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BL2A Simulation Model in G4Beamline

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Abstract: This report documents the G4Beamline model that has been developed for Beam Line 2A, incorporating its magnetic components, field strengths, and layout in a 3D geometry setting. The origin and pre-processing of beam data for input to G4Beamline is also documented.

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1 Introduction

Beam line 2A (BL2A) transports up to 80 μA of 480 MeV protons from the TRIUMF cyclotron to ISOL targets located in the ISAC rare isotope facility. Due to scattering in the cyclotron extraction foil and other factors, there are beam losses in BL2A. Although these losses have generally been kept within the limits required, there is evidence of activation and radiation damage in some areas. The simulation code REVMOC has been the reference code for estimating losses in this and the other TRIUMF beam lines, and has played an important role in their design and operation. The limitations of REVMOC and the availability of Geant4-based beam line simulations has prompted this development of a new BL2A model using the G4Beamline code, which due to its fully 3D geometry, as well as advanced scattering and energy loss treatments, provides more accurate and detailed estimates of losses (and their consequences) than REVMOC. There is also the potential for more advanced simulations, e.g. related to the BL2A target modules, that go beyond the scope of REVMOC.

This report also documents the origin and pre-processing of the beam data that is used in the G4Beamline application. This involves the TRIUMF codes COMA and ACCSIM, as well as some small data conversion programs.

A single input file is used in G4Beamline to specify beam and field inputs, the beam line component and geometry definitions, and all the run steering and output mechanisms. The Appendix to this report contains an annotated listing of the complete input file for BL2A.

2 Reference Run and Its Components

In conjunction with this document a set of "reference run" files has been created. This comprises a complete set of input and output files for the most recent and fully realised BL2A model, as well as the data sets and conversions involved in preparing beam data for G4Beamline. The Reference Run is intended to be self-contained and reproducible.

Here are the roles of the codes used in the reference run.

COMA	Provides beam (multiparticle) data at the extraction foil. The vertical data (y, P_y) are not used.
co4accsim	Converts COMA beam data for input to ACCSIM
ACCSIM (Run A)	Tracks the COMA beam through the extraction foil and the cyclotron fringe field and produces a BLNtuple file for input to G4Beamline. Only the (x, P_x, z, P_z) data will be used.
ACCSIM (Run B)	Tracks a self-generated beam, defined by emittance and twiss parameters, through the extraction foil and the cyclotron fringe field and produces a BLNTuple file for input to G4Beamline. Only the (y, P_y) data will be used.
merge2accsim	Merges the BLNTuple files produced by ACCSIM Run A and Run B, selecting coordinates as above, into a single BLNTuple file.
G4Beamline	Using the merged BLNTuple file, tracks from the combination magnet entrance through to the West ISAC target.

The reason for the dual ACCSIM runs and coordinate merging described above is that the accuracy of the vertical tune in COMA is limited by the near-cancellation of defocusing and focusing effects due to the rising isochronous field and the large spiral angle, respectively. However, the vertical emittance and Twiss parameters of the beam at the extraction foil have been measured and a distribution having these properties can be readily generated in ACCSIM. Moreover, ACCSIM has an accurate iterated single-scatter model for the passage through the extraction foil, comparable to what is available in G4Beamline. Finally, the "fringe field" of the cyclotron (from the foil to the combination magnet entrance) has no straightforward implementation in G4Beamline, but can be easily represented in ACCSIM as a rotated dipole. In summary, the pre-processing consists of COMA as (horizontal) beam generator, as (vertical) beam generator and tracker.

Now we are in a position to describe each file in the Reference Run.

`coma/Coma_coords-ORIG.dat` Output from a COMA run for the cyclotron, giving beam at the BL2A extraction foil.

`coma/co4accsim.f` Converts `Coma_coords-ORIG.dat` to `fort.4` for input to ACCSIM

`accsim/prep-coma-foil/bl2a.com` Main input file for ACCSIM run, using beam from `fort.4` above.

`accsim/prep-coma-foil/fort.81` Output from the ACCSIM run, in BLNTuple format suitable for input to G4Beamline.

`accsim/prep-newtwiss-foil/bl2a.com` Input file for ACCSIM run, with beam internally generated using emittance, twiss parameters, and distribution shape.

`accsim/prep-newtwiss-foil/fort.81` Output from the ACCSIM run, in BLNTuple format suitable for input to G4Beamline.

`accsim/prep-merge-foil/merge2accsiim.f` Merges the two `fort.81` files into a single one.

`bl2a.in` G4Beamline input file for BL2A, specifying the merged `fort.81` as the starting beam.

`bl2a.log` Output to the terminal during the G4Beamline run, including input and derived parameters, the layout process, the tracking process, and names of output files.

3 G4Beamline Input File

Most of the input data for BL2A was derived from a TRANSOPTR run. Initially there was some confusion about different TRANSOPTR runs provided, which did not agree with each other and did not represent the actual operating tune, but eventually a definitive run of the Standard Operational Tune was identified. Some output files from this run, originally received in August 2009, can be found in `reference/transoptr/` Unfortunately the complete set of the files for this run cannot be located. The TRANSOPTR data is used as follows:

`bl2a.1` Element lengths and positions in the layout. The foil scattering effect on the RMS beam sizes is included via the `addscatter` element in TRANSOPTR.

`bl2a-unscattered.1` Element lengths and positions in the layout. To facilitate optical comparison the `addscatter` element is omitted.

`bl2a.8` The beam line in TRANSPORT notation, used to obtain the Quadrupole pole-tip field values, converted to gradients in `bl2a.in` by the scale factor `qsf`. All quads have the same pole half-gap of 5.159 cm.

`bl2a.f` (missing) Beam line definition subroutine, used to obtain bend parameters and derive the nominal field strengths of the dipoles.

`bl2a.11` Beam envelope (2 times RMS) data for plotting.

`bl2a-EDIT.11` Measured envelope data has been added.

The initial TRANSOPTR and G4Beamline runs were configured for the beam path to the East ISAC target. Later, the simulation was switched to the West target and the geometry was extended with a vacuum window and target module. This required changing the sense of B3 and B4 and new settings for Q13 and Q14, as will be seen in `bl2a.in`.

For future reference, a newer complete TRANSOPTR run, reflecting an updated Standard Operational Tune, is found in `reference/transoptr-7mmProductionTune/`. This tune has not been implemented in G4Beamline.

4 Tuning and Beam Envelopes

Using the initially on-axis reference particle at the nominal momentum, the dipoles were hand-tuned to obtain horizontal centering within 1 mm throughout the beam line. In adjusting the optics to best agree with TRANSOPTR, the `fringeFactor` for all dipoles was set to 0.5 and for quadrupoles it was set to 0.1. The quadrupole strengths acquired from TRANSOPTR did not require further adjustment to obtain acceptable agreement between the two codes and measured data for the beam envelopes, as shown in Figure 1.

5 ACCSIM Halo Beam

One of the objectives of the BL2A simulation was to see if foil scattering, which was responsible for considerable initial proton losses in the vault section of the beam line, was also giving rise to smaller "distributed losses" that extended far down the beam line. No such losses were observed with the default multiple scattering treatment in ACCSIM, so we used ACCSIM's single-scatter model for the foil and additionally introduced a cut in the total scattering angle of 3 milliradians, thus producing a "halo beam" which would improve the loss statistics.

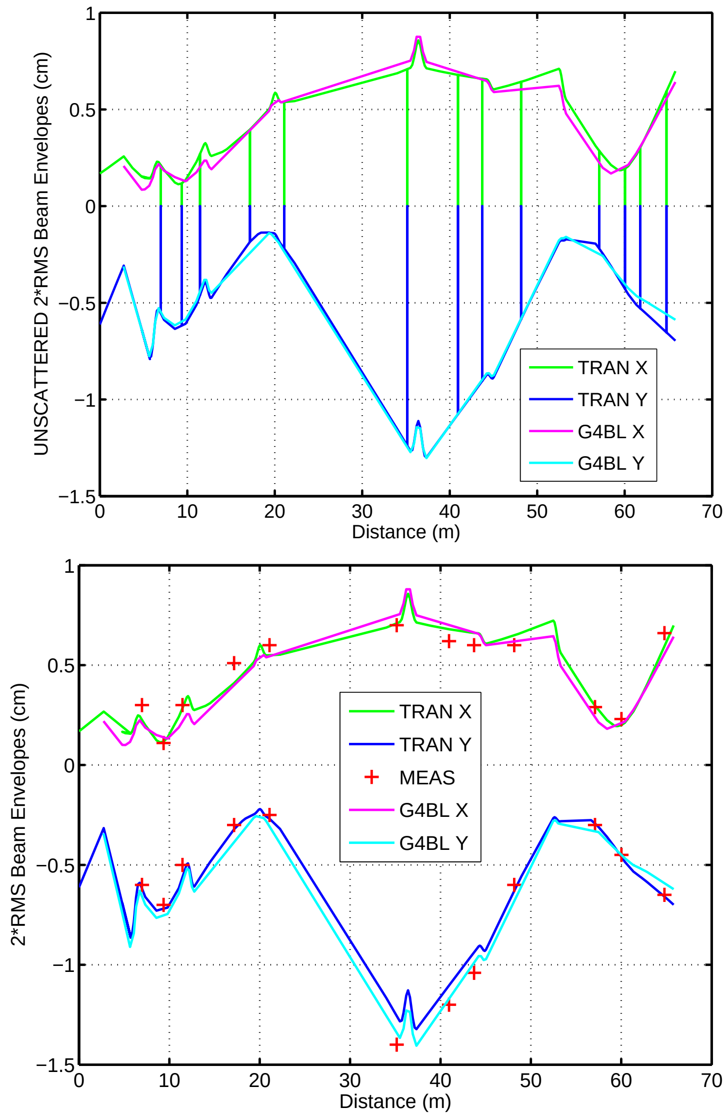

Figure 1: RMS beam envelopes of Transoptr and G4Beamline. The top plot is without foil scattering. The bottom plot is with foil scattering and includes measured beam sizes.

At this time new initial beam parameters were available from experiments and measurements in BL2A, enabling the complete initial beam data to be generated in ACCSIM.

The reader is referred to our ICAP09 paper [4] for the results of this study.

Later, it was revealed that I had not been provided with complete information about BL2A. There was an aperture restriction in the beam line that I had not been aware of: the vacuum chamber of the switching magnet B3, originally specified as 4 inches in height, was in fact only 3 inches high. This of course would lead to significant proton losses at B3. I therefore reduced the height of this vacuum chamber and added a “reduction flange” in front of it to make the transition from 4 to 3 inches. A reference run for the halo beam with the corrected aperture at B3 is here:

`reference-halo/`

and files are as follows:

`accsim/bl2a.com` ACCSIM input file for generating halo beam with 3 milliradian cut (parameter `THETCUT`)

`accsim/fort.81.halo3mr.100k` ACCSIM output file in BLNTuple format for use in G4Beamline

`bl2a.in` G4Beamline input file for BL2A, specifying the ACCSIM halo beam as the starting beam.

`bl2a.log` Output to the terminal during the G4Beamline run, including input and derived parameters, the layout process, the tracking process, and names of output files.

`B3D1.txt` BLNTuple file for a virtual detector placed at the entrance to B3.

6 Future Applications

The BL2A simulation study confirmed that large-angle scattering in the cyclotron extraction foil leads to proton losses far downstream. The 3 inch aperture limitation at the Y magnet B3 and resulting higher fluxes of gammas and neutrons may be a factor in the radiation damage seen just upstream of this magnet.

6.1 Beam spill monitors

Virtual detectors of the approximate size and location of the beam spill monitors were included in the geometry, but even with the halo beam, spill rates were far too small to give a statistical estimate of the signals in the BSMs, which intercept only a very small fraction of secondary charged particles. In particular, any shadowing effects in the beam line geometry cannot be investigated. With faster computers and/or the use of biasing techniques this could become possible.

6.2 Validation by controlled spills

In G4Beamline it is easy to simulate controlled spills by manipulating magnetic elements in the beam line. In conjunction with real beam experiments this could be a way to further validate and hopefully gain confidence in the BL2A model.

6.3 Loss mitigation

The simulation does not reveal any single “quick fix” that could dramatically reduce beam loss, other than the usual expedient of reducing the foil thickness. In the event of a beam line upgrade, the sensitivity of losses to various design and tuning changes could be investigated.

References

[1] F.W. Jones, Development of the ACCSIM Tracking and Simulation Code, IEEE PAC97, Vancouver, 1997.
`http://accelconf.web.cern.ch/accelconf/pac97/papers/pdf/8P097.PDF`

[2] T.J. Roberts et al., Particle Tracking in Matter-Dominated Beam Lines, IPAC10, Kyoto, 2010.
`http://accelconf.web.cern.ch/AccelConf/IPAC10/papers/tupec063.pdf`
`http://g4beamline.muonsinc.com/`

[3] R. Baartman, TRANSOPTR: Changes since 1984, TRIUMF Beam Physics Note TRI-BN-16-06 (2016).
`http://lin12.triumf.ca/text/design_notes/b2016_06`

[4] F.W. Jones, R. Baartman, and Y.N. Rao, Using Geant4-Based Tools to Simulate a Proton Extraction and Transfer Line, ICAP09, San Francisco, 2009.
`http://accelconf.web.cern.ch/AccelConf/ICAP2009/papers/th3iopk04.pdf`

Appendix: BL2A beam line definition

```
* Beam Line 2A  F.W. Jones TRIUMF
*  BEND parameters from original TRANSOPTR run instead of TRANSPORT.
*  DIPOLE FIELDS calculated using Geant4 constants.
*       Dipoles tweaked for centering
*       ALL fringe fields
*       Beam generated by ACCSIM
*       FOIL and cyclotron fringe field pre-tracked by ACCSIM
*  QUADRUPOLE settings from Yi-Nong's STANDARD OPERATING TUNE
*       Q13/114 adjusted for beam spot on WEST target.

physics QGSP_BIC

param -unset pMomentumRef=1090.0790384187

# BEAM.....

# Distribution file generated by ACCSIM
beam ascii filename=fort.81 beamZ=2716 nEvents=$nEvents

# Calibration file w/single proton and PMomentumRef
#beam ascii filename=fort.81.calib 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=2716 \
   beamX=0 beamXp=0 beamY=0 beamYp=0

# MATERIALS.....

param worldMaterial=Vacuum
particlecolor proton=1,0,0 pi+=0,1,0 mu+=0,0,1 plus=1,0,1 minus=1,1,0 \
        neutral=0,1,1 reference=0,0,1

# 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.
```

```
# COMBINATION MAGNET for tuning, currently not powered

# Bend g/2=5.08cm L=0.3516m nominal B=1.2452kG
genericbend CM1 fieldWidth=1000 fieldHeight=101.6 fieldLength=351.6 \
             By=0.19*0.0 fringe=1 kill=1 fringeFactor=0.5 \
ironColor=1,0,0 ironWidth=1000 ironHeight=1000 ironLength=351.6


# DIPOLES.....

# Prototype for B1 and B2
# Bend g/2=5.08cm L=1.2479m B=-13.9851kG
# Tweaked for centering
genericbend B12 fieldWidth=1000 fieldHeight=102 fieldLength=1235.9666 \
        By=-1.398504723633193*1.00015 fringe=1 kill=0 fringeFactor=0.5 \
   ironColor=1,0,0 ironWidth=1000 ironHeight=1000 ironLength=1235.9666

# Prototype for B3 and B4
# Bend g/2=5.08cm L=0.9425m B=10.1003kG
# NOW REVERSED FOR WEST TARGET
genericbend B34 fieldWidth=1000 fieldHeight=102 fieldLength=939.78858 \
            By=-1.010031189290639*1.00004 fringe=1 kill=0 fringeFactor=0.5 \
   ironColor=1,0,0 ironWidth=1000 ironHeight=1000 ironLength=939.78858

tubs pipeCM1 innerRadius=50.8 outerRadius=52.8 length=351.6 \
        material=ss kill=1
tubs pipeB12 innerRadius=50.8 outerRadius=52.8 length=1235.9666 \
        material=ss kill=0
tubs pipeB34 innerRadius=50.8 outerRadius=52.8 length=939.78858 \
        material=ss kill=0


# QUADRUPOLES.....

# Scale factor to get Tesla/meter from pole tip field B0
# Half-gap for all quads is 5.159 cm
param qsf=1.9383601

genericquad QL fieldLength=406.4 apertureRadius=51.59 ironRadius=500 \
ironLength=406.4 ironColor=0,.6,0 fringe=1 kill=0 fringeFactor=0.1
genericquad QS fieldLength=261.8 apertureRadius=51.59 ironRadius=500 \
ironLength=261.8 ironColor=0,.6,0 fringe=1 kill=0 fringeFactor=0.1


# PIPES.....

# Beam pipe for straight section
tubs pipeSTRAIGHT innerRadius=50.8 outerRadius=52.8 length=57483.4-11041.556 \
```

```
        material=ss kill=0

tubs pipeCM1B1 innerRadius=50.8 outerRadius=52.8 \
        length=513.95+406.4+252.48+406.4+243.08+367.59 \
        material=ss kill=1

tubs pipeB1B2 innerRadius=50.8 outerRadius=52.8 length=389.31+387.35+446.46 \
        material=ss kill=0
tubs pipeB3B4 innerRadius=50.8 outerRadius=52.8 length=1603.77+368.82 \
        material=ss kill=0

# Shorten for window 47.94" c-c from target
param lenB4TARG=64590-61338.311
tubs pipeB4TARG innerRadius=50.8 outerRadius=52.8 \
        length=$lenB4TARG \
        material=ss kill=0


# WINDOW.....

# Window thickness in mm
param Wlength=0.1
box WINDOW width=200 height=200 length=$Wlength material=Al \
color=1,0,1


# PROTECT MONITOR.....
# Modelled as total thicknesses not interleaved

# Support layers total 0.180" (0.189 minus 0.009) thick
tubs PM1 innerRadius=0.5*1.5*25.4 outerRadius=3*25.4 \
     initialPhi=0 finalPhi=360 length=0.180*25.4 material=Al
# Signal and HT plates 0.009" total thickness
tubs PM2 innerRadius=0 outerRadius=3*25.4 \
     initialPhi=0 finalPhi=360 length=0.009*25.4 material=Al
# Aperture 0.006" deep (remainder is HT+Total+HT plates)
box PM2aper width=0.5*25.4 height=0.5*25.4 length=0.006*25.4 material=Vacuum


# COLLIMATOR.....

# Collimator size in mm
param Clength=6*25.4
# Radius of central bore
param RCbore=0.5*0.75*25.4
# These lengths are increased a bit to avoid gaps
# Length of central bore
param LCbore=2.39*25.4+1
# Length of tapers
```

```
param LCtaper1=2.38*25.4+1
param LCtaper2=1.23*25.4+1
# Max radius of tapers
param RCtaper=0.5*(1.0*25.4)

box COLL height=$Clength width=$Clength length=$Clength material=Cu  \
     color=0,1,0
tubs CBORE innerRadius=0 outerRadius=$RCbore initialPhi=0 finalPhi=360 \
     length=$LCbore material=Vacuum color=0,0,1
extrusion TAPER1 length=$LCtaper1 \
     vertices=1.000000,-0.000000;0.866025,-0.500000;0.500000,-0.866025; \
     0.000000,-1.000000;-0.500000,-0.866025;-0.866025,-0.500000; \
    -1.000000,-0.000000;-0.866025,0.500000;-0.500000,0.866025; \
    -0.000000,1.000000;0.500000,0.866025;0.866025,0.500000 \
     scale1=$RCtaper scale2=$RCbore material=Vacuum color=0,0,1
extrusion TAPER2 length=$LCtaper2 \
     vertices=1.000000,-0.000000;0.866025,-0.500000;0.500000,-0.866025; \
     0.000000,-1.000000;-0.500000,-0.866025;-0.866025,-0.500000; \
    -1.000000,-0.000000;-0.866025,0.500000;-0.500000,0.866025; \
    -0.000000,1.000000;0.500000,0.866025;0.866025,0.500000 \
     scale1=$RCbore scale2=$RCtaper material=Vacuum color=0,0,1


# TARGET.....

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


#-------------------------------------------------------------
# Beamline definition in centerline (the default) coordinates
#-------------------------------------------------------------

# Cyclotron exit
zntuple format=ascii z=2717 referenceParticle=1

# CM1 entrance
zntuple format=ascii z=4968-352/2 referenceParticle=1

# No corners because beamline goes straight through CM1!
place CM1 z=4968.8
place pipeCM1 z=4968.8


place QL rename=Q1 front=1 z=5658.6 gradient=$qsf*(-3.71160)

place QL rename=Q2 front=1 z=6317.5 gradient=$qsf*4.57723
```

```
place pipeCM1B1 front=1 z=4968.8+0.5*351.6

corner B1c1 z=7334.5 rotation=Y+13.75
place B12 rename=B1 z=7952.4782
place pipeB12 z=7952.4782
corner B1c2 z=8570.4563 rotation=Y+13.75

place pipeB1B2 z=0.5*(8570.4563+9805.6)

corner B2c1 z=9805.6 rotation=Y+13.75
place B12 rename=B2 z=10423.578
place pipeB12 z=10423.578
corner B2c2 z=11041.556 rotation=Y+13.75

place QS rename=Q3 front=1 z=11942.1 gradient=$qsf*5.517

place QS rename=Q4 front=1 z=12497.8 gradient=$qsf*(-3.84855)

place QS rename=Q5 front=1 z=19339.9 gradient=$qsf*(-1.45611)

place QS rename=Q6 front=1 z=19905.0 gradient=$qsf*3.25003

place QS rename=Q7 front=1 z=20457.5 gradient=$qsf*(-1.45611)

place QL rename=Q8 front=1 z=35510.4 gradient=$qsf*(-1.338)

place QL rename=Q9 front=1 z=36211.4 gradient=$qsf*2.519

place QL rename=Q10 front=1 z=36935.3 gradient=$qsf*(-1.386)

place QS rename=Q11 front=1 z=44223.0 gradient=$qsf*0.990

place QS rename=Q12 front=1 z=44775.4 gradient=$qsf*(-1.247)

# Add c200 Gs to correct beam spot for West side
place QS rename=Q13 front=1 z=52482.8 gradient=$qsf*(2.992+0.99)

place QS rename=Q14 front=1 z=53035.3 gradient=$qsf*(-2.492-1.4)

# Pipe for long straight
place pipeSTRAIGHT z=0.5*(11041.556+57483.4)

# NOW CORNERS REVERSED FOR WEST TARGET
corner B3c1 z=57483.4 rotation=Y+7.5
place B34 rename=B3 z=57953.305
place pipeB34 z=57953.305
corner B3c2 z=58423.211 rotation=Y+7.5
```

```
place pipeB3B4 z=0.5*(58423.211+60398.5)

# NOW CORNERS REVERSED FOR WEST TARGET
corner B4c1 z=60398.5 rotation=Y+7.5
place B34 rename=B4 z=60868.405
place pipeB34 z=60868.405
corner B4c2 z=61338.311 rotation=Y+7.5

zntuple format=ascii z=61339 referenceParticle=1
zntuple format=ascii z=61400 referenceParticle=1
zntuple format=ascii z=61500 referenceParticle=1

# Final doublet
place QS rename=Q15 front=1 z=62100.1 gradient=$qsf*0.00

place QS rename=Q16 front=1 z=62646.2 gradient=$qsf*0.00

place pipeB4TARG front=1 z=61338.311

# WINDOW placement corrected to 47.94" from center of target
zntuple format=ascii z=64591 referenceParticle=1
place WINDOW front=1 z=64592
zntuple format=ascii z=64593 referenceParticle=1

zntuple format=ascii z=65237-3*25.4-1 referenceParticle=1

# PROTECT MONITOR

# Support layer 0.180" thick
place PM1 front=1 z=65237-3*25.4-10
# HT + Signal plates layer 0.009" thick
place PM2 front=1 z=65237-3*25.4-10+0.180*25.4
# Aperture 0.006" deep
place PM2aper front=1 z=65237-3*25.4-10+0.180*25.4

zntuple format=ascii z=65237-3*25.4-1 referenceParticle=1

# COLLIMATOR

# Placement corrected to 22.53" c-c from target
place COLL z=65237
place TAPER1 z=65237-1.81*25.4
place CBORE z=65237+0.575*25.4
place TAPER2 z=65237+2.385*25.4

virtualdetector VCOLL height=$Clength width=$Clength format=ascii
place VCOLL front=1 z=65237-3*25.4

zntuple format=ascii z=65237+3*25.4+1 referenceParticle=1
```

```
# Halfway to target
zntuple format=ascii z=0.5*(65237+65798) referenceParticle=1

# Coordinates at TARGET:
zntuple format=ascii z=65797 referenceParticle=1
place TARGET front=1 z=65798

virtualdetector VTARG radius=9.5 format=ascii
place VTARG front=1 z=65798

trace nTrace=10 format=ascii primaryOnly=1

beamlossntuple BLNT filename=LostParticles.txt format=ascii

g4ui when=4 ’/run/beamOn 100’
```