactly the same location of that cell in which they locate). 4NWS30 shall be a 5-wire monitor to allow reconstruction of the beam tomography near the target.

4NBPM30A and 4NBPM30B in pair shall be used to capture the beam position with sufficient precision so that we can predict the rastered beam size at target. The 4NBPM30A shall be placed outside the shielding wall and downstream of the raster magnets; while the 4NBPM30B, placed downstream from 4NBPM30A by $\geq$2.26 m, shall form part of the target entrance-module. With a minimum separation of 2.26 m between these two BPMs, we shall expect to predict the rastering radius on the target with an accuracy better than

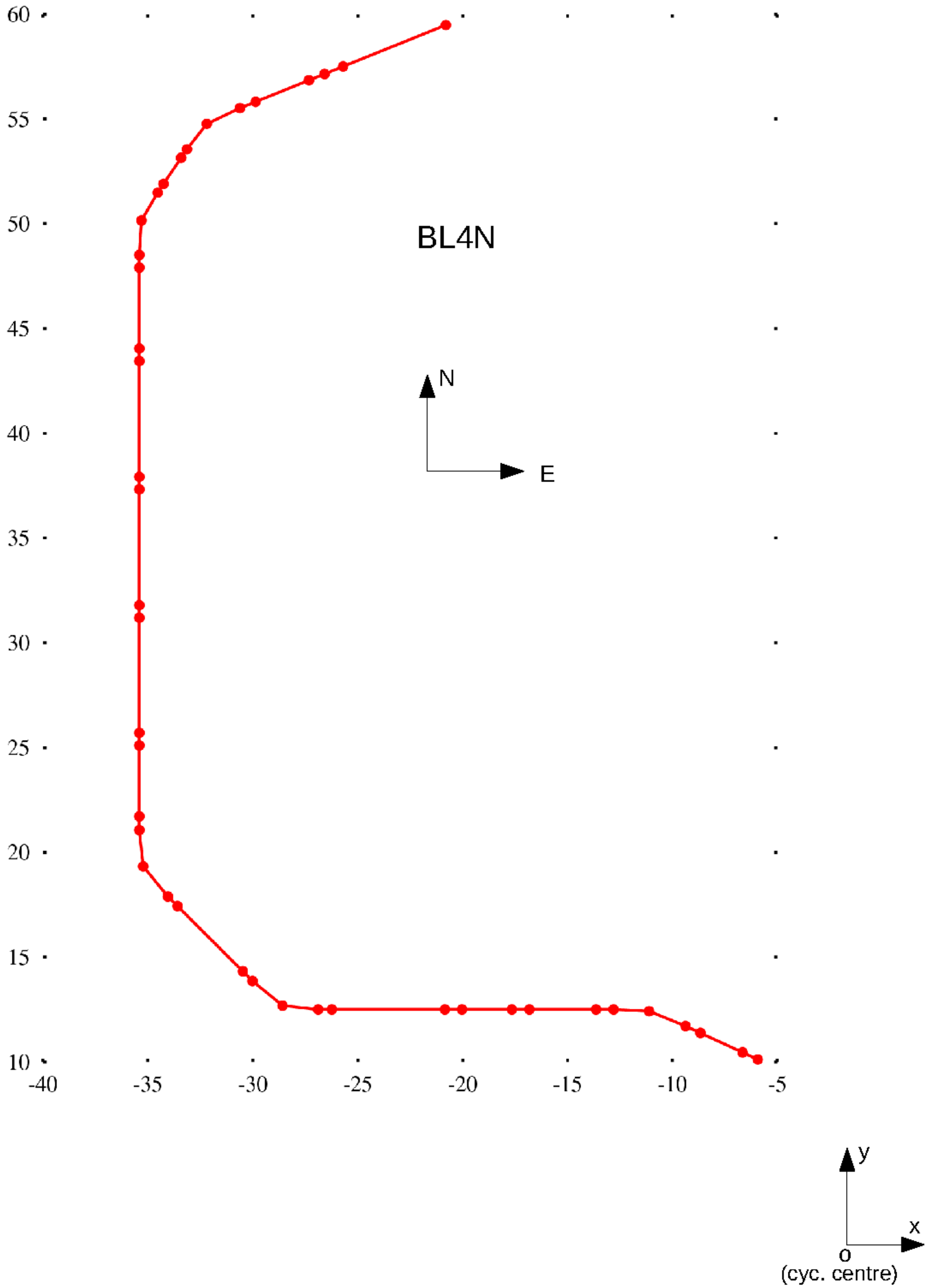

Figure 3: BL4N layout. The dots mark the magnets (except for the last one marking the target). This diagram is for illustrative purposes.

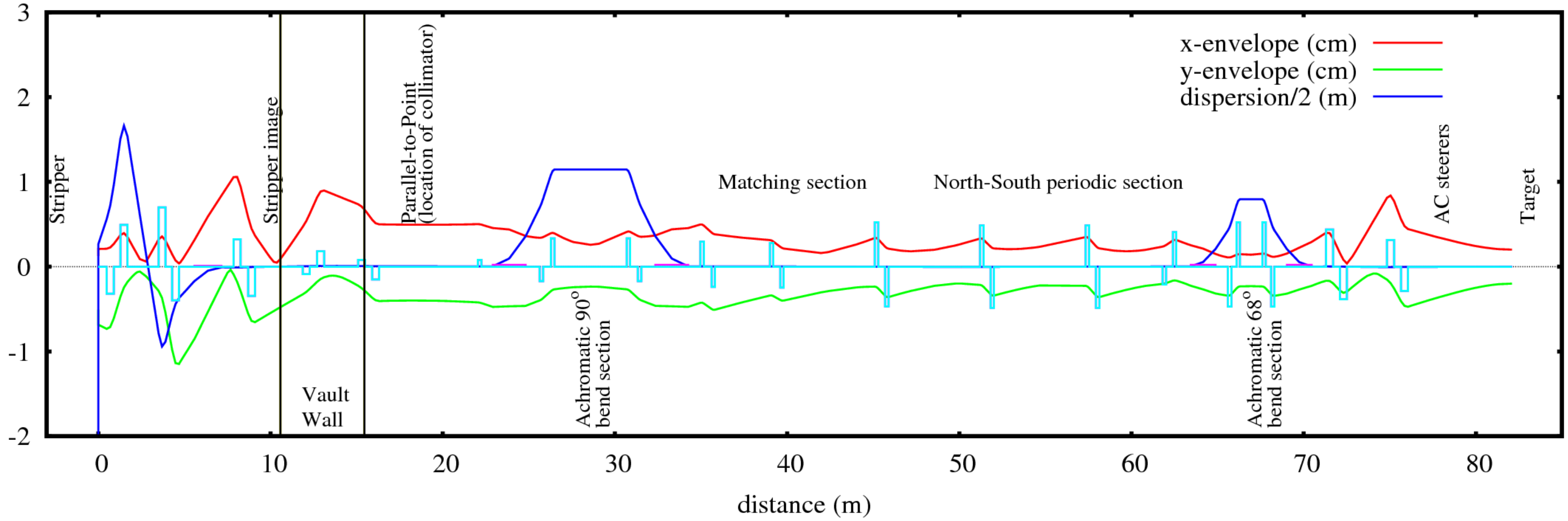

Figure 4: BL4N beam envelope (2rms) and dispersion. The instantaneous beam size is 2 mm (2rms) on the target.

±0.30 mm, and predict the rastering angle (relative to the beamline axis) with an error less than ±0.10 mrad, given a resolution [9] of the BPMs better than ±100μm.

Besides, we shall need a protect monitor 4NPM30 placed near the target to measure the halo and/or transverse density distribution of the rastering beam. This 4NPM30 shall be incorporated into the target entrance-module along with 4NBPM30B, 4NWS30 and a collimator 4NCOL30, 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 4NBPM30B, 4NWS30, 4NPM30 and 4NCOL30 shall be determined by the Target Group.**

A toroid [10] 4NTNIM16 shall be placed in the periodic section to measure the beam current. Fig.5 shows the layout of these elements.

6 Magnetic Elements List

The table 1 that follows lists, in sequence, the coordinates of magnetic elements, including dipoles and quadrupoles.

```
Edge is either the entrance or exit of a dipole (hard edge model).

4VBx or 4NBx 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)
and bend angle. The cross-over point is the point where the axis of the incoming
beam and the axis of outgoing beam intersect. All the dipoles are rectangular
shape.

Dipoles of the same bend angles are powered in series with a single power
supply.

4VQx or 4NQx means a quadrupole. For each quadrupole, I give the mid-point.
The quads powered in series with a single power supply are separately:
4NQ7 + 4NQ10;  4NQ8 + 4NQ9;  4NQ17 + 4NQ18 + 4NQ19 + 4NQ20;  4NQ23 + 4NQ26;
4NQ24 + 4NQ25. All the others are run as singlet. The 2nd column gives the
polarity of each quadrupole (F means horizontal focusing; D means horizontal
defocusing).

The 3rd column is the reference trajectory length in meter. The x, y and z
coordinates are such that +x points to East, +y points to North, +z points
upward. The origin is cyclotron centre.
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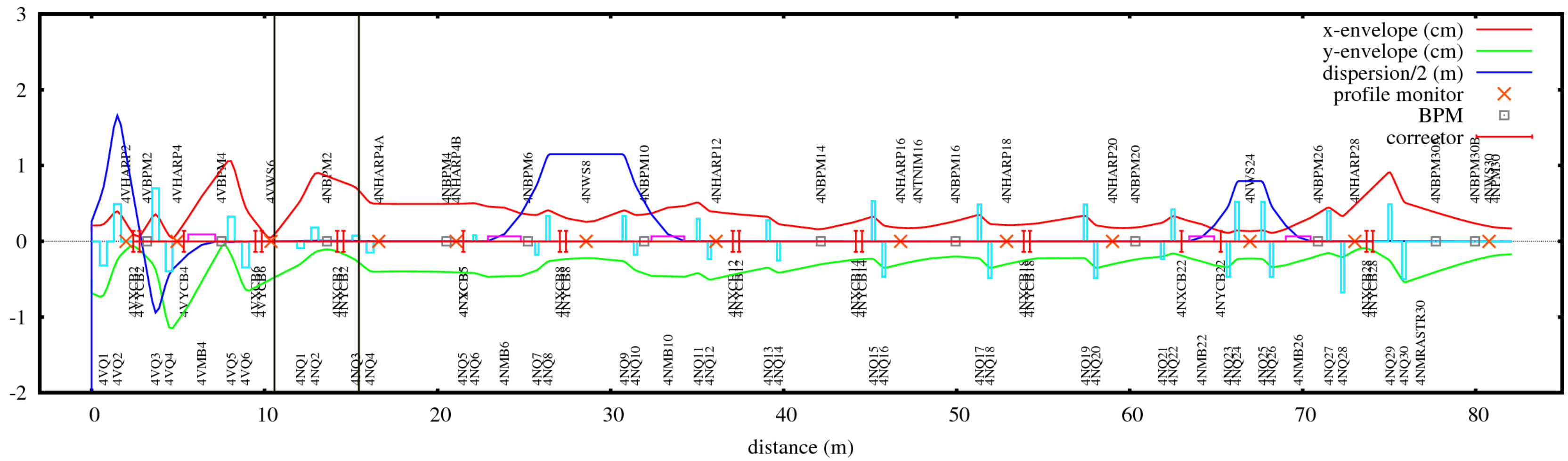

Figure 5: Layout of BPM's, profile monitors and correctors etc.

The longitudinal positioning latitude for each quadrupole on drawing is +/-1 cm for 4VQ1, 4VQ2, 4VQ3, 4VQ4, 4VQ5, 4VQ6; +/-2 cm for 4NQ1, 4NQ2, 4NQ3, 4NQ4; -8 cm for 4NQ5 and +8 cm for 4NQ12 (movements must be symmetrical); and +/-5 cm for the others but any movements must be symmetrical wherever the optics dictates. Note that the + means downstream while - means upstream. These tweak ranges are not given arbitrarily; instead the basis comes from the afore-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 spot size on the target.

Table 1 Coordinates of Dipoles and Quadrupoles

Name	Pol.	s[m]	x[m]	y[m]	z[m]	Bend Angle[degr]
Front-End Section						
4VQ1	D	0.68820	-5.93567	10.11840	0.00000	
4VQ2	F	1.48725	-6.66096	10.45373	0.00000	
4VQ3	F	3.69616	-8.66595	11.38070	0.00000	
4VQ4	D	4.48336	-9.38048	11.71105	0.00000	
edge		5.58040	-10.37625	12.17142	0.00000	
4VMB4		6.36185	-11.11539	12.42031	0.00000	24.8126
CoP			-11.09686	12.50458	0.00000	
edge		7.14329	-11.89074	12.50458	0.00000	
4VQ5	F	8.05895	-12.80641	12.50458	0.00000	
4VQ6	D	8.89535	-13.64281	12.50458	0.00000	
4NQ1	D	12.07175	-16.81921	12.50458	0.00000	
4NQ2	F	12.90816	-17.65561	12.50458	0.00000	
4NQ3	F	15.28455	-20.03201	12.50458	0.00000	
4NQ4	D	16.10095	-20.84841	12.50458	0.00000	
2x45 degr Achromatic Bend Section						
4NQ5	D	21.48704	-26.23450	12.50458	0.00000	
4NQ6	F	22.13705	-26.88450	12.50458	0.00000	
edge		22.90705	-27.65450	12.50458	0.00000	
4NMB6		23.85895	-28.58212	12.68910	0.00000	45
CoP			-28.65854	12.50458	0.00000	
edge		24.81085	-29.36852	13.21456	0.00000	
4NQ7	D	25.73085	-30.01906	13.86509	0.00000	
4NQ8	F	26.38085	-30.47868	14.32471	0.00000	
4NQ9	F	30.78085	-33.58995	17.43598	0.00000	
4NQ10	D	31.43085	-34.04957	17.89560	0.00000	
edge		32.35085	-34.70011	18.54614	0.00000	
4NMB10		33.30275	-35.22557	19.33254	0.00000	45

CoP			-35.41008	19.25611	0.00000	
edge		34.25465	-35.41008	20.26017	0.00000	
4NQ11	F	35.05965	-35.41008	21.06517	0.00000	
4NQ12	D	35.70965	-35.41008	21.71517	0.00000	
Matching Section						
4NQ13	F	39.09825	-35.41008	25.10376	0.00000	
4NQ14	D	39.69825	-35.41008	25.70377	0.00000	
4NQ15	F	45.18825	-35.41008	31.19376	0.00000	
4NQ16	D	45.78825	-35.41008	31.79377	0.00000	
Periodic Section						
4NQ17	F	51.31325	-35.41008	37.31876	0.00000	
4NQ18	D	51.91325	-35.41008	37.91877	0.00000	
4NQ19	F	57.43825	-35.41008	43.44376	0.00000	
4NQ20	D	58.03825	-35.41008	44.04377	0.00000	
2x34 degr Achromatic Bend Section						
4NQ21	D	61.90075	-35.41008	47.90626	0.00000	
4NQ22	F	62.50075	-35.41008	48.50626	0.00000	
edge		63.44075	-35.41008	49.44626	0.00000	
4NMB22		64.15997	-35.30416	50.15497	0.00000	34
CoP			-35.41008	50.18736	0.00000	
edge		64.87918	-34.99567	50.80175	0.00000	
4NQ23	D	65.69918	-34.53713	51.48156	0.00000	
4NQ24	F	66.19918	-34.25753	51.89608	0.00000	
4NQ25	F	67.69918	-33.41874	53.13963	0.00000	
4NQ26	D	68.19918	-33.13915	53.55415	0.00000	
edge		69.01918	-32.68061	54.23396	0.00000	
4NMB26		69.73840	-32.19649	54.76228	0.00000	34
CoP			-32.26620	54.84835	0.00000	
edge		70.45761	-31.57907	55.12597	0.00000	
Matching to Target						
4NQ27	F	71.50081	-30.61183	55.51676	0.00000	
4NQ28	D	72.30721	-29.86415	55.81885	0.00000	
4NQ29	F	75.04361	-27.32700	56.84392	0.00000	
4NQ30	D	75.85001	-26.57932	57.14600	0.00000	
4NMRASTR30		76.80321	-25.69553	57.50308	0.00000	
TARG		82.08321	-20.80000	59.48100	0.00000	

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7 Diagnostic Elements and Correctors List

The table 2 below lists, in sequence, the coordinates of BPM's, profile monitors (namely multi-wire monitors (HARP) and wire scanners (WS)), XY-correctors, toroid (TNIM), target protect monitor (PM) and collimators (COL).

For each element listed below, I give the mid-point coordinate. The 2nd column 's' is the reference trajectory length in meter. The x, y and z coordinates are in meter.

The longitudinal positioning latitudes on drawing are as follows: 0 mm for the 4VWS6, 4NWS8 and 4NWS24, +/-30 cm for other profile monitors and BPM's (but any movements must be symmetrical wherever the optical symmetry dictates), +/-40 cm for the correctors, and +/-100 cm for the toroid.

Note that 4NCOL4n,4NCOL4c and 4NCOL4x respectively mark the collimator shielding's entrance, centre-point and exit. The 4NXCB5 and 4NYCB5 are in-quad correctors (by means of asymmetrical powering of the quad 4NQ5).

Table 2 Coordinates of Diagnostic Elements and Correctors

Name	s[m]	x[m]	y[m]	z[m]
4VHARP2	1.98800	-7.11548	10.66387	0.00000
4VXCB2	2.41260	-7.50088	10.84205	0.00000
4VYCB2	2.77260	-7.82765	10.99313	0.00000
4VBPM2	3.20260	-8.21795	11.17358	0.00000
4VHARP4	4.93531	-9.79071	11.90071	0.00000
4VYCB4	5.33531	-10.15378	12.06857	0.00000
4VBPM4	7.50135	-12.24881	12.50458	0.00000
4VXCB6	9.46855	-14.21601	12.50458	0.00000
4VYCB6	9.82855	-14.57601	12.50458	0.00000
4VWS6	10.36856	-15.11601	12.50458	0.00000
4NBPM2	13.60135	-18.34881	12.50458	0.00000
4NXCB2	14.20135	-18.94881	12.50458	0.00000
4NYCB2	14.56136	-19.30881	12.50458	0.00000
4NHARP4A	16.59415	-21.34161	12.50458	0.00000
4NCOL4n	16.89415	-21.64161	12.50458	0.00000
4NCOL4c	17.89415	-22.64161	12.50458	0.00000
4NCOL4x	20.19415	-24.94161	12.50458	0.00000
4NBPM4	20.51415	-25.26161	12.50458	0.00000
4NHARP4B	21.07415	-25.82161	12.50458	0.00000

4NYCB5	21.48704	-26.23450	12.50458	0.00000
4NXCB5	21.48704	-26.23450	12.50458	0.00000
4NBPM6	25.22085	-29.65844	13.50447	0.00000
4NXCB8	27.06085	-30.95951	14.80555	0.00000
4NYCB8	27.42085	-31.21407	15.06010	0.00000
4NWS8	28.58085	-32.03431	15.88035	0.00000
4NBPM10	31.94085	-34.41019	18.25623	0.00000
4NHARP12	36.08754	-35.41008	22.09306	0.00000
4NXCB12	37.06075	-35.41008	23.06627	0.00000
4NYCB12	37.42075	-35.41008	23.42627	0.00000
4NBPM14	42.14575	-35.41008	28.15126	0.00000
4NXCB14	44.16825	-35.41008	30.17376	0.00000
4NYCB14	44.52825	-35.41008	30.53376	0.00000
4NHARP16	46.75825	-35.41008	32.76376	0.00000
4NTNIM16	47.76825	-35.41008	33.77376	0.00000
4NBPM16	49.93325	-35.41008	35.93876	0.00000
4NHARP18	52.88325	-35.41008	38.88876	0.00000
4NXCB18	53.87325	-35.41008	39.87877	0.00000
4NYCB18	54.23325	-35.41008	40.23877	0.00000
4NHARP20	59.00825	-35.41008	45.01376	0.00000
4NBPM20	60.32825	-35.41008	46.33376	0.00000
4NXCB22	62.99075	-35.41008	48.99627	0.00000
4NYCB22	65.25918	-34.78317	51.11678	0.00000
4NWS24	66.94918	-33.83814	52.51786	0.00000
4NBPM26	70.87761	-31.18965	55.28331	0.00000
4NHARP28	73.01041	-29.21215	56.08227	0.00000
4NXCB28	73.69041	-28.58167	56.33700	0.00000
4NYCB28	74.05041	-28.24788	56.47186	0.00000
4NBPM30A	77.69321	-24.87034	57.83648	0.00000
4NBPM30B	79.95321	-22.77490	58.68309	0.00000
4NWS30	80.76321	-22.02388	58.98652	0.00000
4NPM30	81.13321	-21.68082	59.12512	0.00000
4NCOL30	81.30821	-21.51857	59.19068	0.00000

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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.

References

[1] R. Baartman, Y. Bylinski, *ARIEL Tunnel and Beam Transport Functional Requirements*, 2011.

[2] R. Baartman, *Beamline 4N Design*, 14 Dec. 2009.

[3] Y.-N. Rao, TRI-DN-14-04: Optics Design for Electron High Energy Beam Transport (EHBT) in the BL4N Era, Document-108561, Release 2, 2015-03-18.

[4] R. Baartman, *Cyclotron Primary Achromaticity*, TRIUMF Design Note, TRI-DN-10-05, May 2010.

[5] A. Trudel, *BL4N Collimator Requirements*, June 4, 2013.

[6] Doug Evans, *DIPOLE MAGNETS IN PRIMARY BEAMLINES*, MAY 2009.

[7] Bill Gyles, *TRIUMF AC Ratser Magnets for ISAC*, ACSI Project Design Note 14-001, Revision A, 2014-03-07.

[8] P. Bricault, *ARIEL Driver Beams, Targets and Beam-Dump Specification*, 2014 Dec. 02. http://documents.triumf.ca/docushare/dsweb/Services/Document-114273

[9] V.A. Verzilov et al, *A NEW BEAM POSITION MONITOR FOR THE TRIUMF CYCLOTRON BEAMLINES*, Proc. 18th Int. Conf. on Cyclotrons and Their Applications 2007, pp.331-333.

[10] W.R. Rawnsley et al, *Wide Dynamic Range Frontend Electronics for Beam Current and Position Measurement*, BIW06, Batavia, AIP vol. 868 p.454 (2006)