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Proton Collimation in BL4N with New Optics

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Abstract: This report updates the simulation study of collimation in Beam Line 4-North which was documented in TRI-BN-16-15. A new series of simulations have been done which reflect the latest quadrupole specifications and assignments, vacuum chamber dimensions, and retuning of the optics. The optimum dimensions of the collimator and the precision requirements for beam tuning and steering are discussed.

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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[2, 3] 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.

A previous report TRI-BN-16-15[1] described a simulation study of collimation in the beam line using ACCSIM[4] and G4Beamline[5]. Please refer to this report for an overview of the simulation models, software configuration, and results based on the prototype BL4N design.

This study indicated that the strategic placement of a single long collimator, consisting of a tapered section followed by a cylindrical section, in the first straight section after the exit from the vault, would be sufficient to control losses to within the 1nA/m limit, provided that precision (1mm) alignment, steering, and beam position monitoring are available.

Subsequently, the BL4N design has been refined in several areas:

1. Dipole vacuum chamber shapes have been finalized. The in-vault dipole VB4 will retain its existing rectangular vacuum chamber with a 2.345 inch inner height, and each of the other four dipoles will have a curved chamber of circular cross section (i.e. a segment of a torus) with a 2.87 inch inner diameter.
2. Quadrupole assignments: a specific quadrupole type (either existing or newly manufactured) has been assigned to each quadrupole location.
3. Quadrupole vacuum chamber dimensions (based on commercially-available pipes) have been specified for each quadrupole family.
4. Quadrupole strengths have been adjusted to suit the new hardware assignments. The tune is very similar to the previous one but has slightly increased beam sizes at certain locations.
5. In the G4Beamline model the VB4 vacuum chamber height was set to 3.6 inches and this has now been corrected to 2.345 inches in accordance with the technical drawing.

The G4Beamline model of BL4N has been updated to reflect these changes, and also to correct the vacuum chamber height in VB4 which and the relevant simulations of the previous study have been repeated. A second series of runs with a longer collimator have also been done, in which a better margin of performance is achieved.

2 New Configuration and Beam Line Definition

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

The new configuration was developed using TRANSOPTR and no subsequent REVMOC runs were done to estimate losses (deferring to the more accurate G4Beamline simulations described here). The main input to TRANSOPTR is via a user-written Fortran subroutine with some

Table 1: Dipole types and vacuum chamber dimensions

Dipole	Angle	Gap	Chamber	Inner H or D	Wall	L_{eff} (mm)
VB4	24.8126	3.06″	Rectangular	2.345″	0.125″	1562.8914
B6/B10	45	3.06″	Circular	2.87″	0.065″	1903.8051
B22/B26	34	3.06″	Circular	2.87″	0.065″	1438.4304

Table 2: Quadrupole types and vacuum chamber dimensions

Series	Type	Gap	OD	Wall	L_{eff} (mm)
VQ1 – VQ2	Q14/8	4.06″	4″	0.083″	406.4
VQ3	Q19/8	4.06″	4″	0.083″	526.542
VQ4 – VQ6	Q14/8	4.06″	4″	0.083″	406.4
Q1 – Q4	Q14/8	4.06″	4″	0.083″	406.4
Q5 – Q6	4Q10/3.6 (HERA)	108mm	105mm	2.5mm	260.35
Q7 – Q10	Q14/8	4.06″	4″	0.083″	406.4
Q11 – Q14	4Q8/5/8.5 (BUNNY)	4.06″	4″	0.083″	261.8
Q15 – Q16	KEK	110mm	105mm	2.5mm	459.4
Q17 – Q20	DanFysika-L5	71mm	70mm	1mm	205.5
Q21 – Q26	TUDA-S	85mm	83mm	1.5mm	296.672
Q27	4Q8/5/8.5 (BUNNY)	4.06″	4″	0.083″	261.8
Q28 – Q30	4Q12/6 (UofA)	4.08″	4″	0.083″	357.124

additional data file(s) loaded into common blocks. It is some work to extract G4Beamline-compatible element parameters from these files, however, much of the necessary information can be retrieved from two TRANSOPTR output files:

data.1: Element lengths and accumulated S-values of at the entry and exit of each element. Quads are typically split so the their center coordinate is also available.

data.22: Dipole bend angle, field, gap, and edge angle. Quadrupole aperture and field gradient. The latter quantity can be copied directly into the quadrupole `gradient` parameter which is used in G4Beamline.

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.

3 BL4N Optics

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.

The layout and previous optics of BL4N are shown in Figure 1 reproduced from Reference [2]. Below it is the updated envelope and dispersion plot for the current optics.

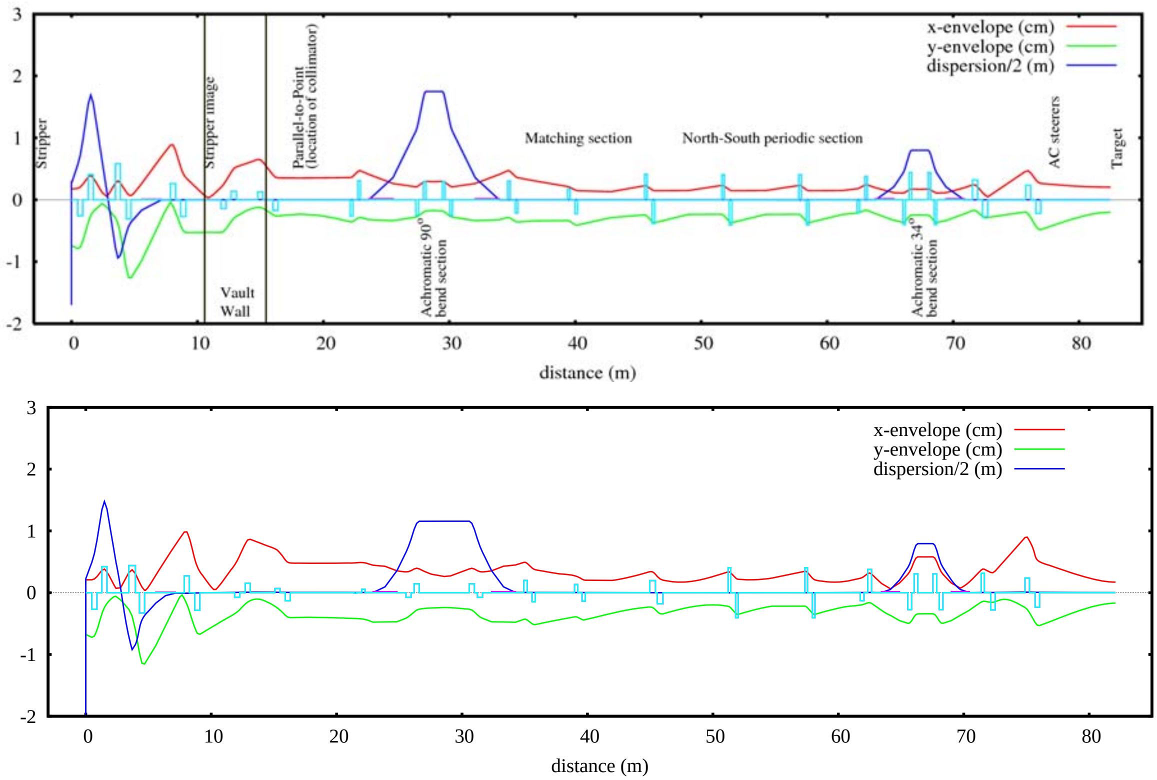

Figure 1: BL4N layout and optics: previous version (top) and current version (courtesy Y.-N. Rao).

The beam envelopes are not radically different but generally the beam sizes are slightly larger with the new optics, and dispersions are slightly smaller. In the last ∼20 meters where quadrupoles are adjusted to obtain a smaller beam spot allowing beam rastering on the target.

As before, the RMS beam sizes calculated by TRANSOPTR (envelope tracking) have been compared with those of G4Beamline (statistics of multi-particle tracking), as shown in Figure 2. The parameters of the initial beam distributions (at the extraction foil) have been determined by fitting to measurements made during previous BL4N operation.

Generally the strengths of one or a few quadrupoles need to be adjusted by a few percent in order to obtain agreement of the beam sizes within 1mm. Certain quads tend to be very sensitive in this regard. But in this case, using gradients calculated by TRANSOPTR, no adjustments in the strengths were needed! Rather, good agreement was found be setting the `fringeFactor` of each quad in G4Beamline to zero, i.e. using a hard-edge field representation. The reason for this behavior is unknown, but I note that this parameter is more of a fudge factor than anything describing the true field profile of the magnet.

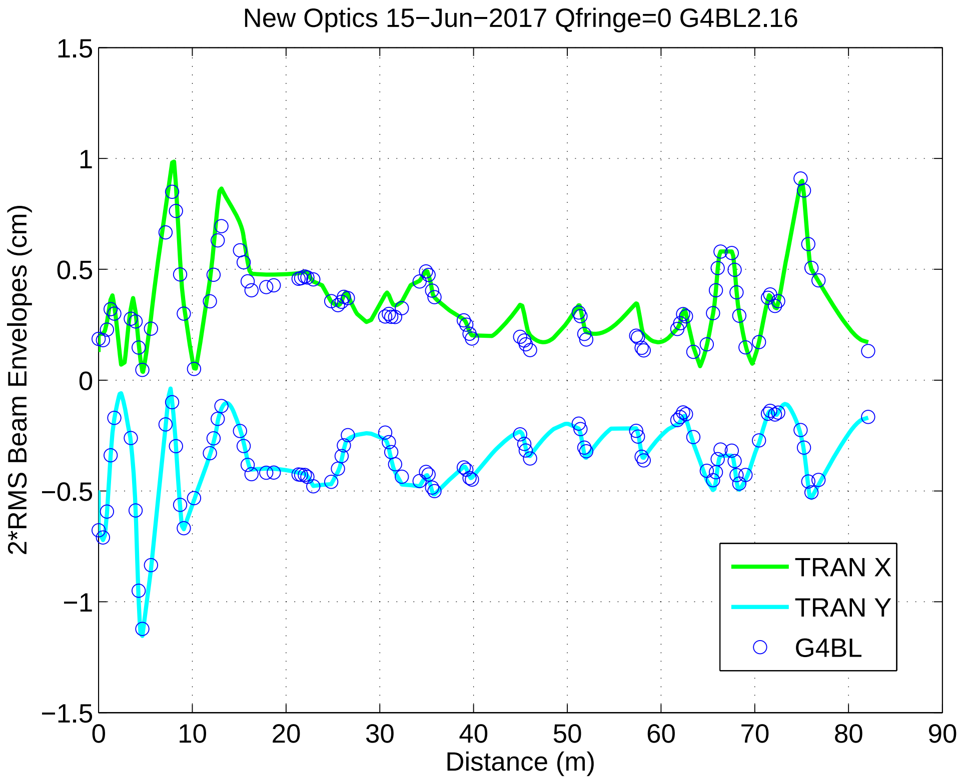

Figure 2: RMS beam envelopes of Transoptr and G4Beamline.

4 Geometry of Collimator

For the new configuration and optics, the first set of runs were done using the same collimator geometry and the same position of the collimator as before, to readily see the consequences of the changes to the layout and quadrupole strengths. The collimator consists of a 20cm tapered section followed by a 60cm cylindrical section.

In view of the space available and the need to mitigate the losses in the few meters downstream from the collimator, a second series of runs were done with a longer collimator having a 100cm cylindrical section and placed somewhat farther upstream to preserve the drift space between it and the quadrupole Q5.

5 Sensitivity of Losses to Collimation

In the following, all runs were done with 1 million primary protons. All histograms 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.

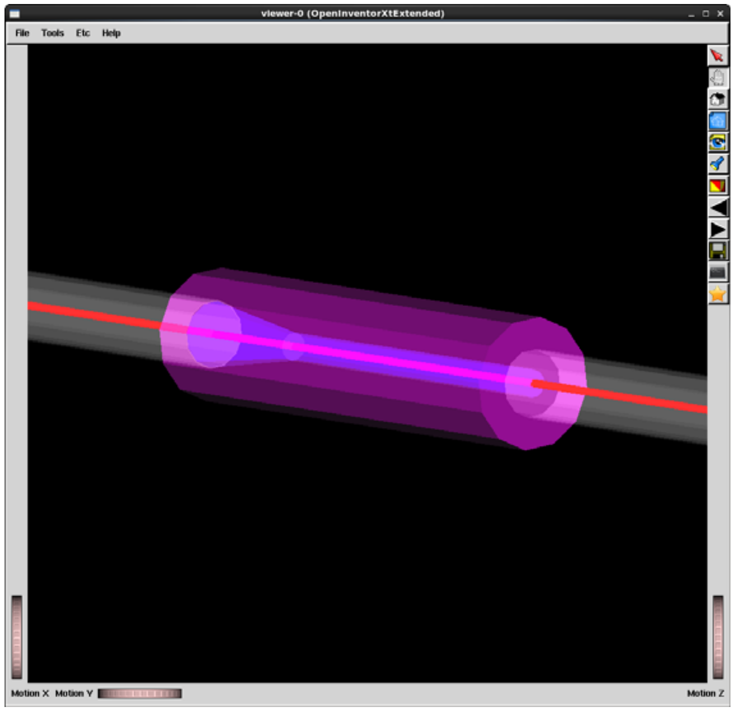

Figure 3: Geant4 visualization of collimator.

5.1 Idealized collimator

For comparison with the previous study, a series of runs with successive reductions of the collimator radius (of the cylindrical part) to see the threshold of where 1nA/m loss control is achieved. First this is done as an idealized "geometric" test where all protons are stopped when they hit something (collimator or wall). In G4Beamline this is easily set up by adding a `kill=1` tag to the relevant geometry volumes.

Table 3: Idealized collimator performance (losses in nA) for previous configuration (top) and the current one (bottom).

R_{coll}	Pre-Coll	On Coll	Post-Col	On Target
18 mm	11.0	27.9	1.9	99959.2
17 mm	11.0	33.0	0.8	99955.2
16 mm	11.0	40.4	0.6	99948.0
18 mm	9.2	26.6	2.2	99962.0
17 mm	9.2	31.3	1.2	99958.3
16 mm	9.2	37.4	0.5	99952.9

As seen in Table 3, with the new optics the collimator performance as a function of radius is very similar to the previous case, with post-collimator losses limited to the B10 region as before. Figure 4 indicates that the threshold of local loss control below 1nA/m is again reached at a collimator radius of 17mm.

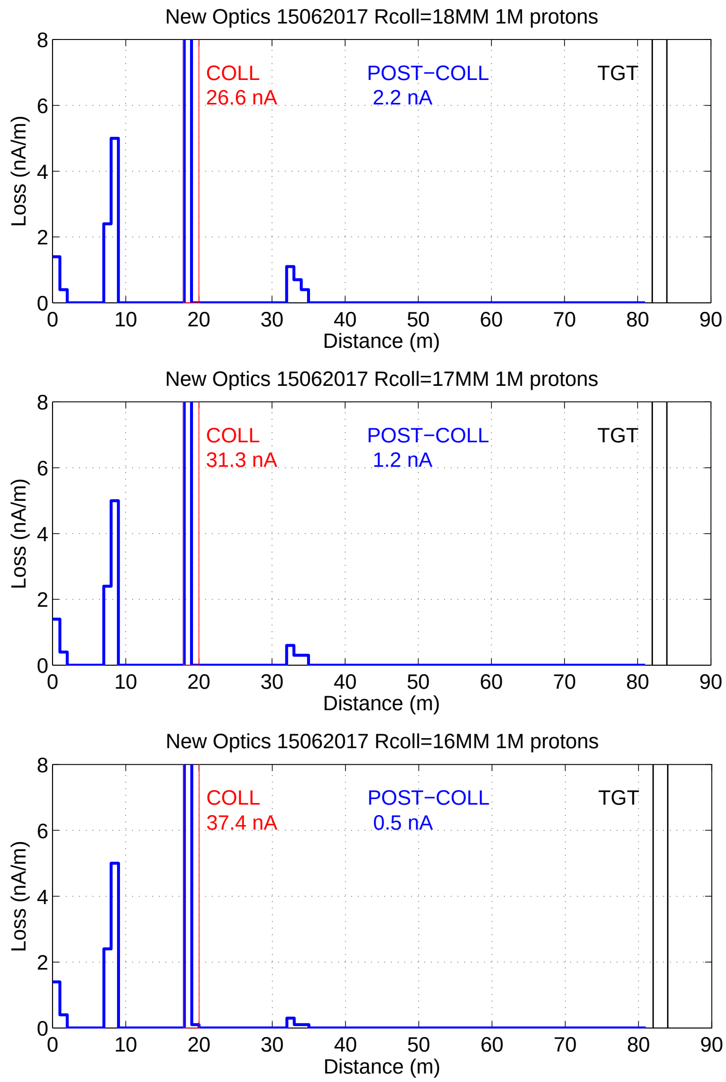

Figure 4: Losses with 18mm, 17mm and 16mm collimator radii (scattering of protons disabled).

5.2 Effect of proton scattering

We then move to the more realistic case including the effect of proton scattering in the collimator material and the vacuum chamber walls. In the collimator, scattered protons may acquire large angles yet still pass through the aperture, as shown in Figure 5. This leads in particular to losses extending a few meters downstream of the exit of the collimator (21–26m), and to losses at critical points farther downstream as seen in Figure 6.

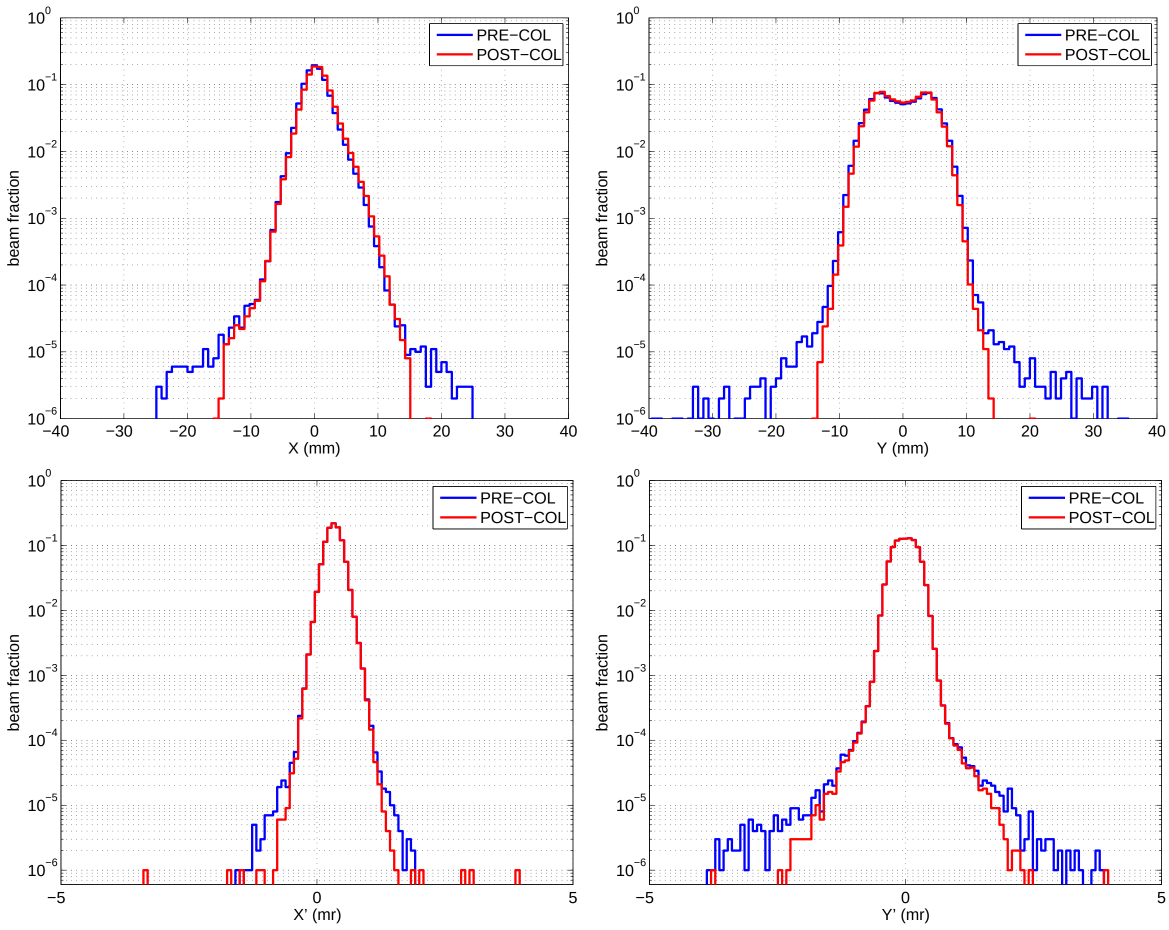

Figure 5: Beam profiles at entry (blue) and exit (red) of the collimator, with a collimator radius of 15mm.

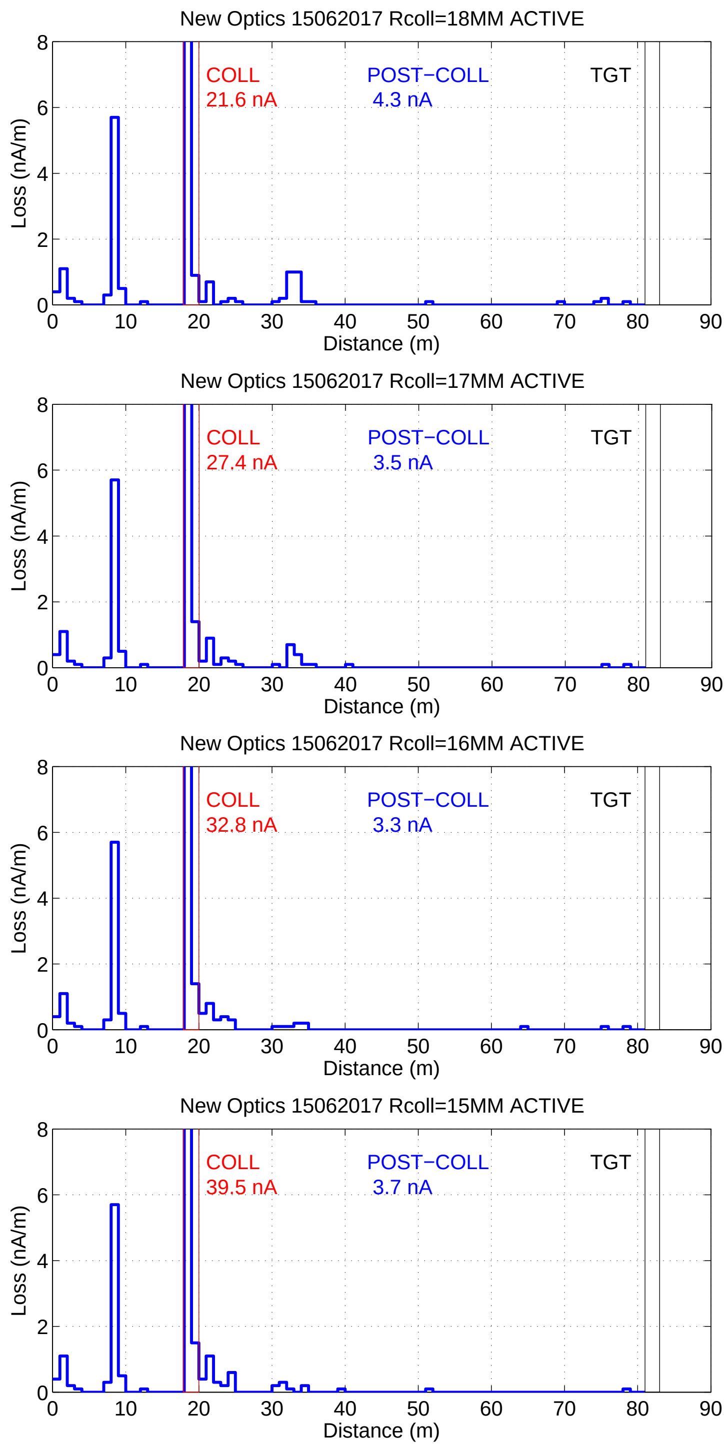

Figure 6: Effect of proton scattering in collimator and vacuum chamber walls, with successive reductions of the collimator radius.

These loss patterns are very similar to those of the previous configuration (see Figure 7, R=16mm) with losses of ∼1nA/m inside Q5 which extends from 21.387 to 21.587 meters, and with comparable losses further downstream, in particular in and around the dipole B10, which extends from 32.351 to 34.254 meters.

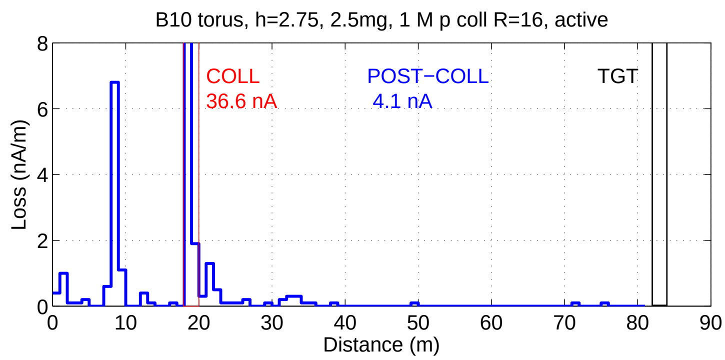

Figure 7: Effect of proton scattering in the previous optics, at optimal collimator radius (16mm).

In general, somewhat better loss control is achieved with the new optics, particularly in the Q5 region, although the losses there are still only marginally acceptable.

6 Long Collimator

In the beam line design the collimator is located in the 5.4 meter long drift space between quadrupoles Q4 and Q5, which it will share with BPMs and wire scanners located fore and aft of the collimator. There is approximately 3.3 meters of space to accommodate the collimator and its supporting apparatus. The proposed core length of 0.8m (0.2m taper + 0.6m cylinder) is sufficient (just) to achieve the specified loss control throughout the rest of the beam line, and would appear to allow considerable margins for the rest of the collimator assembly.

At this point, the engineering constraints have not been determined completely, and it is potentially useful to measure the benefits of having a longer cylindrical section, in case this can be implemented. To clearly show the effect the cylinder length has been increased to 1 meter, for a total collimator length of 1.2 meters.

In Figure 8 are seen the loss profiles with the same collimator radii as shown in Figure 6 for the 0.6m collimator.

In comparison with the shorter collimator the long collimator shows significantly improved loss control through the range of radii, with the optimal radius being the same at 16mm.

In this context of point-to-parallel optics and single-stage collimation, the added length is effective in cleaning up outscattered protons without itself contributing too much to the outscattering.

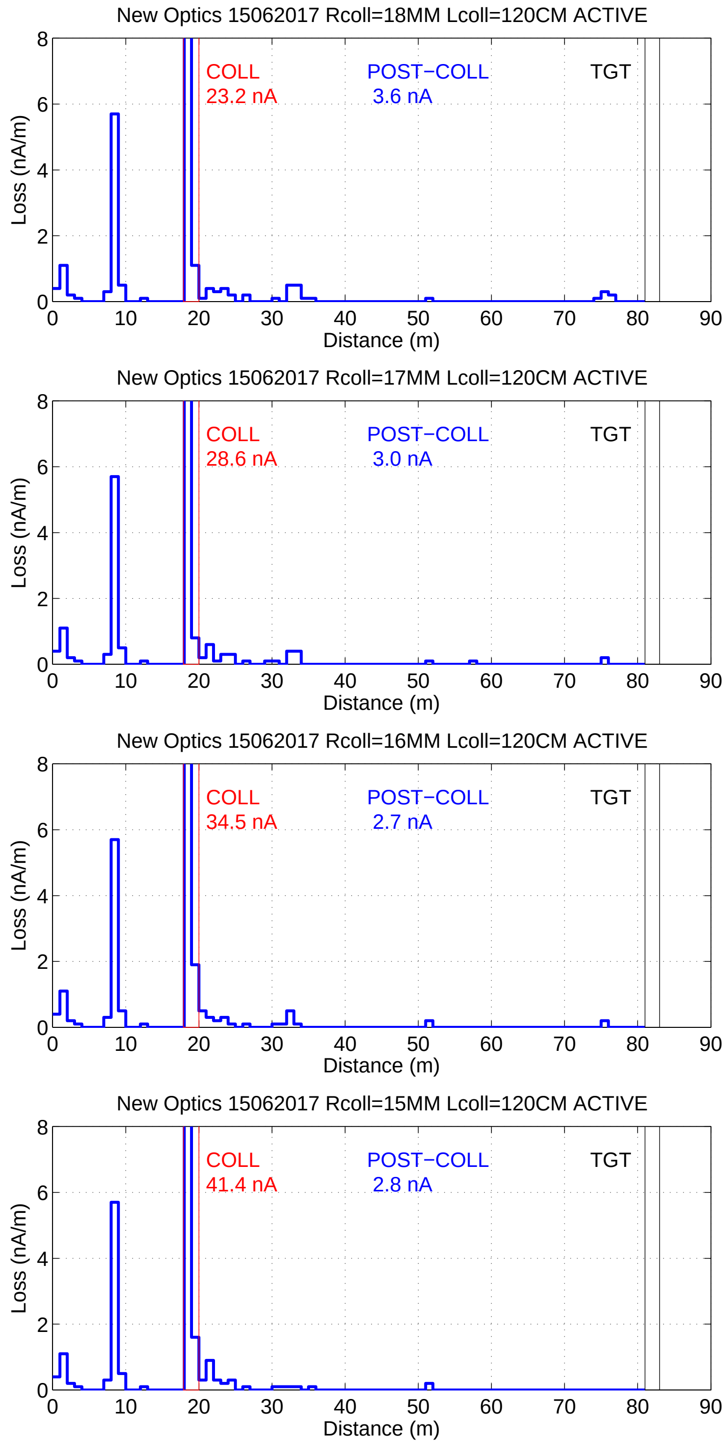

Figure 8: Effect of proton scattering in collimator and vacuum chamber walls, with successive reductions of the collimator radius, for a 1.2m long collimator.

7 Optimal Collimation

In a comprehensive series of runs, the 80cm and 120cm collimator performances have been evaluated over a range of aperture radii, as shown in Figure 9. These runs were performed with 10^6 protons, with proton scattering enabled. The plots show there is some latitude in the choice

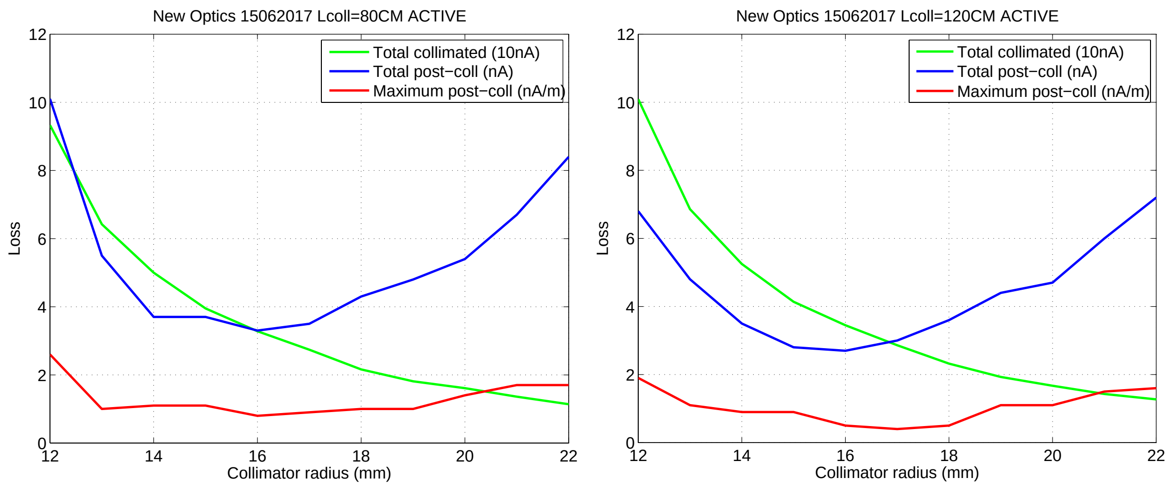

Figure 9: Loss control performance of 80cm (left) and 120cm (right) collimators as a function of aperture radius.

of radius. Favourable results, where peak losses do not exceed 1nA/m, are found roughly in the range of 15–18mm. In view of the limitations and uncertainties of the G4Beamline model, the additional criterion of minimizing the *total losses* between collimator and target seems like a good one to adopt, in which case the *optimal collimation* radius is seen to be ∼16mm for both collimator lengths.

8 Location of Beam Halo Monitors

Although BL4N is well provided with BPMs and wire scanners, an additional diagnostic in aid of successful collimation would be the placement of "halo monitors" at strategic locations in the beam line. These would be of similar construction to the protect monitor mounted at the front end of the collimator, and give sensitive indications of the beam centering and the presence of halo particles. To identify useful monitor locations, Figure 10 shows the persistence of losses in three locations, over a sub-optimal range of collimation, from radius 22mm down to 18mm, as follows:

1. 21–22 meters: Q5 region (Q5 at 21.357m). Halo monitor placement either immediately before Q5 or between Q5 and Q6.

2. 32–36 meters: B10 region (B10 at 32.351–34.255m). Halo monitor placement immediately before B10.

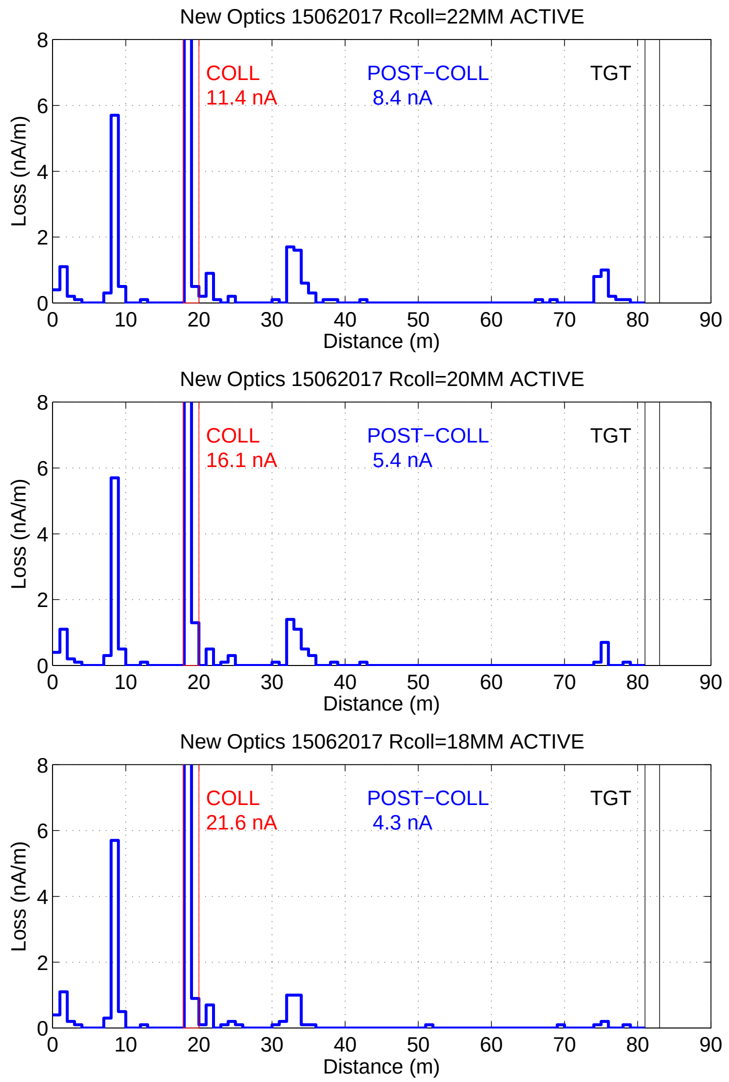

Figure 10: Losses when collimator radius is higher than optimal.

3. 74–76 meters: Q29–Q30 region (Q29 at 75.060m and Q30 at 75.886m). Halo monitor placement between Q29 and Q30, or immediately after Q30.

At the first location the loss due to outscattering from the collimator will be seen. The latter two locations are associated with large RMS beam sizes, seen most clearly in Figure 2. In the G4Beamline model, these are the most promising locations for a minimal set of halo monitors.

8.1 Tolerance of beam tuning errors

In the G4Beamline model, in each run the dipoles are successively tuned to achieve a high degree of beam centering, within ± 0.25 mm throughout the beam line.

In these simulations there are no significant built-in errors, in the sense that the magnetic elements are perfectly aligned with the geometric axis and the fields are assumed to have no intrinsic errors. The collimator itself is also perfectly aligned. It is assumed that these kinds of errors will be small compared to errors in beam size and beam steering that may arise during operation. Given the extensive complement of steerers and diagnostics in the beam line, these errors may also be expected to be small, but it is important to evaluate the collimation system in terms of how much headroom there is in respect of such errors.

Due to the size of the parameter space it is not practical to introduce errors in the model by, say, putting in steering magnets and mis-adjusting them, or by detuning quadrupoles, which would induce downstream effects and require further adjustments to create a realistic scenario. However, first order estimates of error tolerances can be obtained by manipulating the collimator itself.

Given accurate centering, an error in the beam size is roughly equivalent to an error in the collimator radius, and the tolerance for this can be seen directly from Figure /ref(fig-bl4ncoll) in the preceding section, to be about $\pm$3mm for both collimator lengths.

With regard to centering (steering) errors, these can be characterized by the beam being off-center in X and/or Y at one or both of BPM4A and BPM4B which are positioned in the drifts before and after the collimator, respectively. Any such errors can be simulated by one or both of the following manipulations of the collimator, which are easily done in G4Beamline:

1. A parallel offset of the collimator from the reference axis in X and/or Y.
2. A rotation of the collimator around its X and/or Y axes, thus tilting it with respect to the reference axis.

Due to the cylindrical symmetry of the collimator, the “worst case” scenarios are with errors being equal in X and Y, giving the maximum parallel deviation, and with errors being equal in X and Y but of the opposite sign at the two BPMs, giving the maximum tilt. Thus we have determined the error tolerance by running these cases, as well as isolated errors in the X and Y planes, in 1mm error increments. The BPMs are 4.06 meters apart, so a tilt error for $\pm$1mm in the X or Y plane is equivalent to a rotation of the collimator of 0.02865 degrees around the Y or X axis, respectively.

The error tolerances for parallel offset, tilt, and combined offset and tilt are shown in Table 4, for the 80cm and 120cm collimators, at the “optimum” collimator radius of 16mm (see Figure 9). These are the maximum errors for which the peak losses remain consistently below 1nA/m throughout the beam line.

For both collimator lengths, an offset component of the net steering error is better tolerated than a tilt component. One might expect that a longer collimator would be more sensitive than the shorter one to given steering errors at BPM4A and 4B, owing to increased proton interception, however the runs indicated that increased length also provided increased clean-up of outscattered protons, as in the case of no errors.

The 16mm radius used in these tests gives the most stringent control of both peak and total losses, as shown in Figure 9. In a more conservative design, steering error tolerance could be increased by making the collimator radius larger, using the small headroom of 1-2mm that is available within the acceptable-loss range of acceptable losses. For example, Figure 11 shows

Table 4: Steering error tolerances (millimeters) at BPM4A and BPM4B, for collimators of radius 16mm.

Collimator length	80cm	120cm
Offset X	2	5
Offset Y	2	2
Offset X and Y	2+2	3+3
Rotation X	0.5	4
Rotation Y	1	3
Rotation X and Y	1+1	1+1
Rotation+Offset X and Y	0.5+0.5	1+1

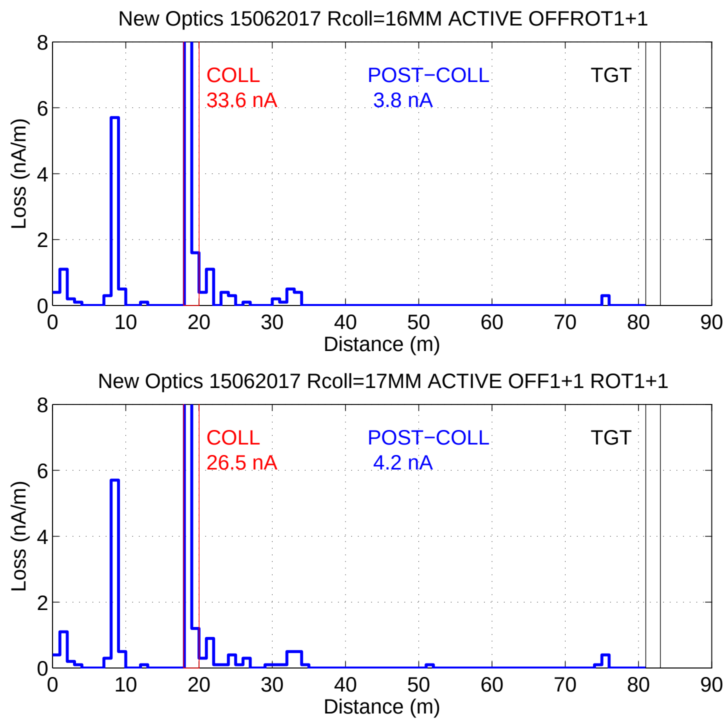

Figure 11: Effect of increased collimator radius on steering-error losses.

the remedial effect of increasing the radius to 17mm in the presence of 1+1mm tilt and offset errors in both X and Y planes.

9 Conclusions

The G4Beamline model has been updated to reflect the specific assignments of quadrupole types, the specification of beam pipe dimensions, and a light re-tuning of the optics. With the new quadrupole strengths plugged in to the model, the RMS beam sizes are in good agreement with those calculated by Transoptr.

As in the previous study, loss control at acceptable levels could be achieved in a single stage collimator which imposes a radical aperture reduction to about 1/3 of the size of the beam pipe. High-precision beam tuning and centering (within 1–2mm tolerances) will be required to maintain low-loss operation.

There is a clear benefit to using the longest collimator that can be accommodated with the space and shielding constraints, preferable 1.2 meters or greater. This helps to reduce losses just downstream from the collimator, in and around Q5, and also increases the tolerance to beam steering errors.

The scattering model and G4beamline model employed here are of course subject to systematic and statistical uncertainties. Beam experiments without a collimator will be essential to validate the models and to calibrate the beam fractions in the tails, which are a determining factor in the absolute loss values coming out of the simulations. The collimator aperture radius is a critical parameter, with rather small margins between success and failure to achieve loss control. It may be possible to gain more flexibility by a process of fine-tuning the beam to best adapt it to a given collimator radius. This should be investigated at the beam optics level, and followed by further simulations if needed.

References

[1] F.W. Jones, Proton Collimation in Beam Line 4-North (BL4N), TRIUMF Beam Physics Note TRI-BN-16-15 (Revised 2017).

[2] Y.N. Rao and R. Baartman, Beam Line 4 North (BL4N) Optics Design, TRIUMF Design Note TRI-DN-13-13 (Revised 2015).

[3] Y.N. Rao, Requirement Specification for BL4N Machine Protection System, TRIUMF Beam Physics Note TRI-BN-16-BL4N-MPS (2016).

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

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

[6] R. Baartman, TRANSOPTR, TRIUMF Beam Physics Note TRI-BN-16-06 (2016).

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

Appendix: BL4N beam line definition

```
* Beam Line 4N  F.W. Jones TRIUMF
*  +++  VERSION 2 based on new quadrupole layout,  +++
*  +++  vacuum chamber dimensions, and optics.     +++
*  +++  JUNE 2017                                  +++
*
*  LAYOUT based on TRANSOPTR 15-JUN-2017
*       ALL fringe fields
*       Beam generated by COMA
*       FOIL to CYCFF exit pre-tracked by ACCSIM
*  QUADRUPOLE settings from TRANSOPTR data.22
*
*  +++  4 INCH APERTURE TO END OF Q14  +++

physics QGSP_BIC doStochastics=1

##### NO SECONDARIES #####
trackcuts killSecondaries=1

# Mean P from REVMOC at cyclotron FF exit.
# Run using Accsim-foil-scattered rays
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

# Torus 4 inch outer diameter
#param oheightVB4=4*25.4
#param hchordVB4=$LVB4/2
#param radiusVB4=$hchordVB4/sin(0.5*24.8126*pi/180)
#param sagVB4=$radiusVB4-sqrt($radiusVB4*$radiusVB4-$hchordVB4*$hchordVB4)
#torus pipe-VB4 innerRadius=$oheightVB4/2-4 outerRadius=$oheightVB4/2 \
#      majorRadius=$radiusVB4 initialPhi=-24.8126/2 finalPhi=24.8126/2 \
#      material=Vacuum  color=.2,.2,.2,.9
## Magnet is rotated to give edge angle so must rotate chamber
#place pipe-VB4 parent=VB4 x=$radiusVB4-$sagVB4 rotation=X+90,Z+180,Y-7.5937

# 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=3*25.4 fieldLength=$LB610 \
        fringeFactor=0.2 \
   ironColor=1,0,0 ironWidth=1000 ironHeight=1000 ironLength=$LB610

# Torus 2.87 inch inner diameter and 0.065 inch wall thickness
param iheightB610=2.87*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=$iheightB610/2+0.065*25.4 \
      majorRadius=$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=82080 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 2.87 inch inner diameter and 0.065 inch wall thickness
param iheightB2226=2.87*25.4
param hchordB2226=$LB2226/2
param radiusB2226=$hchordB2226/sin(17*pi/180)
param sagB2226=$radiusB2226-sqrt($radiusB2226*$radiusB2226-$hchordB2226*$hchordB2
```

```
torus pipe-B2226 innerRadius=$iheightB2226/2 \
      outerRadius=$iheightB2226/2+0.065*25.4 \
      majorRadius=$radiusB2226 initialPhi=-17 finalPhi=17 \
      material=ss  color=.2,.2,.2,.9
place pipe-B2226 parent=B2226 x=-$radiusB2226+$sagB2226 rotation=x+90

# 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

param LQ14s8=406.4
genericquad Q14s8 fieldLength=$LQ14s8 ironLength=$LQ14s8 \
      apertureRadius=25.4*4.06/2 ironRadius=914.4/2 \
      ironColor=0,.6,0 fringe=0
param LQ19s8=526.542
genericquad Q19s8 fieldLength=$LQ19s8 ironLength=$LQ19s8 \
      apertureRadius=25.4*4.06/2 ironRadius=914.4/2 \
      ironColor=0,.6,0 fringe=0
param LFQ10s3p6=260.35
genericquad FQ10s3p6 fieldLength=$LFQ10s3p6 ironLength=$LFQ10s3p6 \
            apertureRadius=108/2 ironRadius=914.4/2 \
            ironColor=0,.6,0 fringe=0
param LFQ8p5s8p5=261.8
genericquad FQ8p5s8p5 fieldLength=$LFQ8p5s8p5 ironLength=$LFQ8p5s8p5 \
             apertureRadius=25.4*4.06/2 ironRadius=914.4/2 \
             ironColor=0,.6,0 fringe=0
param LKEK=459.4
genericquad KEK fieldLength=$LKEK ironLength=$LKEK \
            apertureRadius=110/2 ironRadius=914.4/2 \
            ironColor=0,.6,0 fringe=0
param LDanFysikaL5=205.5
genericquad DanFysikaL5 fieldLength=$LDanFysikaL5 ironLength=$LDanFysikaL5 \
             apertureRadius=71/2 ironRadius=914.4/2 \
             ironColor=0,.6,0 fringe=0
param LTUDAS=296.672
genericquad TUDAS fieldLength=$LTUDAS ironLength=$LTUDAS \
             apertureRadius=85/2 ironRadius=914.4/2 \
             ironColor=0,.6,0 fringe=0
param LFQ12s6=357.124
genericquad FQ12s6 fieldLength=$LFQ12s6 ironLength=$LFQ12s6 \
            apertureRadius=25.4*4.08/2 ironRadius=914.4/2 \
            ironColor=0,.6,0 fringe=0

tubs pipe-B10-BPM14 innerRadius=48.7 outerRadius=50.8 length=42145-34255 \
```

```
        material=ss  color=.2,.2,.2,.9
# New Optics: Three quad types from here to B22
# KEK quads
tubs pipe-BPM14-Q17 innerRadius=50 outerRadius=52.5 length=51211-42145 \
        material=ss  color=.2,.2,.2,.9
# DanFysika quads
tubs pipe-Q17-Q20 innerRadius=34 outerRadius=35 \
     length=57936+$LDanFysikaL5-51211 \
     material=ss  color=.2,.2,.2,.9
# TUDA-S quads
tubs pipe-Q20-B22 innerRadius=40 outerRadius=41.5 \
     length=63441-(57936+$LDanFysikaL5) \
     material=ss  color=.2,.2,.2,.9

tubs pipe-B22-B26 innerRadius=40 outerRadius=41.5 length=69019-64879 \
        material=ss  color=.2,.2,.2,.9

# New Optics now large quads here
tubs pipe-B26-ATW innerRadius=48.7 outerRadius=50.8 length=81383-70458 \
        material=ss  color=.2,.2,.2,.9

# COL with TAPER and STRAIGHT section
# Cf REVMOC COLLN COLX
# RAP1 is inner radius of 4" pipe
param RAP1=48.7 RAP2=16
#param RAP1=48.7 RAP2=20.8
param LTAPER=200
#param LTAPER=500
extrusion COL1 length=$LTAPER \
   vertices=1.000000,-0.000000;0.866025,-0.500000;0.500000,-0.866025;0.000000,-1.0
   scale1=$RAP1 scale2=$RAP2 material=Vacuum color=0,0,1,.9
param LCOL2=600
#param LCOL2=200
#param LCOL2=500
tubs COL2 length=$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
# Q5 and Q6 HERA quads w 105mm OD pipe
```

```
tubs pipe-COLL-B6 innerRadius=50 outerRadius=52.5 \
     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 kill=1

# DETECTORS...

# Placeholder for beam spill monitors


#-------------------------------------------------------------
# LAYOUT
# Beamline definition in centerline (the default) coordinates
# S-values are taken directly from TRANSOPTR data.1
#-------------------------------------------------------------

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

# VAULT magnets ...

# S-values from TRANSOPTR replacing those from REVMOC
#    (where different)
# Gradients directly from TRANSOPTR data.22

param S=485
place Q14s8 rename=VQ1 front=1 z=$S gradient=-9.53286

param S=1284
place Q14s8 rename=VQ2 front=1 z=$S gradient=14.9544

param S=3432.9
place Q19s8 rename=VQ3 front=1 z=$S gradient=15.5670

param S=4280.2
place Q14s8 rename=VQ4 front=1 z=$S gradient=-11.6592

param S=5580.4
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

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

param S=7855.8
```

```
place Q14s8 rename=VQ5 front=1 z=$S gradient=9.64140

param S=8692.2
place Q14s8 rename=VQ6 front=1 z=$S gradient=-10.1008

# Foil image
param S=10189

# Tunnel WEST ...

param S=11869
place Q14s8 rename=Q1 front=1 z=$S gradient=-2.68657

param S=12705
place Q14s8 rename=Q2 front=1 z=$S gradient=5.38283

param S=15081
place Q14s8 rename=Q3 front=1 z=$S gradient=2.39969

param S=15898
place Q14s8 rename=Q4 front=1 z=$S gradient=-4.56096

# 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=21357
place FQ10s3p6 rename=Q5 front=1 z=$S gradient=-0.174155

param S=22007
place FQ10s3p6 rename=Q6 front=1 z=$S gradient=2.00834

param S=22907
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

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

param S=25528
place Q14s8 rename=Q7 front=1 z=$S gradient=-2.67106
```

```
param S=26178
place Q14s8 rename=Q8 front=1 z=$S gradient=5.05137

param S=30578
place Q14s8 rename=Q9 front=1 z=$S gradient=5.05137

param S=31228
place Q14s8 rename=Q10 front=1 z=$S gradient=-2.67106

param S=32351
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

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

param S=34929
place FQ8p5s8p5 rename=Q11 front=1 z=$S gradient=7.00911

param S=35579
place FQ8p5s8p5 rename=Q12 front=1 z=$S gradient=-5.22194

param S=38967
place FQ8p5s8p5 rename=Q13 front=1 z=$S gradient=4.70440

param S=39567
place FQ8p5s8p5 rename=Q14 front=1 z=$S gradient=-4.81876

# BPM14 TRANSITION TO KEK quad 100 mm APERTURE
param S=42145
place pipe-BPM14-Q17 front=1 z=$S

param S=44959
place KEK rename=Q15 front=1 z=$S gradient=6.95273

param S=45559
place KEK rename=Q16 front=1 z=$S gradient=-6.33455

param S=51211

place pipe-Q17-Q20 front=1 z=$S

place DanFysikaL5 rename=Q17 front=1 z=$S gradient=14.3403

param S=51811
place DanFysikaL5 rename=Q18 front=1 z=$S gradient=-14.3403
```

```
param S=57336
place DanFysikaL5 rename=Q19 front=1 z=$S gradient=14.3403

param S=57936
place DanFysikaL5 rename=Q20 front=1 z=$S gradient=-14.3403

place pipe-Q20-B22 front=1 z=$S+$LDanFysikaL5

param S=61752
place TUDAS rename=Q21 front=1 z=$S gradient=-4.59592

param S=62352
place TUDAS rename=Q22 front=1 z=$S gradient=13.3595

param S=63441
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

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

param S=65544
place TUDAS rename=Q23 front=1 z=$S gradient=-9.70485

param S=66044
place TUDAS rename=Q24 front=1 z=$S gradient=10.7803

param S=67544
place TUDAS rename=Q25 front=1 z=$S gradient=10.7803

param S=68044
place TUDAS rename=Q26 front=1 z=$S gradient=-9.70485

param S=69006
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

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

param S=71386
place FQ8p5s8p5 rename=Q27 front=1 z=$S gradient=11.1998

param S=72145
place FQ12s6 rename=Q28 front=1 z=$S gradient=-9.90428

param S=74881
```

```
place FQ12s6 rename=Q29 front=1 z=$S gradient=8.41439

param S=75688
place FQ12s6 rename=Q30 front=1 z=$S gradient=-8.31017

# RASTER MAGNET
param S=76803

# ARIEL TARGET WEST

param S=82083
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"
```