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Proton Collimation in Beam Line 4-North

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Abstract: Angular scattering in the cyclotron extraction foil motivates the provision of a collimator to remove the resulting beam halo. Particle simulations in 3D are used to model the collimator and evaluate its effectiveness in mitigating uncontrolled losses which may otherwise exceed the desired limits for hands-on maintenance of the beam line.

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1 Scenario

Beam line 4-North (BL4N) is planned to transport up to 100 μA of 480 MeV protons from the TRIUMF cyclotron to an ISOL target located in the ARIEL rare isotope facility. The BL4N requirements[1, 2] specify that distributed losses shall not exceed 1 nA per meter at any location, i.e. losses are sufficiently low to permit hands-on maintenance and prevent inordinate activation and damage to hardware components.

Provision has been made in the BL4N design for the strategic placement of a collimator, with the necessary shielding, in the first straight section after the exit from the vault, as shown in Figure 1.

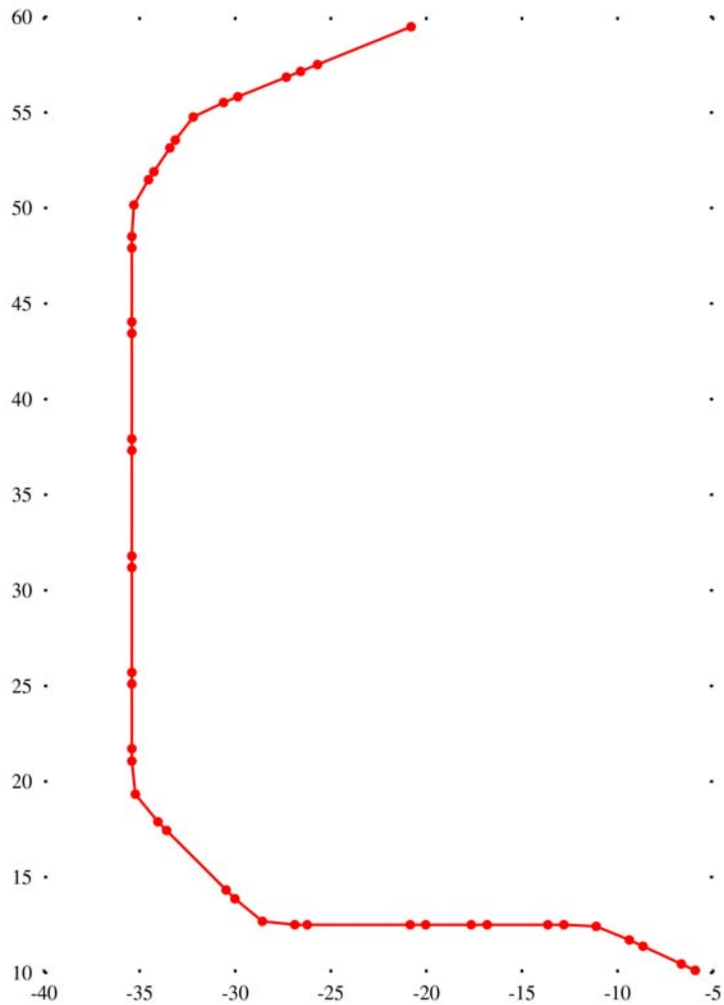

Figure 1: BL4N layout in coordinates with respect to the cyclotron centre (courtesy Y.-N. Rao). The collimator occupies the section (-21,13) to (-27,13).

2 Programs and Connections

The simulation tracks protons from the cyclotron extraction foil through to the ISOL target. This is accomplished in two stages using the programs:

1. **ACCSIM**: Tracking through the extraction foil and cyclotron field to the beam line entrance (combination magnet). Protons which do not enter the aperture of the combination magnet are discarded.
2. **G4Beamline**: Tracking through the beam line to the ISOL target, with proton losses and interactions in matter.

ACCSIM[3] is a multi-purpose tracking and simulation code with many features including scattering, decays, space charge, linear and momentum-scaled transport maps, and others. A procedure has been implemented to output the beam data in the required NTuple format (`BLTrackFile`) for reading by G4Beamline.

Based on a foundation of the simulation toolkit Geant4[4], the G4Beamline[5] application allows the collimator and magnetic components of BL4N to be modelled in a fully 3D geometry. G4Beamline tracks the beam accounting for all proton interactions in the collimator material, vacuum chamber walls, and other structures, including energy loss, multiple scattering, and elastic and inelastic scattering with optional tracking of all secondary particles produced.

Auxiliary programs employed include:

1. **REVMOC**: this is a code of reference for estimating scattering and losses in beam lines such as BL1A and BL2A. Only coulomb and elastic scattering of protons is simulated, so no secondary particles are generated[6]. The REVMOC run for BL4N is expected to define all relevant apertures and materials which play a role in proton losses, and serves as a reference for defining the G4Beamline components and layout.

2. **MATLAB:** output from G4Beamline simulations is in the form of *ntuple* files containing particle data. MATLAB scripts have been written to process these files and perform analysis and plotting.

3 Beam Line Definition

BL4N is constructed in G4Beamline via a direct conversion of the layout and element strengths as defined in the REVMOC reference run[7].

The distance coordinate defining each element position (the z coordinate in G4Beamline) is the same as in REVMOC. Quadrupole strengths (gradients) are calculated from the pole-tip field and gap size as given in REVMOC. Dipole field strengths are as in REVMOC, and the reference momentum (defined by a reference particle in G4Beamline) is identical with the reference momentum (P card) in REVMOC.

For laying out the elements, the reference path in G4Beamline must be composed only of straight line segments (circular arcs through the dipoles, as in the conventional curvilinear coordinate system, are not supported) Instead of the arc, a straight line segment of the same length as the effective length of the dipole is used, turning by half the bend angle at each vertex. The center of the dipole is placed at the midpoint of this line segment, with an appropriate displacement to correct for the sagitta. This method entails a small discrepancy with the actual path length followed by tracked particles, but in practice this is corrected for by tuning the dipoles to achieve the correct bending angle, and has virtually no effect on the edge focusing of the dipole.

All the dipoles are rectangular, but vault dipole VB4 is slightly rotated so as to achieve different edge angles at entry and exit. This is easily implemented in G4Beamline via a rotation of 7.5937 degrees around the Y axis. All dipoles are enabled to use G4Beamline's COSY-style edge field parameterization.

In the Appendix the G4Beamline input file `bl4n.in` is shown in full. This is a complete description of the beam line and all operations to be performed by the program. Running G4Beamline requires only this file and the additional file of initial particle coordinates as generated by ACCSIM.

4 BL4N Optics

The functional layout of BL4N is shown in Figure 2 reproduced from Reference [1]. The beam line is tuned to obtain point-to-parallel focusing from the stripper foil to the collimation straight section just outside the cyclotron vault. The beam is nearly a pencil beam in this region and angles are mapped to displacements allowing large-angle collimation.

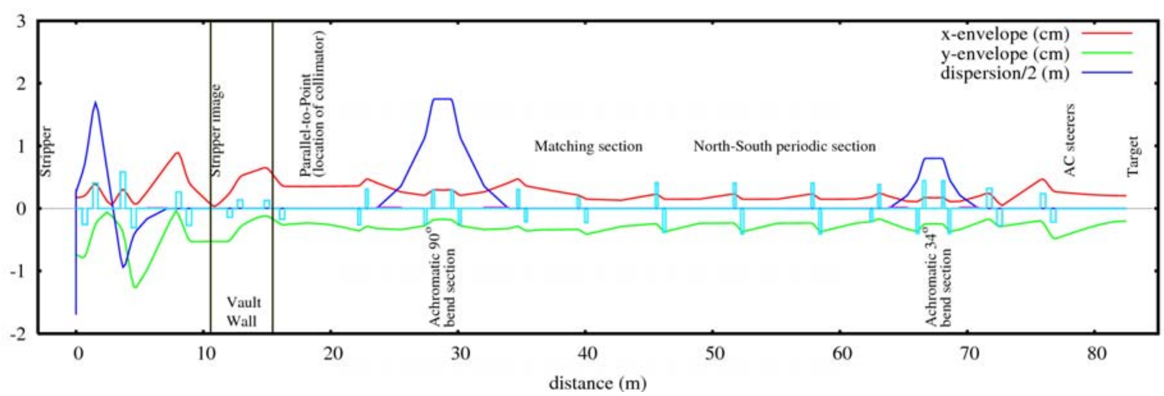

Figure 2: BL4N functional layout with beam sizes and dispersion (courtesy Y.-N. Rao).

The horizontal and vertical beam sizes (RMS envelopes) have been calculated using TRANSOPTR (envelope tracking) and REVMOC (multi-particle tracking) and are shown in Figure 3. The parameters of the initial beam distributions (at the extraction foil) have been determined by fitting to measurements made during previous BL4N operation. Although the details of beam transport are different in the two programs, at the RMS envelope level the consistency between them is quite acceptable.

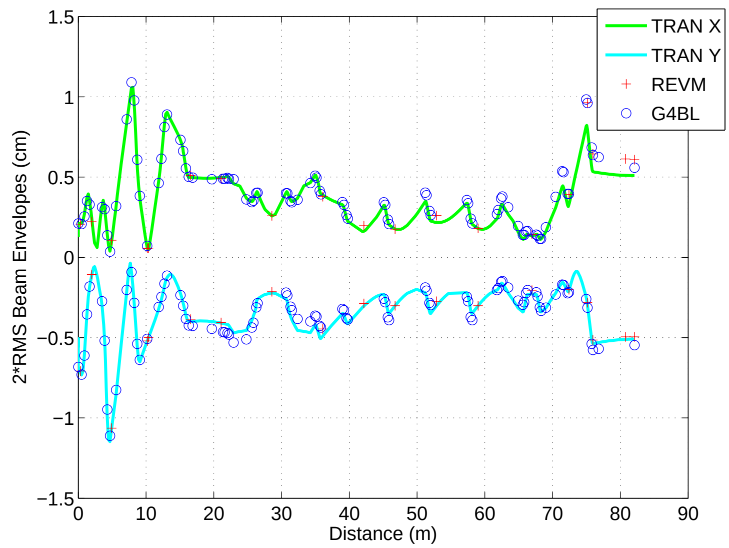

Figure 3: Beam envelopes of Transoptr, REVMOC, and G4Beamline.

A criterion for accurate simulation in G4Beamline is to be able to reproduce these envelopes sufficiently well to support a collimation study within a few mm of precision. In this case we have used particle ensembles identical to those in REVMOC, via a small converter program `revmoc2g4bl` to prepare the input ntuple. With some minor tuning, the G4Beamline result conforms within 1mm for most of the beam line and does not exceed 2mm. This is a non-trivial achievement as G4Beamline does not provide fitting to beam statistics and the RMS envelopes are in fact extremely sensitive to quadrupole strengths as well as the edge-focusing of the dipoles. In this case only two adjustments were made: the Q4 strength was decreased by 5% and the dipole fringe factor (fractional length of the fringe field region) was set to 0.2. It should be kept in mind that all tracking in Geant4 and G4Beamline is done by *integrating through field maps,*, either parametric ones provided by the program or data supplied by the user.

5 Extraction Foils

Since emittance growth due to foil scattering is proportional to foil thickness, it is desirable to use as thin a foil as possible. Foils of $\sim$ 1 mg/cm^2 can fulfill the H$^-$ stripping requirement. However for this study we have specified a thickness of **2.5 mg/cm^2** which is based on foils actually used in current operations of the other cyclotron beam lines, and anticipated to be used in BL4N for initial extraction studies. Meeting the low-loss requirement at this foil thickness ensures stable operation without issues of foil procurement and handling.

6 Multiple Scattering

Many particle simulation codes incorporating Coulomb scattering use aggregate models which directly compute the final state (angle and lateral displacement) of a charged particle traversing a certain distance of material, assuming that it undergoes a sufficiently large number ($m > 20$) of scatters during the traversal. For smaller m, this type of model has diminished accuracy due to the increasing significance of the individual scattering events, and in particular the large-angle scattering tends to be suppressed.

To estimate the mean free path and hence the average number of Coulomb scattering events for protons in the extraction foil, following Jackson[8] and others we use the Rutherford scattering law modified to account for small-angle scattering. To do this, a cutoff angle $\theta_{\rm min}$ is introduced, yielding a differential cross section

$$\frac{d\sigma}{d\Omega} = \left(\frac{2zZe^2}{pv}\right)^2 \frac{1}{\left(\theta^2 + \theta_{\rm min}^2\right)^2} \tag{1}$$

where z and Z are the atomic numbers of the incident particle and the scattering medium, e is the elementary charge, and p and v are the incident momentum and velocity. The cutoff angle is based on a Fermi-Thomas model for which the atomic radius is

$$a = \mu a_0 Z^{-1/3},$$

where $a_0 = 0.52917706 \times 10^{-8}\rm cm$ is the Bohr radius. Here we have introduced a parameter μ to indicate a constant variously given as 1.4 (Jackson) or 0.885 (others), but which we allow to be set by the user. The resulting cutoff angle is given by

$$\theta_{\rm min} = \frac{\hbar}{pa}.$$

Setting $z = 1$ for protons and integrating (1) yields the total cross section

$$\sigma_T = 4\pi \left(\frac{Ze^2}{pv}\right)^2 \frac{1}{\theta_{\rm min}^2}. \tag{2}$$

Knowing the total cross section we can derive the probability density function

$$f(\theta) = \frac{1}{\sigma_T}\frac{d\sigma}{d\theta} = \frac{2\theta_{\rm min}^2\theta}{\left(\theta_{\rm min}^2 + \theta^2\right)^2} \tag{3}$$

which describes the distribution of angles θ for a single scatter.

If A is the atomic weight and ρ is the density of the foil material then the number of target atoms per unit volume is $N = N_A\rho/A$ where N_A is Avogadro's number. It follows that for a given foil thickness t the average number m of single scattering events for a proton passing through the foil is given by

$$m = Nt\sigma_T.$$

For 480 MeV protons in foils of 1.65–2.5 mg/cm^2 thickness, the range of m is **42–63**.

6.1 Molière scattering

Limitations in computation speed motivated the development of aggregate methods to generate the distribution of the net angular displacement acquired by a macroparticle after undergoing a series of scatters in the foil. Kaminsky *et al.*[9] have noted that for $m \geq 20$ the bulk of the distribution can be described by Molière's formula for multiple scattering. The Molière scattering option is available in ACCSIM and has been implemented in the same way as in REVMOC, using a CERN library routine modified for fast interpolation (MLRL).

It is known that this scattering theory does not well describe the large-angle tail of the scattering angle distribution. This tail may only constitute a small fraction of the total beam, but for this study it is essential that the distribution of samples in the tail, and the fraction of beam in the tail, are not affected by intrinsic limitations of the model. We have therefor preferred the discrete model described in the next section.

6.2 Iterated single scattering

ACCSIM's alternative model (ASCAT) is based on tracking each particle through the foil keeping track of each coulomb scattering as it occurs. The number of single scatters per foil traversal has a Poisson distribution with mean m. It follows that the distance travelled between scatters has an exponential distribution. This can be seen by considering that $m = N\sigma_T t$ is proportional to the distance t travelled through the foil material. The constant $t_s = t/m$ is the "mean free path" or average distance between scatters. Considering t as a free variable, the probability of n scatters in distance t is:

$$p(n; t/t_s) = \frac{(t/t_s)^n e^{-t/t_s}}{n!}.$$

The probability that no scattering events occur in distance t is

$$p(0; t/t_s) = e^{-t/t_s},$$

so the probability that the first scatter occurs in a distance $< t$ is

$$H(t) = 1 - e^{-t/t_s}. \tag{4}$$

This is the cumulative distribution function for the distance between scatters, and the corresponding density function is the exponential distribution

$$h(t) = \frac{1}{t_s} e^{-t/t_s}$$

which has mean t_s as expected.

Using Equation (4), the desired distribution can be generated from uniformly-distributed random numbers $R \in [0, 1]$ by calculating distances

$$d = t_s(-\ln R).$$

For a given particle hitting the foil, we calculate the distance d_1 to the first scatter. We then apply the single-scattering distribution to generate a scattering angle. Then the distance d_2 to the next scatter is calculated, a new scattering angle generated, and so on, until the accumulated distance exceeds the foil thickness, i.e. the particle has exited the foil. For some particles the first distance d_1 will exceed the foil thickness, meaning that the particle did not scatter at all.

As the foil is traversed the scattering angles are randomly projected into the horizontal and vertical planes and a vector sum is accumulated, yielding the net angular displacements $\delta x'$ and $\delta y'$ to be applied to the particle.

To generate the single-scattering angles we first obtain the cumulative distribution function

$$F(\theta) = \int_0^\theta f(x)dx = \frac{\theta^2}{\theta_{\min}^2 + \theta^2}.$$

This function is invertible so that for random numbers $R \in [0, 1]$ we can generate scattering angles θ by

$$\theta = \theta_{\min}\sqrt{\frac{R}{1-R}}.$$

It is seen that this single-scatter model has the advantage of being analytically tractable and does not require any look-up tables or interpolation schemes. Moreover, it can be considered more accurate at large angles since no explicit upper limit on the single-scatter angle or total angle has to be imposed.

Figure 4 compares the two ACCSIM methods, and the default multiple scattering model in Geant4, for 480 MeV protons on a 2.5 mg/cm^2 foil.

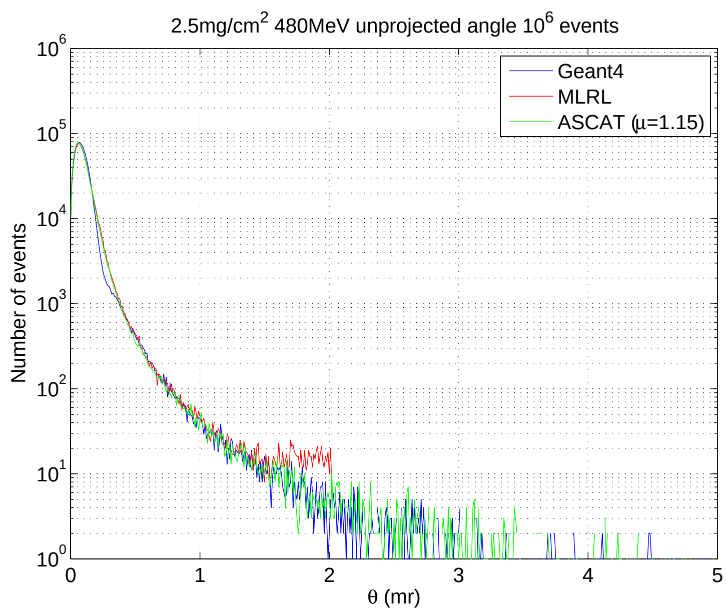

Figure 4: Distribution of exit angles from a 2.5mg foil, using ACCSIM (MLRL, ASCAT) and Geant4.

7 Energy Loss

Ionization energy loss in the extraction foil affects the energy distribution of protons in BL4N and is included in the ACCSIM treatment. For very thin layers of material the net energy loss of a proton is desribed by the Landau distribution which which results in the beam having a very long, sparse low-enery tail, as seen in Figure 5.

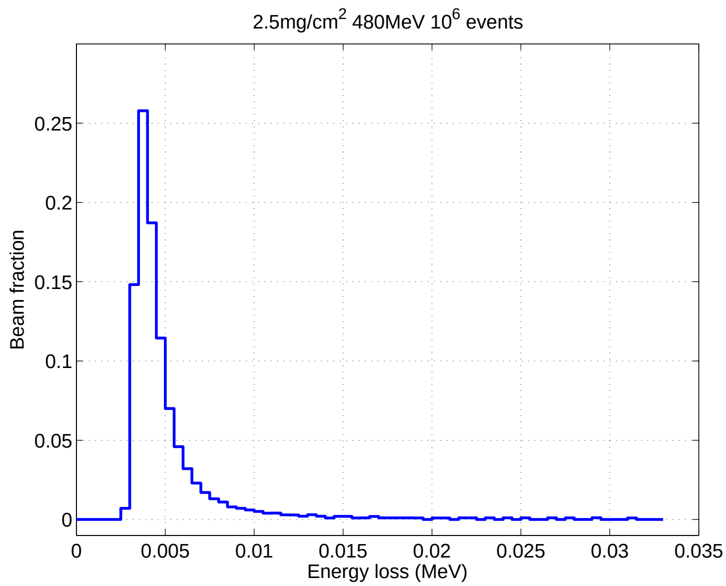

Figure 5: Energy loss distribution of 480 MeV protons traversing a 2.5 mg/cm^2 foil.

For the 2.5 mg/cm^2 carbon foil the mean energy loss is about 5 keV, whereas the maximum tabulated energy loss is about 33 keV, corresponding to a maximum $\delta p/p$ of about $4 \cdot 10^{-5}$, or a displacement of $7 \cdot 10^{-4}$ mm at the maximum dispersion of 1.8 cm. These quantities are insignicant in view of the intrinsic energy spread of the extracted cyclotron beam.

8 Scope of study

The ACCSIM+G4Beamline configuration is nearly a "start to end" simulation but not quite: it is for protons only and does not include any subtle differences of H^- and H^0 versus proton scattering in the foil. A solid "target" is included in the geometry and the beam fraction delivered to the target is measured, but no details of the target are considered.

In the cyclotron vault there will be considerable losses of protons that do not make it into the aperture of the combination magnet. These protons are discarded by ACCSIM and not included in the particle data passed to G4Beamline. The benchmark for beam intensity is *100 μA into the beam line*, and all beam fractions quoted should be referred to this.

8.1 Stages of Simulation

The flexibility of G4Beamline allows a staged approach to simulation:

1. **Passive:** the primary proton tracks are killed as soon as they hit a material surface (collimator or vacuum chamber). This reduces the problem to geometry and shows clearly the patterns of primary impact.
2. **Active collimator:** Protons are allowed to scatter in the collimator but tracks of all primary and secondary particles are killed if they hit the vacuum chamber. This clearly shows the effect of scattering in the collimator itself.
3. **Active:** Proton scattering is enabled everywhere and all primary and secondary particles are tracked until they either stop in a material (including the target) or they exit the simulation "world" (about 1 meter from the beam line).

Most results shown will be for the Passive stage. After the collimation is optimized geometrically, additional runs to show the effects of Stage 2 and 3 simulation are performed. In general, it will be see that these effects are small, which indicates that the collimation system is performing well and that proton scattering in the collimator does not produce significant problems with collateral losses downstream. However, losses at the borderline of acceptibility are evident for a short distance immediately following the collimator, as will be shown in Section 17.

9 Loss requirements and guidelines

BL4N is by design a "low loss" beamline allowing hands-on maintenance, for which the industry standard benchmark is that uncontrolled losses shall not exceed 1 Watt per meter, which for BL4N is equivalent to maximum losses of **1 nanoAmp per meter**. What this means is a bit open to interpretation, but here I have taken the strong requirement that the loss shall not exceed **1 nA in any 1-meter section of the beam line**, to a resolution of 1 meter. In other words, losses will be tallied using a fixed 1-meter bin size along the line. Of course, higher peak losses might be found by using a smaller bin size, but the 1-meter resolution seems reasonable in light of the distributed nature of radiation damage and activation due to losses.

10 Pipes and Apertures

The beam pipe and dipole vacuum chambers are modeled in G4Beamline using appropriate 3D shapes which provide accurate loss detection. The dimensions of these are based on the magnet gap sizes and apertures, mostly as specified in REVMOC[7]. The inner dimensions for the vacuum chambers in use for different regions of BL4N are shown in Table 1. Note: it has been advised that four existing 4-inch quadrupoles are available for Q11 through Q14, so the aperture has been increased accordingly in this region. This is very favourable to loss reduction downstream of B10.

Location	Aperture (inch)
CM1 to VB4	4.0
VB4	2.345–2.75
VB4 to Collimator	4.0
Collimator to B6	2.63
B6	2.345–2.75
B6 to B10	4.0
B10	2.345–2.75
B10 to BPM14	4.0
BPM14 to B22	2.63
B22	2.345–2.75
B22 to B26	2.63
B26	2.345–2.75
B26 to ATW	2.63

Table 1: Inner vacuum chamber dimensions used in G4Beamline.

The 4 inch aperture is based on existing 4” inner diameter pipe, whereas the 2.63 inch pipe aperture is based on the REVMOC quadrupole gap size of 35.5 mm minus a 2.1 mm wall thickness.

For the dipoles, the aperture is based on the known 2.345” vertical clearance in the existing box-style chamber of VB4. The horizontal clearance depends on the actual shape adopted for the dipoles (see Section 13). Due to the space limitations and stray field considerations, it is expected that the gap size of B6, B10, B22 and B26 will be 3 inches, the same as VB4. In this case, if a toroidal chamber is used the available aperture may be increased up to 2.75”.

11 No Collimation

What about not implementing a collimator at all? This scenario is not realistic because of the necessary reduction of the beam pipe diameter from its 4-inch size in the first 18 meters (up to the proposed collimator location) to the 3-inch diameter which exists in the remainder of the beam line (with the exeption of 4-inch sections between B6–B10 and B10–Q14).

Thus the minimal simulation that is meaningful must involve a “reducer” coupling of some type. This has been implemented as a 20-cm long conical shape with thick walls, which is in effect a kind of minimal collimator. For illustration purposes the results of this case for 1 million protons are shown in Figure 6.

The losses in the region of this coupler, and downstream, exceed the acceptable limits and establish the case for implementing a “real” collimator of sufficiently small aperture to bring losses within specification.

The key finding is that the most of the losses occur in the region of B10 and downstream (between 30 and 40 m) where the vertical beam size is relatively large. Optimal collimation will be mainly a matter of addressing these losses.

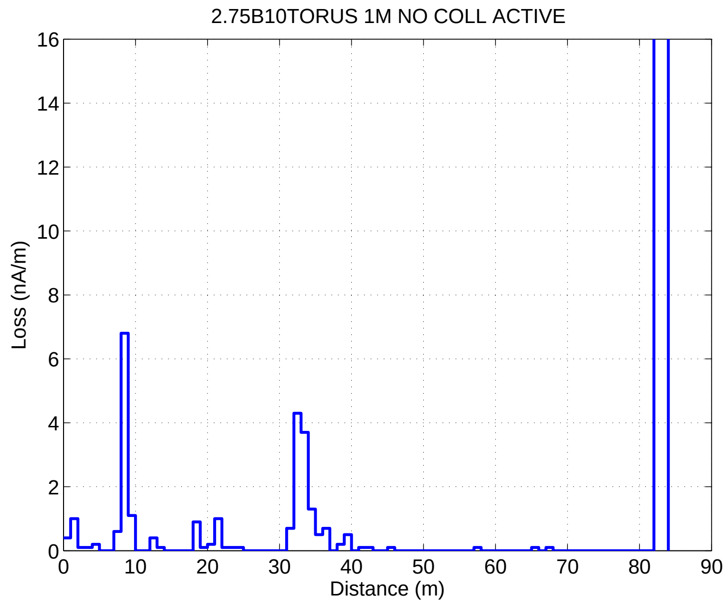

Figure 6: Losses without a collimator (reducer coupling is required)

12 Geometry of Collimator

In these simulations a simple geometry for the collimator, based on elementary considerations, is used. As with collimators in the other TRIUMF proton lines, it has a cylindrical cross section (of varying radius) and is made of copper.

The first section has a tapered shape, decreasing from the beam pipe radius to the radius that defines the collimator aperature. This is chosen for two reasons: (1) the collimated beam is distributed along the taper, reducing energy density, easing cooling, and reducing the chance of melting due to accidental impact of a high-current beam; (2) the chance of protons hitting the surface and then scattering back out into the vacuum (and possibly continuing down the beam line) is reduced.

The remainder of the collimator is a straight cylinder with the same internal radius as the final radius of the tapered section. This is needed to provide sufficient material to stop any protons that enter the latter part of the taper, but it also acts to “clean up” any protons outscattered from the taper surface, and even to collect some protons that escaped the taper due to phase space considerations. For these functions, the longer the cylinder the better, within the constraints of the beam optics and the need for shielding space downstream.

13 Dipole Vacuum Chambers

Because of limited space and the proximity of the electron beam line, and the need to limit the stray field seen by electrons, the bends B6, B10, B22 and B26 are conceived to have a 3-inch gap size, consistent with the existing dipole VB4.

The parameters of the vacuum chambers in these bends are not yet determined, but as a starting

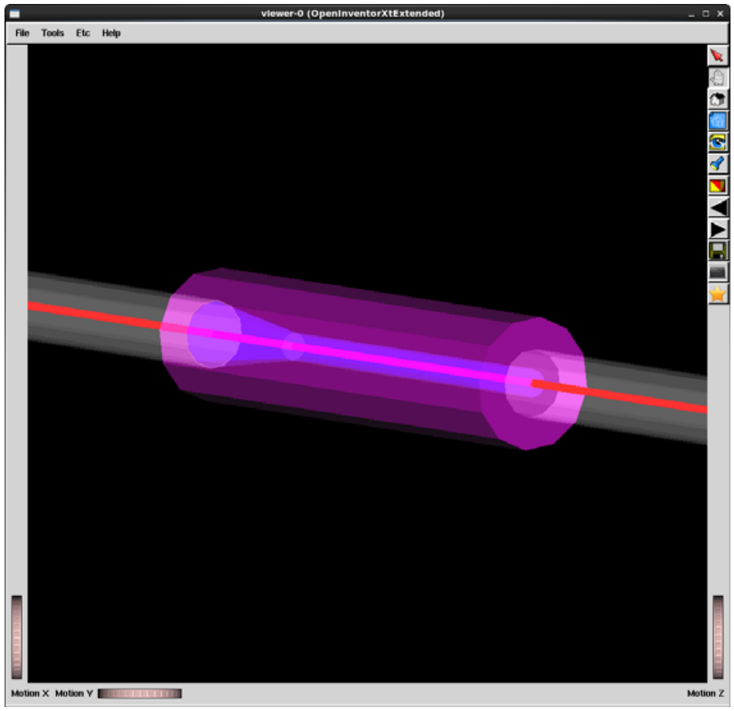

Figure 7: Geant4 visualization of collimator.

point we use the known 2.345 inch vertical clearance in the existing VB4 chamber, and look at three possible chamber shapes.

13.1 Rectangular box

Motivation: this approximates an old-style box-like vacuum chamber which is extended horizontally to accommodate the arc of the beam and also sighting ports for alignment. Compared to the beam pipe, vertical clearance is reduced and horizontal clearance is increased.

13.2 Curved box

Motivation: alignment technology no longer requires sighting ports, so the chamber is made square in cross section and is curved around the arc of the beam. Compared to a circular pipe, the square pipe may reduce losses if there are correlations in the large-amplitude particles.

13.3 Torus segment

Motivation: the circular cross section allows better rigidity and hence thinner walls than the rectangular chambers, hence giving greater vertical clearance for a given dipole gap size.

Table 2: Collimator performance: proton losses (as beam fraction and current in nA) for different vacuum chamber shapes in B10.

B10 VC	Pre-Col		On Col		Post-Col		On Target	
Box	0.000110	11.0	0.000170	17.0	0.000113	11.3	0.999607	99960.7
Curved box	0.000110	11.0	0.000170	17.0	0.000113	11.3	0.999607	99960.7
Torus	0.000110	11.0	0.000170	17.0	0.000143	14.3	0.999577	99957.7
Box h=32mm	0.000110	11.0	0.000404	40.4	0.000035	3.5	0.999451	99945.1
Box h=28mm	0.000110	11.0	0.001107	110.7	0.000001	0.1	0.998782	99878.2

14 Sensitivity of Losses to Collimation

Since G4Beamline has fitting facilities only for single-particle tracking, and not for aggregate (statistical) quantities, the choice of collimator aperture is achieved by making incremental changes in the aperture setting.

We begin with a collimator diameter of 20.8mm, based on an earlier REVMOC study[7]. The 3D geometry and accuracy of the G4Beamline model represent a refinement of what is available from REVMOC so we expect to see additional losses compared to what is seen in REVMOC.

All histograms subsequently shown use a bin size of **1 meter** and have been normalized to a total beam current of 100 μA. Thus losses in each meter of the beam line can be read directly from the plots.

In the histograms the collimator and target bins are off scale, but all losses have been tabulated in Table 2 for the three different vacuum chamber shapes.

The results indicate that we are dealing with quite small fractions of the beam, even on the collimator itself, and the effect of losses and/or collimation on the amount of beam delivered to the target is negligible.

The curved box (of square cross section) shows the same losses as the wide box, indicating that the horizontal aperture plays no role, however the toroidal chamber shows about 3 nA of additional loss due to the further restricted aperture. Further examination of the nature of these losses will be given in the next section.

The latter part of the table shows the effect of successive reductions in the collimator aperture. It is seen that the losses on the restricted vertical aperture (2.345”) of B10 are not a marginal effect. To reduce them within the limits requires a substantially lower collimator aperture of 28 mm or about 1/3 of the nominal aperture of the beam pipe.

15 Back-Tracing

In G4Beamline all primary particles are tagged with a unique event number. A small program `eventselector` has been written to select out those protons lost after the collimator (i.e. those lost in or near B10) and copy the starting coordinates for those protons from the full-

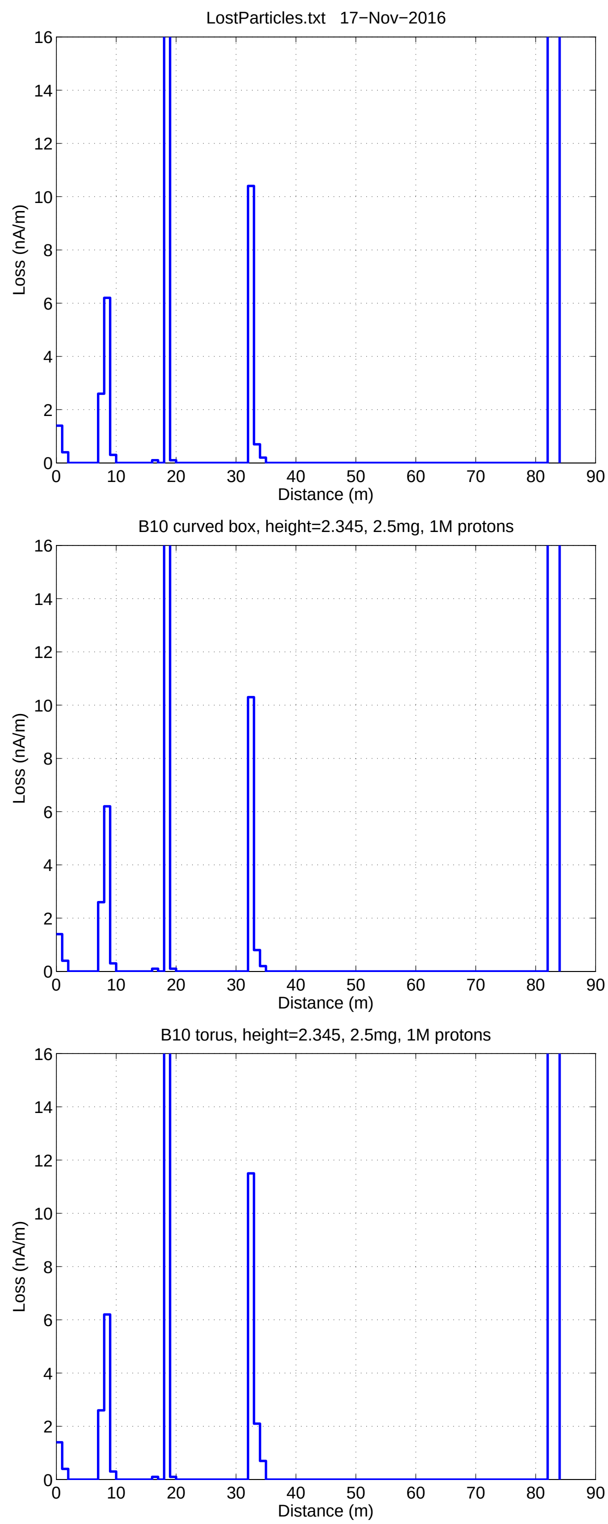

Figure 8: Loss maps for three different B10 vacuum chambers

beam input file to a new input file.

Figure 9 shows the coordinates of these eventually-lost particles as they enter the beam line (at the entrance to the combination magnet).

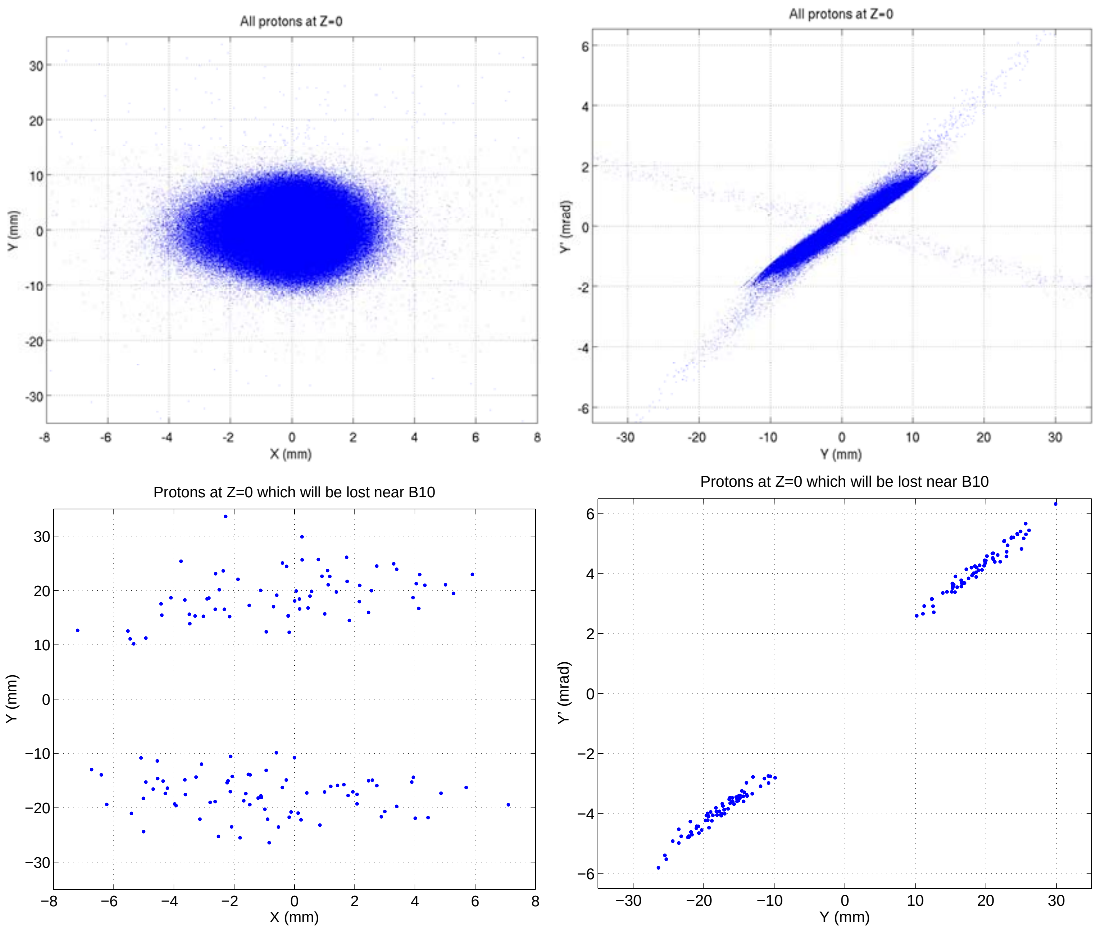

Figure 9: Real space and vertical phase space initial coordinates of the entire beam (top) and of protons eventually lost near B10

and Figure 10 shows the same protons' coordinates at the collimator, and then at their point of loss.

The vertical phase space plots reveal that these particles initially have both a large displacement and a large angle, but their displacement at the collimator lies within the aperture, and then transforms into large displacements again in the 30-40 meter region where they hit the walls and are lost.

Cleaning up these protons completely would require a collimator aperture reduction from 40 mm to less than 20 mm, however a reduction to 28mm is sufficient to bring losses within the required limit (Figure 11.

16 Gaining Vertical Headroom

With current alignment methods, lines of sight through the dipole vacuum chambers are no longer needed, so we are free to choose either a curved (or segmented) box or a curved pipe (toroidal) shape for B10 (and similarly for B6, B22 and B26). The advantage of the toroidal

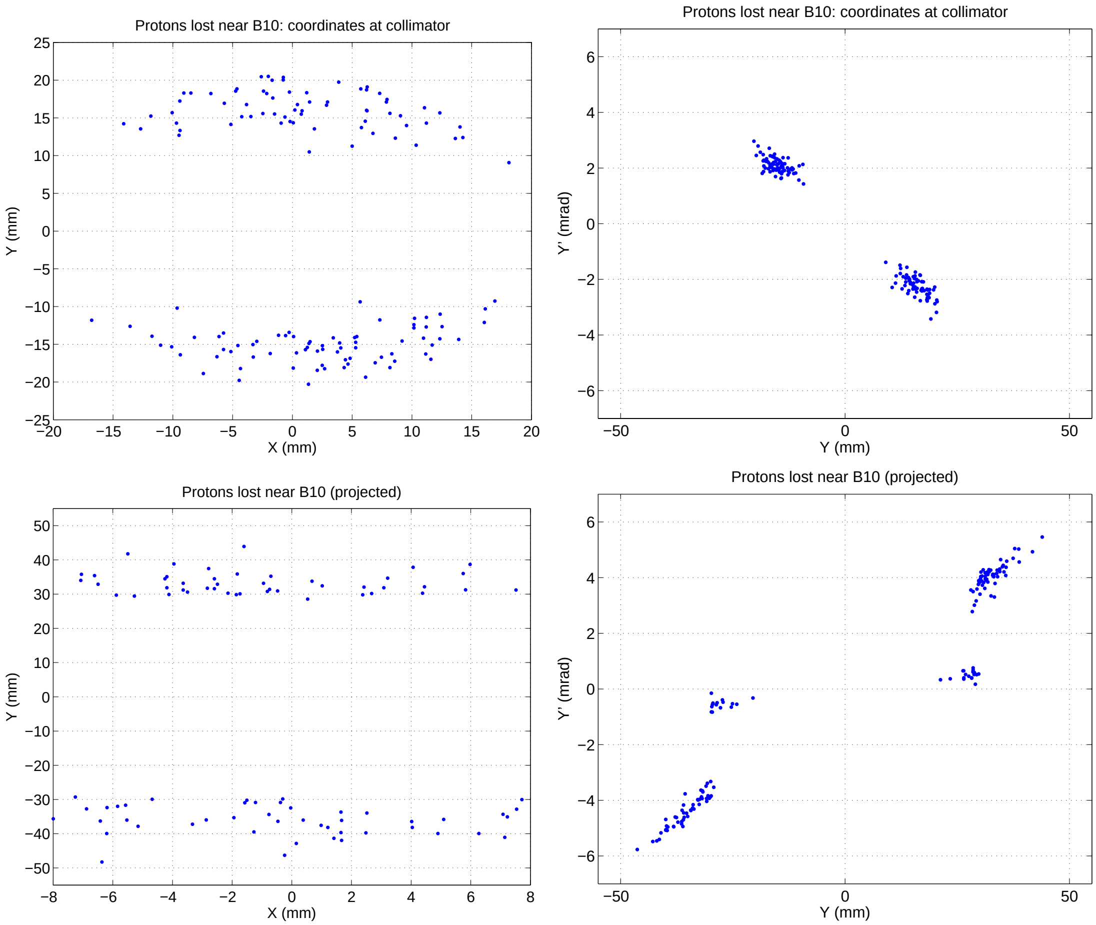

Figure 10: Coordinates of protons eventually lost, at the collimator (top) and at their point of loss (bottom).

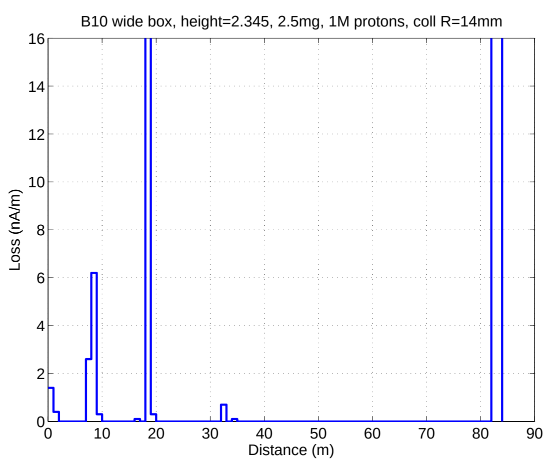

Figure 11: Loss map with collimator aperture diameter of 28 mm.

shape is that it allows a thinner wall and additional vertical headroom. The design for this chamber type is not yet available, but the best-guess from designers is that it can be fabricated with an inner diameter of at least 2.75 inches.

Repeating the sequence of collimator reductions, we find that using this chamber eases the collimation requirements and that a collimator diameter of 34 mm will achieve loss mitigation, as shown in Figure 12 and Table 3.

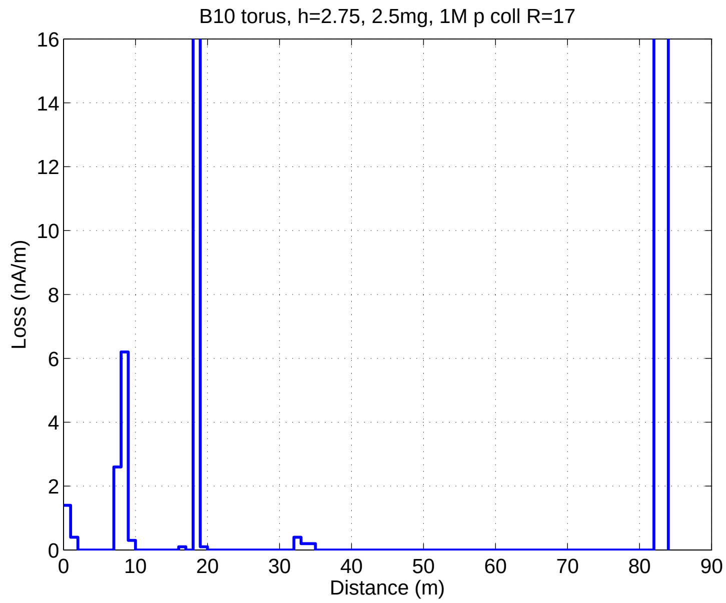

Figure 12: Loss map for optimal collimation: 2.75” dipole vacuum chambers and 34 mm collimator aperture.

Table 3: Collimator performance: proton losses (as beam fraction and current in nA) for dipole toroidal vacuum chambers of 2.75” inner diameter and different collimator apertures.

Aperture	Pre-Col		On Col		Post-Col		On Target	
41.6 mm	0.000110	11.0	0.000170	17.0	0.000062	6.2	0.999658	99965.8
36 mm	0.000110	11.0	0.000279	27.9	0.000019	1.9	0.999592	99959.2
34 mm	0.000110	11.0	0.000330	33.0	0.000008	0.8	0.999552	99955.2

17 Influence of Proton Scattering

As in any collimator, some particles will scatter back out of the material into the vacuum chamber and will eventually be lost, sometimes quite far downstream. Figure 13 shows the effects of enabling proton scattering in the collimator material alone, and then enabling it for the vacuum chamber walls as well.

One characteristic of a effective collimation system is that the collimator reduces downstream losses without contributing addional ones. In this case, there are no significant additional losses in most of the downstream beam line, however there is noticable loss redistribution in the few meters immediately following the collimator. In particular, there are losses of $\sim$1 nA inside Q5 which extends from 21.387 to 21.587 meters.

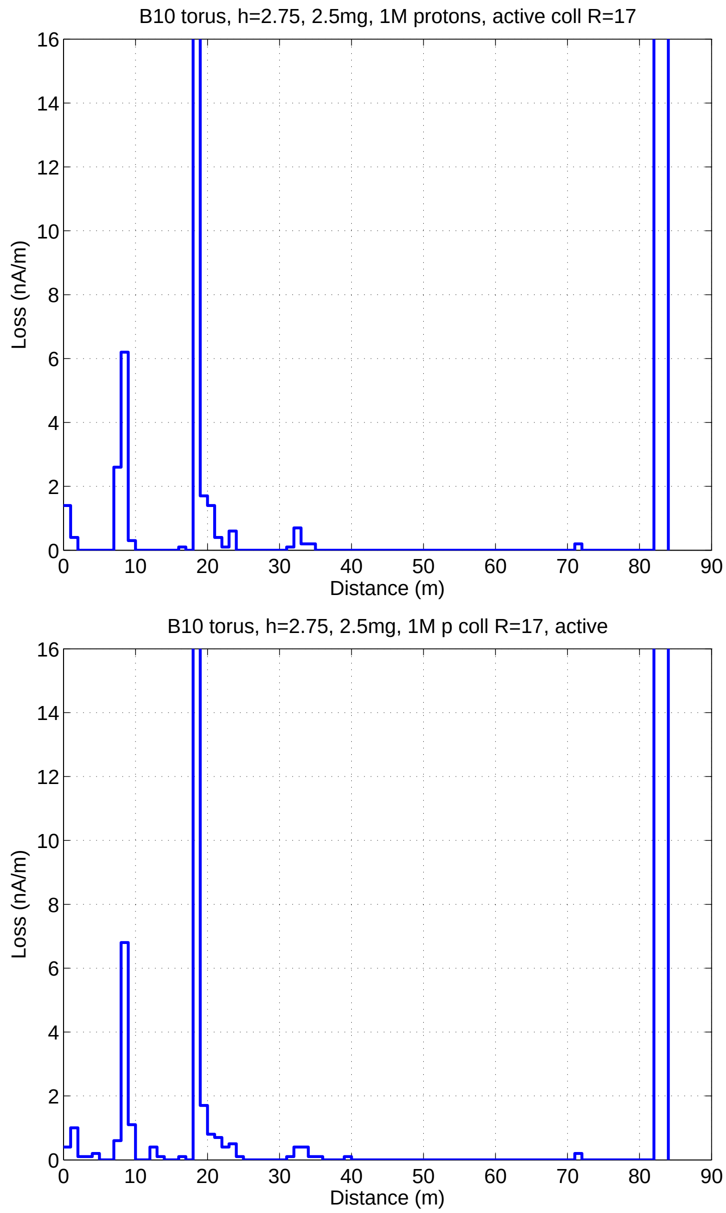

Figure 13: Effect of proton scattering in the collimator alone (top) and in the collimator and vacuum chamber walls.

It is possible that further optimization of the collimator position and geometry could reduce these Q5 losses. This will be dependent on the engineering design of the collimator and the proportion of fore/aft shielding deemed to be appropriate. At this point, it would be useful to make a preliminary shielding and activation study.

18 Tolerance of Beam Tuning Errors

In these simulations the dipoles are successively tuned to achieve a high degree of beam centering, within ± 1 mm throughout the beam line. The initial beam is assumed to be perfectly centered at the entrance to the combination magnet. The magnetic elements are perfectly aligned with the geometric axis, and the fields are assumed to have no intrinsic errors.

Although the BL4N design has been fitted out with an extensive compliment of steerers and diagnostics, the question arises, how robust is the collimation system in respect of beams that are off-center and/or out of alignment with the reference axis? The number of magnetic and tuning variables does not permit this to be studied globally, but it is possible to consider simplified cases of beam steering errors in the collimator region by adjusting the collimator itself:

1. Beam off-center: the collimator is displaced from the axis by 1–2 mm in X and Y.
2. Beam off-parallel: the collimator is rotated around the X and Y axes to create 1–2 mm of displacement at each end of the collimator.

The cases for which losses begin to exceed 1 nA/m are 2+2 mm of offset, and 1+1 mm of tilt, as shown in Figure 14.

These numbers indicate that although successful proton collimation in this configuration works well in principle, it is rather precarious and errors in the few-mm range can result in reduced effectiveness and eventually failure to meet the loss specification.

19 Heating and Cooling

The fraction of beam power intercepted by the collimator is sufficiently small (about 20 Watts) the cooling requirements should not pose any difficulty, provided that the proton losses are well distributed along the tapered portion of the collimator. For the 48.7mm–16mm taper, Figure 15 shows qualitatively that the taper is doing its job.

In the technical design stage, a detailed thermal analysis of the collimator can be done using energy deposition data from large-scale G4Beamline simulations (10^7 protons).

20 Collimator Length

The cylindrical part of the collimator performs two functions:

1. Since the point-to-parallel focusing in the collimator straight section may not be exactly achieved in real life, and protons may be drifting transversely, those missed in the taper may be collected in the cylinder.
2. Protons elastically scattered out of the copper and back into the vacuum chamber, as well as secondary particles from inelastic scatters, may be collected in the cylinder.

From this point of view, the longer the cylinder the better, within the constraints of beam steering and tunability. If the nominal cylinder length of 60 cm presented here must be reduced due to space limitations or shielding requirements, this will have some impact on collimator

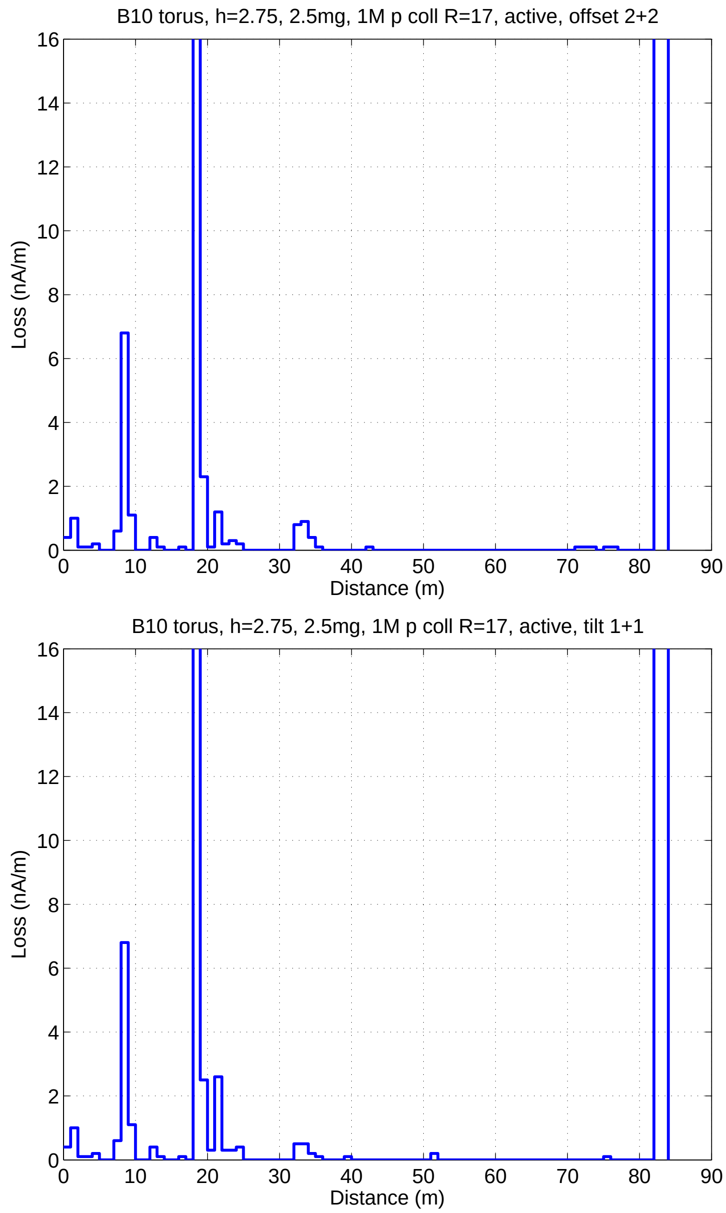

Figure 14: Effect of 2 mm parallel offset (top) and of 1 mm tilt (bottom) of X and Y.

performance, as seen in Figure 16 where the cylinder length is reduced to 20 cm, the minimum needed to stop all primary protons that stay in the material.

As with the 60-cm-long cylinder length, losses are observed inside Q5 but here they are far above the 1 nA/m limit. This is of concern because shielding the body of Q5 could be much more problematic than shielding the upstream collimator and beam pipe.

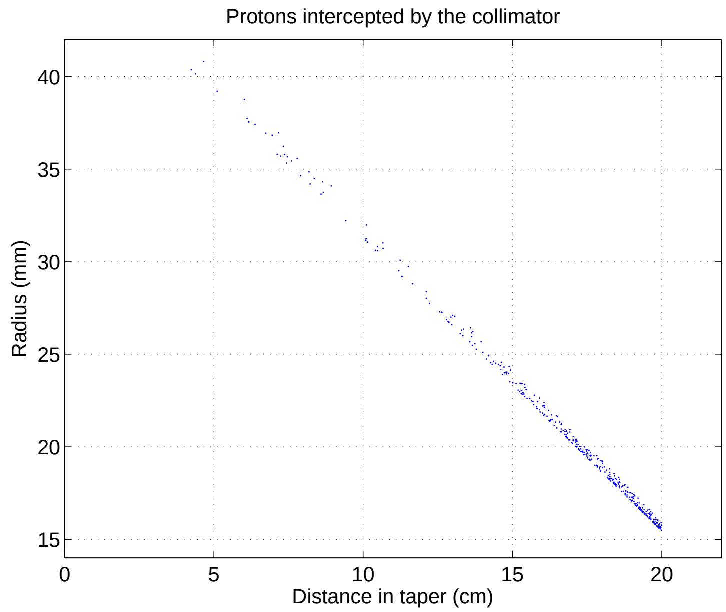

Figure 15: Distribution of intercepted protons along the tapered collimator section.

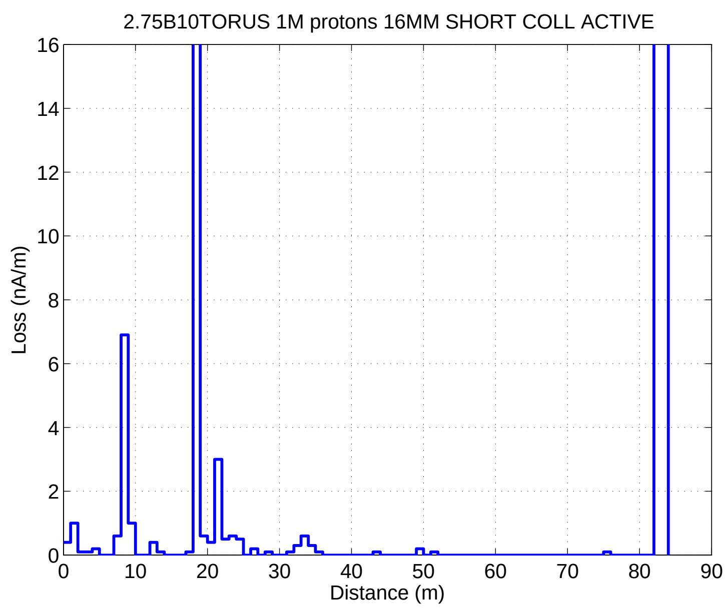

Figure 16: Effect of reducing collimator cylindrical section length to 20 cm.

21 Conclusions

Beam losses in BL4N due to scattering in the extraction foil can be controlled by a collimator with a basic geometry consisting of a tapered section and a cylindrical section. This is a tribute to the good design principles incorporated in the beam line, where collimation is designed in rather than added as an afterthought.

Bringing all losses within the specification of 1 nA/m requires a considerable aperture reduction in the collimator, to about 1/3 of the beam pipe aperture. In this well-instrumented beam line, with the high beam quality and low emittances available from the cyclotron, this “bottleneck” may not necessarily pose any operational risks or tuning difficulties. If questions do arise they could be addressed by additional analyses or simulations. At a minimum, halo plates should be incorporated into the design to help protect against accidents involving impact of the full beam onto the collimator.

High precision fabrication and alignment of the collimator, as well as precise beam tuning to the few-mm level, will be required to avoid downstream losses due to protons scattering out of the collimator into the vacuum chamber. Errors as small as a few mm will cause losses in the 21-22 meter region downstream, including inside Q5. It may therefore be prudent to consider a larger gap size for Q5 than the nominal 2.8” specified for this family of quads.

These simulations are exploratory and should be followed by a technical design phase in which the dimensions of the collimator, the shape and dimensions of the dipole vacuum chambers, and possibly other beam line aspects, are worked out in more detail. This will allow further study of specific cases in a more refined geometry and with higher statistics.

References

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[3] F.W. Jones, Development of the ACCSIM Tracking and Simulation Code, IEEE PAC97, Vancouver, 1997.

[4] S. Agostinelli et al., Geant4 – A Simulation Toolkit, *Nucl. Instrum. Meth.* **A 506** (2003). J. Allison et al., Geant4 developments and applications, *IEEE Trans. Nuc. Sci.* **53**:1 (2006).

[5] T.J. Roberts et al., Particle Tracking in Matter-Dominated Beam Lines, IPAC10, Kyoto, 2010. `http://g4beamline.muonsinc.com/`

[6] C. Kost and P. Reeve, REVMOC: A Monte Carlo Beam Transport Program, TRIUMF Design Note TRI-DNA-82-28 (Revised 2015)

[7] Y.N. Rao, private communication.

[8] J.D. Jackson, *Classical Electrodynamics,* John Wiley & Sons, 1962.

[9] A.K. Kaminsky, R.A. Meshcherov and M.I. Popova, “The efficiency of charge-exchange injection in proton accelerators and storage rings,” *Nucl. Instrum. Methods* **137:**183 (1976).

Appendix: BL4N beam line definition

```
* Beam Line 4N  F.W. Jones TRIUMF
*
*  LAYOUT based on REVMOC
*       ALL fringe fields
*       Beam generated by COMA
*       FOIL to CYCFF exit pre-tracked by ACCSIM
*  QUADRUPOLE settings from REVMOC
*

physics QGSP_BIC doStochastics=1

# Mean P from REVMOC at cyclotron FF exit.
param -unset pMomentumRef=1063.1830066

# BEAM.....

# Distribution file generated by ACCSIM
beam ascii \
     filename=/home/g4beamline/BL4N/accsim-matrix/wholebeam-1M-2.5mg/fort.81 \
     beamZ=0 nEvents=$nEvents

# Test particle file for debug
#beam ascii filename=fort.81.debug beamZ=0 nEvents=$nEvents

# REFERENCE PARTICLE.....

reference referenceMomentum=$pMomentumRef particle=proton beamZ=0 \
   beamX=0 beamXp=0 beamY=0 beamYp=0

# MATERIALS.....

param worldMaterial=Vacuum
particlecolor proton=1,0,0 neutron=0,1,1 gamma=0,1,0 e-=0,0,1 \
              plus=1,0,1 minus=1,1,0 neutral=0,1,1 reference=1,1,1

# SS from BDSIM (BDSMaterials.cc)
material ss C,0.0003 Mn,0.02 Si,0.0075 P,0.00045 S,0.0003 \
        Cr,0.17 Mo,0.025 Ni,0.12 N,0.001 Fe,0.65545 \
        density=8.0
# Alternative SS from examples/advanced/composite_calorimeter
# AISI Cr-Ni steel, default is type 304.  Weight fractions SDC definition.
#material ss Fe,0.6996 C,0.0004 Mn,0.01 \
#        Cr,0.19 Ni,0.10 density=8.02

param -unset vacuumColor=0.,0.,0.
```

```
# DIPOLES.....

# REVMOC ref momentum for bends is 1.062854GeV/c

# VB4

# Bend g/2=??cm L=1.5628914m B=9.8236971kG
# Bend angle 24.8126 degrees per DN-13-13
# Edge angles are 20 and 4.8126 degrees

tune VB4By z0=50 z1=20000 initial=-0.966497 step=0.01 \
   expr=x1 tolerance=0.01 maxIter=100

param LVB4=1562.8914
genericbend VB4 fieldWidth=1000 fieldHeight=102 fieldLength=$LVB4 \
        fringeFactor=0.2 \
   ironColor=1,0,0 ironWidth=1000 ironHeight=1000 ironLength=$LVB4

# Existing vacuum box approximated
param oheightVB4=4*25.4
box boxVB4 height=$oheightVB4 width=6*76 length=$LVB4 \
        material=ss  color=.2,.2,.2,.9
box boxVB4i height=2.345*25.4 width=6*76-4 length=$LVB4 \
        material=Vacuum  color=''
place boxVB4i parent=boxVB4
place boxVB4 parent=VB4

tubs pipe-CYCFF-VB4 innerRadius=48.7 outerRadius=50.8 length=5580 \
        material=ss  color=.2,.2,.2,.9

# B6 and B10
# Bend g/2=??cm L=1.9038051m B=14.6258640kG
# Bend angle 45 degrees per DN-13-13
# Edge angles are 22.5 degrees

tune B6By z0=22000 z1=27000 initial=1.42574 step=0.01 \
   expr=x1 tolerance=0.01 maxIter=100
tune B10By z0=28000 z1=37500 initial=1.42571 step=0.01 \
   expr=x1 tolerance=0.01 maxIter=100

param LB610=1903.8051
genericbend B610 fieldWidth=1000 fieldHeight=102 fieldLength=$LB610 \
        fringeFactor=0.2 \
   ironColor=1,0,0 ironWidth=1000 ironHeight=1000 ironLength=$LB610

# Torus 2.75 inch inner diameter
param iheightB610=2.75*25.4
param hchordB610=$LB610/2
param radiusB610=$hchordB610/sin(pi/8)
```

```
param sagB610=$radiusB610-sqrt($radiusB610*$radiusB610-$hchordB610*$hchordB610)
torus pipe-B610 innerRadius=$iheightB610/2 outerRadius=$iheightB610/2+15 \
      majorRadius=$radiusB610 initialPhi=-22.5 finalPhi=22.5 \
      material=ss  color=.2,.2,.2,.9
place pipe-B610 parent=B610 x=-$radiusB610+$sagB610 rotation=x+90

tubs pipe-B6-B10 innerRadius=48.7 outerRadius=50.8 length=32351-24811 \
        material=ss  color=.2,.2,.2,.9

# B22 and B26
# Bend g/2=??cm L=1.4384304m B=14.6258640kG
# Bend angle 34 degrees per DN-13-13
# Edge angles are 17 degrees

tune B22By z0=60000 z1=67000-100 initial=1.44162 step=0.01 \
   expr=x1 tolerance=0.01 maxIter=100
tune B26By z0=67000+100 z1=82083 initial=1.44161 step=0.01 \
   expr=x1 tolerance=0.01 maxIter=100
param B2226By=1.45
param LB2226=1438.4304
genericbend B2226 fieldWidth=1000 fieldHeight=102 fieldLength=$LB2226 \
        By=$B2226By fringeFactor=0.2 \
   ironColor=1,0,0 ironWidth=1000 ironHeight=1000 ironLength=$LB2226

# Torus 2.345 inch inner diameter
param iheightB2226=2.345*25.4
param hchordB2226=$LB2226/2
param radiusB2226=$hchordB2226/sin(17*pi/180)
param sagB2226=$radiusB2226-sqrt($radiusB2226*$radiusB2226-$hchordB2226*$hchordB22
torus pipe-B2226 innerRadius=$iheightB2226/2 outerRadius=$iheightB2226/2+4 \
      majorRadius=$radiusB2226 initialPhi=-17 finalPhi=17 \
      material=ss  color=.2,.2,.2,.9
place pipe-B2226 parent=B2226 x=-$radiusB2226+$sagB2226 rotation=x+90

tubs pipe-B10-BPM14 innerRadius=48.7 outerRadius=50.8 length=42145-34255 \
        material=ss  color=.2,.2,.2,.9
tubs pipe-BPM14-B22 innerRadius=33.4 outerRadius=35.5 length=63441-42145 \
        material=ss  color=.2,.2,.2,.9
tubs pipe-B22-B26 innerRadius=33.4 outerRadius=35.5 length=69019-64879 \
        material=ss  color=.2,.2,.2,.9
tubs pipe-B26-ATW innerRadius=33.4 outerRadius=35.5 length=81383-70458 \
        material=ss  color=.2,.2,.2,.9


# QUADRUPOLES.....

# Scale factor to get Tesla/meter from pole tip field B0
# See: BL2A notes p28
# Half-gap for vault quads and Q1-Q4 is 5.08 cm
```

```
param qsfv=1.9685039
# Half-gap for remaining quads is 3.55 cm
param qsf=2.8169014

genericquad VQ apertureRadius=65 ironRadius=914.4/2 \
        ironColor=0,.6,0 fringeFactor=0.1
genericquad Q apertureRadius=50 ironRadius=914.4/2 \
        ironColor=0,.6,0 fringeFactor=0.1

param LVQ1=411.10
param LVQ2=407.00
param LVQ3=397.20
param LVQ4=397.20
param LVQ5=406.40
param LVQ6=406.40

param LQ1=406.40
param LQ2=406.40
param LQ3=406.40
param LQ4=406.40
param LQ5=200.00
param LQ6=200.00
param LQ7=200.00
param LQ8=200.00
param LQ9=200.00
param LQ10=200.00
param LQ11=200.00
param LQ12=200.00
param LQ13=200.00
param LQ14=200.00
param LQ15=200.00
param LQ16=200.00
param LQ17=200.00
param LQ18=200.00
param LQ19=200.00
param LQ20=200.00
param LQ21=200.00
param LQ22=200.00
param LQ23=200.00
param LQ24=200.00
param LQ25=200.00
param LQ26=200.00
param LQ27=200.00
param LQ28=200.00
param LQ29=200.00
param LQ30=200.00

# COL with TAPER and STRAIGHT section
# Cf REVMOC COLLN COLX
```

```
# RAP1 is inner radius of 4" pipe
param RAP1=48.7 RAP2=17
param LTAPER=200
extrusion COL1 length=$LTAPER \
   vertices=1.000000,-0.000000;0.866025,-0.500000;0.500000,-0.866025;0.000000,-1.0
   scale1=$RAP1 scale2=$RAP2 material=Vacuum color=0,0,1,.9
param LCOL2=600
tubs COL2 length=$LCOL2 innerRadius=0 outerRadius=$RAP2 \
     material=Vacuum color=0,0,1,.9

param LCOL=$LTAPER+$LCOL2
tubs COL length=$LCOL innerRadius=0 outerRadius=97.9 material=Cu \
    color=1,0,1,0.7

place COL1 front=1 z=-0.5*$LCOL parent=COL
place COL2 front=1 z=-0.5*$LCOL+$LTAPER parent=COL

param SCOLFRONT=0.5*(16894+19694-$LCOL)

tubs pipe-VB4-COLL innerRadius=48.7 outerRadius=50.8 length=$SCOLFRONT-7143 \
        material=ss  color=.2,.2,.2,.9
tubs pipe-COLL-B6 innerRadius=33.4 outerRadius=35.5 \
     length=22907-$SCOLFRONT-$LCOL material=ss  color=.2,.2,.2,.9


# TARGET
param Tlength=24
tubs TARGET innerRadius=0 outerRadius=9.5 length=$Tlength material=Ta \
color=1,0,1


# DETECTORS...

# Placeholder for beam spill monitors


#------------------------------------------------------------
# LAYOUT
# Beamline definition in centerline (the default) coordinates
# S-values are taken directly from REVMOC Z-values
#------------------------------------------------------------

# Initial beam zntuple
zntuple format=ascii z=0 referenceParticle=1

place pipe-CYCFF-VB4 front=1 z=0

# VAULT magnets ...
```

```
param S=483

zntuple format=ascii z=$S referenceParticle=1
place VQ rename=VQ1 front=1 z=$S fieldLength=$LVQ1 gradient=$qsfv*(-4.79300) \
      ironLength=$LVQ1
param S=$S+$LVQ1
zntuple format=ascii z=$S referenceParticle=1

param S=1284

zntuple format=ascii z=$S referenceParticle=1
place VQ rename=VQ2 front=1 z=$S fieldLength=$LVQ2 gradient=$qsfv*(7.38300) \
      ironLength=$LVQ2
param S=$S+$LVQ2
zntuple format=ascii z=$S referenceParticle=1

param S=3498

zntuple format=ascii z=$S referenceParticle=1
place VQ rename=VQ3 front=1 z=$S fieldLength=$LVQ3 gradient=$qsfv*(10.50500) \
      ironLength=$LVQ3
param S=$S+$LVQ3
zntuple format=ascii z=$S referenceParticle=1

param S=4285

zntuple format=ascii z=$S referenceParticle=1
place VQ rename=VQ4 front=1 z=$S fieldLength=$LVQ4 gradient=$qsfv*(-5.95100) \
      ironLength=$LVQ4
param S=$S+$LVQ4
zntuple format=ascii z=$S referenceParticle=1

param S=5580
zntuple format=ascii z=$S referenceParticle=1
corner VB4c1 z=$S rotation=Y+24.8126/2
place VB4 rename=VB4. z=$S+0.5*$LVB4 rotation=Y7.5937 By=VB4By
param S=$S+$LVB4
corner VB4c2 z=$S rotation=Y+24.8126/2
zntuple format=ascii z=$S referenceParticle=1

place pipe-VB4-COLL front=1 z=$S

param S=7856
zntuple format=ascii z=$S referenceParticle=1
place VQ rename=VQ5 front=1 z=$S fieldLength=$LVQ5 gradient=$qsfv*(4.86900) \
      ironLength=$LVQ5
param S=$S+$LVQ5
zntuple format=ascii z=$S referenceParticle=1
```

```
param S=8692
zntuple format=ascii z=$S referenceParticle=1
place VQ rename=VQ6 front=1 z=$S fieldLength=$LVQ6 gradient=$qsfv*(-5.17200) \
      ironLength=$LVQ6
param S=$S+$LVQ6
zntuple format=ascii z=$S referenceParticle=1

# Foil image
param S=10189
zntuple format=ascii z=$S referenceParticle=1

# Tunnel WEST ...

param S=11869
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q1 front=1 z=$S fieldLength=$LQ1 gradient=$qsfv*(-1.31500) \
      ironLength=$LQ1
param S=$S+$LQ1
zntuple format=ascii z=$S referenceParticle=1

param S=12705
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q2 front=1 z=$S fieldLength=$LQ2 gradient=$qsfv*(2.75300) \
      ironLength=$LQ2
param S=$S+$LQ2
zntuple format=ascii z=$S referenceParticle=1

param S=15081
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q3 front=1 z=$S fieldLength=$LQ3 gradient=$qsfv*(1.14100) \
      ironLength=$LQ3
param S=$S+$LQ3
zntuple format=ascii z=$S referenceParticle=1

param S=15898
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q4 front=1 z=$S fieldLength=$LQ4 gradient=$qsfv*(-2.25200) \
      ironLength=$LQ4
param S=$S+$LQ4
zntuple format=ascii z=$S referenceParticle=1

# COLLIMATOR

param S=$SCOLFRONT

zntuple file=PRECOL.txt format=ascii z=$S referenceParticle=1
place COL rename=COLLIM front=1 z=$S
param S=$S+$LCOL
zntuple file=POSTCOL.txt format=ascii z=$S+1 referenceParticle=1
```

```
place pipe-COLL-B6 front=1 z=$S

param S=21387
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q5 front=1 z=$S fieldLength=$LQ5 gradient=$qsf*(-0.06000) \
      ironLength=$LQ5
param S=$S+$LQ5
zntuple format=ascii z=$S referenceParticle=1

param S=22037
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q6 front=1 z=$S fieldLength=$LQ6 gradient=$qsf*(0.85600) \
      ironLength=$LQ6
param S=$S+$LQ6
zntuple format=ascii z=$S referenceParticle=1

param S=22907
zntuple format=ascii z=$S referenceParticle=1
corner B6c1 z=$S rotation=Y-22.5
place B610 rename=B6 z=$S+0.5*$LB610 By=B6By
param S=$S+$LB610
corner B6c2 z=$S rotation=Y-22.5
zntuple format=ascii z=$S referenceParticle=1

place pipe-B6-B10 front=1 z=$S

param S=25631
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q7 front=1 z=$S fieldLength=$LQ7 gradient=$qsf*(-1.85600) \
      ironLength=$LQ7
param S=$S+$LQ7
zntuple format=ascii z=$S referenceParticle=1

param S=26281
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q8 front=1 z=$S fieldLength=$LQ8 gradient=$qsf*(3.53200) \
      ironLength=$LQ8
param S=$S+$LQ8
zntuple format=ascii z=$S referenceParticle=1

param S=30681
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q9 front=1 z=$S fieldLength=$LQ9 gradient=$qsf*(3.53200) \
      ironLength=$LQ9
param S=$S+$LQ9
zntuple format=ascii z=$S referenceParticle=1

param S=31331
```

```
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q10 front=1 z=$S fieldLength=$LQ10 gradient=$qsf*(-1.85600) \
      ironLength=$LQ10
param S=$S+$LQ10
zntuple format=ascii z=$S referenceParticle=1

param S=32351
zntuple format=ascii z=$S referenceParticle=1
corner B10c1 z=$S rotation=Y-22.5
place B610 rename=B10 z=$S+0.5*$LB610 By=B10By
param S=$S+$LB610
corner B10c2 z=$S rotation=Y-22.5
zntuple format=ascii z=$S referenceParticle=1

place pipe-B10-BPM14 front=1 z=$S

param S=34960
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q11 front=1 z=$S fieldLength=$LQ11 gradient=$qsf*(3.11600) \
      ironLength=$LQ11
zntuple format=ascii z=$S+$LQ11 referenceParticle=1

param S=35610
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q12 front=1 z=$S fieldLength=$LQ12 gradient=$qsf*(-2.47500) \
      ironLength=$LQ12
zntuple format=ascii z=$S+$LQ12 referenceParticle=1

param S=38998
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q13 front=1 z=$S fieldLength=$LQ13 gradient=$qsf*(2.94000) \
      ironLength=$LQ13
zntuple format=ascii z=$S+$LQ13 referenceParticle=1

param S=39598
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q14 front=1 z=$S fieldLength=$LQ14 gradient=$qsf*(-2.66800) \
      ironLength=$LQ14
zntuple format=ascii z=$S+$LQ14 referenceParticle=1

# TRANSITION TO 3 INCH APERTURE
param S=42145
place pipe-BPM14-B22 front=1 z=$S

param S=45088
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q15 front=1 z=$S fieldLength=$LQ15 gradient=$qsf*(5.56700) \
      ironLength=$LQ15
zntuple format=ascii z=$S+$LQ15 referenceParticle=1
```

```
param S=45688
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q16 front=1 z=$S fieldLength=$LQ16 gradient=$qsf*(-4.90400) \
      ironLength=$LQ16
zntuple format=ascii z=$S+$LQ16 referenceParticle=1

param S=51213
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q17 front=1 z=$S fieldLength=$LQ17 gradient=$qsf*(5.09560) \
      ironLength=$LQ17
zntuple format=ascii z=$S+$LQ17 referenceParticle=1

param S=51813
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q18 front=1 z=$S fieldLength=$LQ18 gradient=$qsf*(-5.09560) \
      ironLength=$LQ18
zntuple format=ascii z=$S+$LQ18 referenceParticle=1

param S=57338
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q19 front=1 z=$S fieldLength=$LQ19 gradient=$qsf*(5.09560) \
      ironLength=$LQ19
zntuple format=ascii z=$S+$LQ19 referenceParticle=1

param S=57938
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q20 front=1 z=$S fieldLength=$LQ20 gradient=$qsf*(-5.09560) \
      ironLength=$LQ20
zntuple format=ascii z=$S+$LQ20 referenceParticle=1

param S=61801
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q21 front=1 z=$S fieldLength=$LQ21 gradient=$qsf*(-2.43000) \
      ironLength=$LQ21
zntuple format=ascii z=$S+$LQ21 referenceParticle=1

param S=62401
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q22 front=1 z=$S fieldLength=$LQ22 gradient=$qsf*(4.41100) \
      ironLength=$LQ22
zntuple format=ascii z=$S+$LQ22 referenceParticle=1

param S=63441
zntuple format=ascii z=$S referenceParticle=1
corner B22c1 z=$S rotation=Y-17
place B2226 rename=B22 z=$S+0.5*$LB2226 By=B22By
param S=$S+$LB2226
corner B22c2 z=$S rotation=Y-17
```

```
zntuple format=ascii z=$S referenceParticle=1

place pipe-B22-B26 front=1 z=$S

param S=65599
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q23 front=1 z=$S fieldLength=$LQ23 gradient=$qsf*(-4.96300) \
      ironLength=$LQ23
zntuple format=ascii z=$S+$LQ23 referenceParticle=1

param S=66099
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q24 front=1 z=$S fieldLength=$LQ24 gradient=$qsf*(5.50100) \
      ironLength=$LQ24
zntuple format=ascii z=$S+$LQ24 referenceParticle=1

param S=67599
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q25 front=1 z=$S fieldLength=$LQ25 gradient=$qsf*(5.50100) \
      ironLength=$LQ25
zntuple format=ascii z=$S+$LQ25 referenceParticle=1

param S=68099
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q26 front=1 z=$S fieldLength=$LQ26 gradient=$qsf*(-4.96300) \
      ironLength=$LQ26
zntuple format=ascii z=$S+$LQ26 referenceParticle=1

param S=69019
zntuple format=ascii z=$S referenceParticle=1
corner B26c1 z=$S rotation=Y-17
place B2226 rename=B26 z=$S+0.5*$LB2226 By=B26By
param S=$S+$LB2226
corner B26c2 z=$S rotation=Y-17
zntuple format=ascii z=$S referenceParticle=1

place pipe-B26-ATW front=1 z=$S

param S=71401
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q27 front=1 z=$S fieldLength=$LQ27 gradient=$qsf*(4.55938) \
      ironLength=$LQ27
zntuple format=ascii z=$S+$LQ27 referenceParticle=1

param S=72207
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q28 front=1 z=$S fieldLength=$LQ28 gradient=$qsf*(-7.30945) \
      ironLength=$LQ28
zntuple format=ascii z=$S+$LQ28 referenceParticle=1
```

```
param S=74944
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q29 front=1 z=$S fieldLength=$LQ29 gradient=$qsf*(4.38813) \
      ironLength=$LQ29
zntuple format=ascii z=$S+$LQ29 referenceParticle=1

param S=75750
zntuple format=ascii z=$S referenceParticle=1
place Q rename=Q30 front=1 z=$S fieldLength=$LQ30 gradient=$qsf*(-4.22967) \
      ironLength=$LQ30
zntuple format=ascii z=$S+$LQ30 referenceParticle=1

# RASTER MAGNET
param S=76803
zntuple format=ascii z=$S referenceParticle=1

# ARIEL TARGET WEST

param S=82083
zntuple format=ascii z=$S referenceParticle=1
place TARGET front=1 z=$S

# END OF BEAM LINE ELEMENTS

# Loss detectors

beamlossntuple BLNT filename=LostParticles.txt format=ascii \
               require=PDGid==2212&&ParentID==0

trace nTrace=1 format=ascii coordinates=Centerline primaryOnly=1

# Only for G4BL 2.16
#survey coordinates=centerline filename=bl1a.svy

g4ui when=4 "/run/beamOn 100"
```