SIMULATION STUDY OF HALO COLLIMATION IN THE TRIUMF[*] ARIEL[†] PROTON BEAM LINE

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Abstract

The TRIUMF 500 MeV H− cyclotron uses stripping foil extraction to drive several proton beam lines serving different experimental programs. As part of the ARIEL facility now under construction, a new proton beam line 4-North will be installed to transport up to 100 microamps of 480 MeV protons to an ISOL target station for rare isotope beam production. This beam line has been designed for low-loss (< 1nA/m) operation and provides space for a collimator to remove the beam halo produced by large-angle scattering in the cyclotron extraction foil. We have studied loss patterns and collimation efficiency in a fully 3D beam line geometry using a Geant4-based simulation code with all particle-matter interactions included. Foil scattering is treated by a separate iterated single-scatter model. Using these tools we arrive at a prototype design for an effective collimator.

OVERVIEW

The requirements [1, 2] for Beam Line 4-North (BL4N) specify that beam losses shall not exceed 1 nA per meter, thus permitting hands-on maintenance and preventing inordinate activation and radiation damage to hardware components. Shielding capacity in the collimator region also poses an additional constraint, that the total losses in this region shall not exceed 0.1% of the beam, or 0.1 μA at full intensity.

The beam extraction from the cyclotron occurs via H− stripping with a carbon foil of 2.5 mg/cm^2 thickness. The coulomb scattering process in the foil results in a large-angle tail in the angular distribution of protons. Some protons will scatter outside the BL4N entrance aperture whereas others will enter the beam line but exceed the acceptance and are lost before reaching the ISOL target. Some losses occur in the cyclotron vault, a high radiation area. The remaining "halo particles" constitute only about 0.015% of the beam but for a 100 μA beam the downstream losses will exceed 1 nA/m unless they are removed by a collimator.

To estimate these losses we have employed multiparticle simulations to track protons from the cyclotron foil through the beam line to the ISOL target. This is accomplished in two stages, using the codes ACCSIM [3] and G4Beamline [4]. The peripheral field of the cyclotron is not known explicitly but is well characterized by a transfer matrix fitted to beam measurements [5]. Since G4Beamline does not have map-based transport, the initial tracking through the foil and cyclotron field to the beam line entrance (combination magnet) is done by ACCSIM. Protons which do not enter the

aperture of the combination magnet are discarded. The starting particle data at the foil azimuth is taken from COMA [6], the reference tracking code for the cyclotron.

Coulomb scattering in the foil is done using an *iterated single scatter* model [7] in which individual scattering events in the foil are simulated, using angles sampled from a Rutherford scattering distribution with suitable cut-offs. This approach gives a much more realistic representation of the large-angle tail than the conventional multiple scattering models based on Molière theory (Figure 1), at the expense of additional computing time (there are ~60 scatters per foil traversal). For the 2.5 mg/cm^2 foil this model agrees quite well with the more complex one available in Geant4.
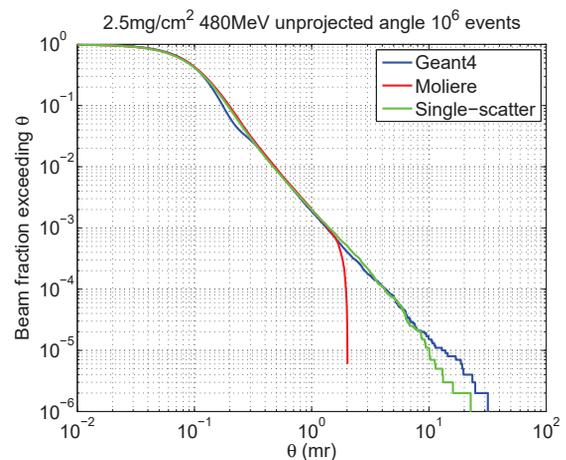

Figure 1: Comparison of foil scattering treatments.

From Accsim, particle coordinates are transferred to the G4Beamline code, a turnkey application based on the Geant4 [8] Toolkit, which tracks through the beam line to the ISOL target. The beam line and collimator are represented as a 3D geometry in which all particle interactions in matter are simulated, providing accurate accounting of proton losses and tracking of all secondary particles. We have used G4Beamline's rich complement of output mechanisms to "instrument" the beam line, providing accurate and comprehensive data on particle trajectories and losses.

BEAM LINE MODEL AND SIMULATION STAGES

The functional layout of BL4N is shown in Figure 2. The collimator section (16–21m) is tuned to obtain a nearly round beam with point-to-parallel focusing from the stripper foil. This maps angles at the foil to displacements at the collimator, allowing the halo to be removed with minimal interception of "good" beam.
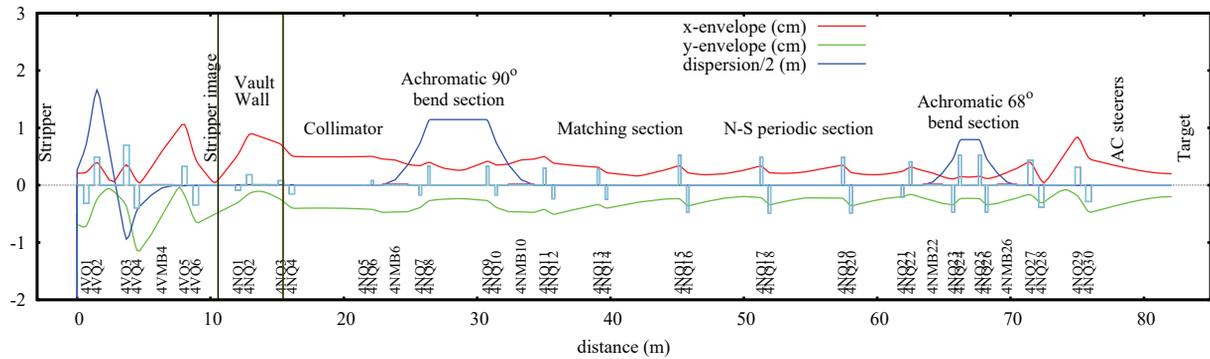
Figure 2: BL4N functional layout with 2×RMS beam sizes and dispersion.

As in the real beam line, magnetic elements in the G4Beamline model have to be tuned to achieve correct beam centering and beam sizes. Initial field values were taken directly from the reference REVMOC [9] file used in earlier studies of the beamline. Only minor adjustments were needed to get beam centering (within 1mm) and beam sizes in good agreement with REVMOC. (Figure 3).
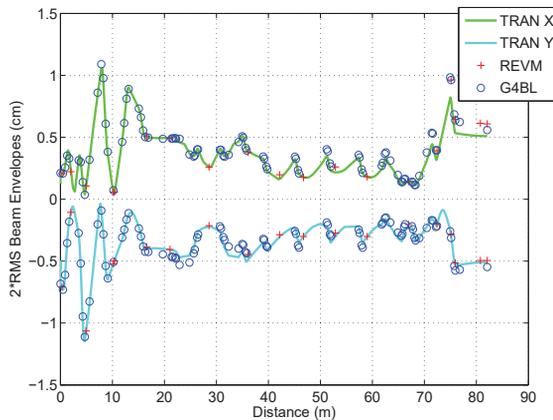

Figure 3: Beam sizes (2×RMS) in G4Beamline, REVMOC, and the envelope tracking code TRANSOPTR.

The flexibility of G4Beamline allows a staged approach to simulation: in a first stage the primary proton tracks are killed as soon as they hit a material surface (collimator or vacuum chamber). This reduces the model to a geometric one and shows clearly the patterns of primary impact. Subsequently, a more realistic simulation is done where protons are allowed to scatter in the collimator and all other materials they encounter, leading to distributed losses downstream from the collimator.

COLLIMATOR GEOMETRY AND PERFORMANCE

The favourable beam properties enable a simple geometry for the collimator, with a cylindrical cross section of varying radius. The proposed material is copper, in which the range of 480 MeV protons is about 18 cm. The initial 20 cm section has a tapered shape, decreasing from the beam pipe radius to the radius that defines the collimator aperture. This is chosen for two reasons: (1) reducing the power density by

distributing the collimated beam along the taper, and (2) reducing outscattering of protons that may continue down the beam line. The 60 cm section shown in Fig. 4 is a straight
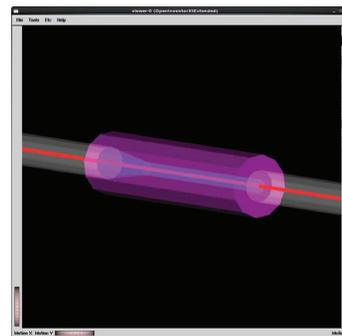

Figure 4: Geant4 visualization of the collimator.

cylinder with the same internal radius as the final radius of the tapered section. This is needed to stop any protons that enter the latter part of the taper, but it also acts to "clean up" protons outscattered from the taper surface, and even to collect some divergent protons that just missed the taper. For better control of these residual losses, this section could be made longer, but this is subject to beam steering and shielding requirements.

Optimizing Primary Losses

In the following, loss maps (histograms) are used to evaluate collimator performance. These 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.

Because there is an aperture reduction from 4 inches in Q4 to 2.63 inches in Q5, the case of using "no collimation" is not really meaningful, so for the sake of comparison we begin with "minimal collimation" in which there is no dedicated collimator but just a simple reducer coupling in the vacuum chamber between the two quadrupoles (Figure 5). The total downstream losses are only 14 nA, but they exceed the 1 nA/m limit in the 30–40 meter region where the vertical beam size is large and there are reduced vertical apertures in bends B6 and B10. With the collimator in place and by successive reductions in its aperture, we determined that a
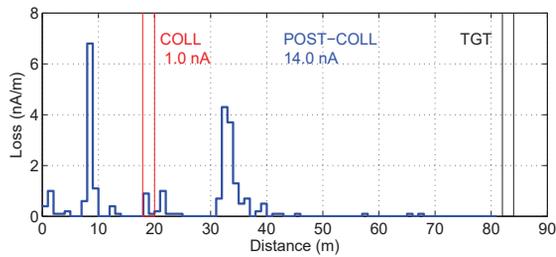
Figure 5: Loss map for minimal collimation.

radius of 17mm is sufficient to bring losses below 1 nA/m, as seen in Figure 6.

Influence of Proton Scattering

One characteristic of a effective collimation system is that the collimator reduces downstream losses without contributing additional ones. Inevitably some particles will scatter back out of the collimator into the vacuum chamber and will eventually be lost. In this case, there are no significant
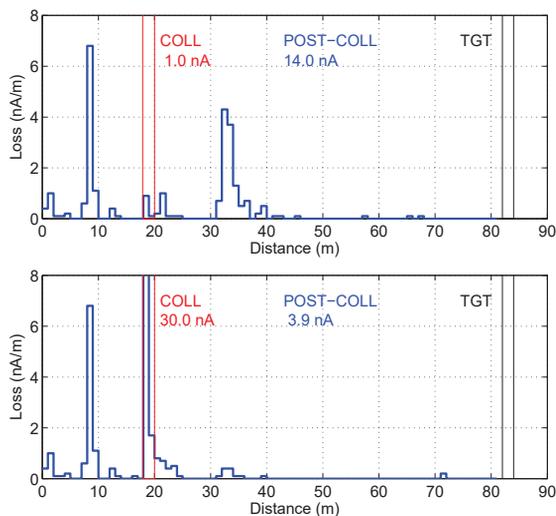

Figure 6: Loss map for collimation at R=17mm, without proton scattering (top) and with proton scattering (bottom).

additional losses in most of the downstream beam line, however there is noticeable loss redistribution in the few meters immediately following the collimator. Some of this will be within the collimator shielding, but some losses are observed in quadrupole Q5 located at 21.5 meters.

Reducing the collimator aperture further in order to mitigate this additional loss is actually counterproductive, as seen in Figure 7 (top), where the radius has been decreased by only 1mm. While the point-to-parallel focusing is advantageous for single-stage collimation, making the aperture too small results in increased outscattering of protons at small angles eventually leading to losses far downstream, as seen in Figure 7 (bottom). Moreover, losses in the collimator region are nearly exceeding the shielding limit of 0.1 μA.

Tolerance of Beam Tuning Errors

The BL4N model is an idealization with no field or alignment errors, and precise control over beam centering and
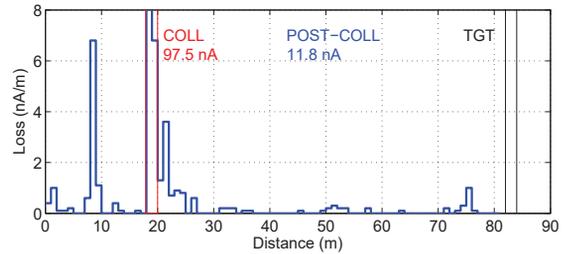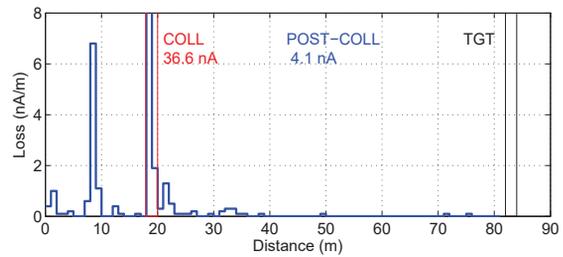

Figure 7: Effect of aperture reduction to 16mm (top) and 12mm (bottom).

steering. Despite the generous provision 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? For small errors this can be simulated by adjusting the collimator itself, either by a parallel displacement from the central axis or by tilting with respect to the axis. The estimated thresholds for which losses begin to exceed 1 nA/m are 2+2 mm of offset and 1+1 mm of tilt (components in X and Y). The latter case is shown in Figure 8. These numbers indicate that although
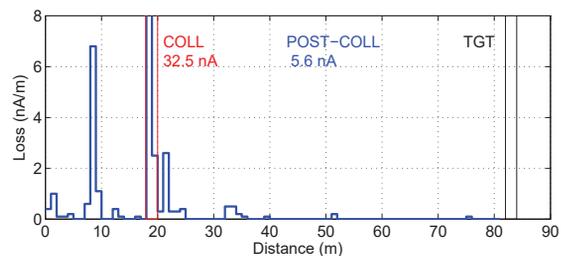

Figure 8: Effect of 1 mm tilt in X and Y.

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. In particular, there are increased losses inside Q5.

CONCLUSION

A 3D simulation model of Beam Line 4N, based on ACC-SIM and G4Beamline, has been constructed. The results indicate that a collimator of cylindrical cross section, with a tapered section followed by a longer straight section, will be effective for removing the beam halo and enabling low-loss operation. The designed-in features (round beam and point-to-parallel focusing) allow sufficient loss control to be achieved with only a single collimation stage. One proviso is that precise beam steering and good beam stability, within ~1mm tolerances, will be needed.

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