A New Simplified Tapering for the Neutrino Factory Capture System

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Abstract

In the Neutrino Factory, a 4 MW proton beam with a kinetic energy between 5 and 15 GeV interacts with a liquid mercury jet target in order to produce pions that will decay to muons, which in turn decay to neutrinos. The baseline-capturing layout consists of a series of solenoids producing a tapered magnetic field from 20 T, near the target, down to 1.75 T at the entrance of the drift section where the captured pions decay into muons to produce a useful beam for the machine. In an alternative layout the magnetic field is rapidly squeezed from 20 T to 1.5 T using only three solenoids, shown in figure 1. This layout showed to produce similar performance, having the advantage being simpler and could potentially be made more robust to radiation[2]. Here we report on further optimization studies taking into account the beam pathlength in the Hg-jet and shape fluctuations of the Hg-jet.

INTRODUCTION

The Neutrino Factory (NF) will provide intense, high energy neutrino beams from the decay of muons [4]. The majority of the muons will be created from the decay of pions, produced by a proton beam impinging on a Hg-target. It will be important to capture a large fraction of the produced pions, then let them decay to muons and transport them through the NF *front-end* to maximize the particle flux into the accelerator. The NF front-end consists of the target and capture section, a longitudinal drift, a buncher, a rotator and finally a muon cooling section. Charged particles from the target are captured in the 20 T magnetic field to form a beam. The beam's divergence is then gradually decreased by the tapered magnetic field, before it enters the constant 1.75 T field in the drift section. Here pions decay and the particles develop a position and energy correlation. The longitudinal phase space is then manipulated in the buncher and phase rotation section to reduce the beam momentum spread. Finally the transverse phase space is reduced in the cooling section.

The production of (mainly) pions from the interaction between the proton beam and the Hg-jet is affected by the entry and exit positions of the beam in the target and the average pathlength. When a Hg-jet is under the influence of a high magnetic field a quadrupole effect has been reported[3], making the jet elliptical. A particle production study has been done by varying the beam angle and also taking into account the elliptical shape of the target and the pathlength. The beam kinetic energy is 8 GeV. Then the results of an optimisation of the particle production with a cylinder Hj-jet is presented. All simulations are done with G4beamline (G4BL)[1].

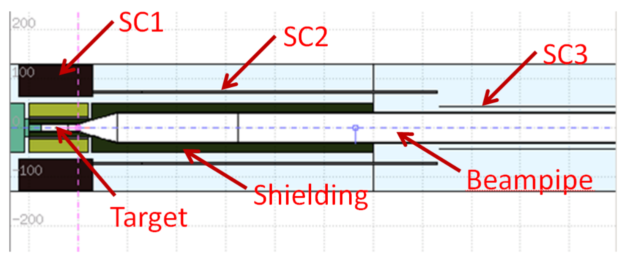

Figure 1: 3sol layout. SC1, SC2 and SC3 are the superconducting solenoids. The beampipe is the white region in the center, the radius is $r_{b1} = 75$ mm in the 20 T region around the target, then in the coned region it increases to $r_{b2} = 274$ mm while the magnetic field is tapered.

ELLIPTICAL HG-JET

The max jet height increase, due to the quadrupole effect, has been studied and jet height ratio reported to be ≈ 1.15 in a 15 T magnetic field [3]. Here it's assumed that the heigh ratio increases to 1.2 when in a 20 T field. Then the major semi-axis of the ellipse should be $a = 6$ mm, when assuming a jet radius of $r = 5$ mm. From conservation of mass for the Hg-jet, the minor semi-axis is calculated to to be $b \approx 4.2$ mm. To approximate the elliptically shaped

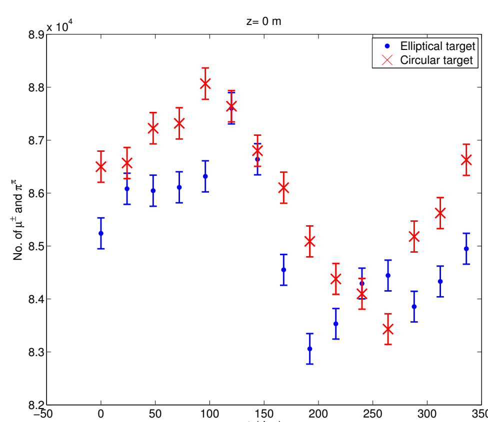

Figure 2: Muon and pion count at z=0 mm. The maximum is found when the beam enters the jet from the side, on the negative x-axis, having $\phi = 96$ deg and $\phi = 120$ deg for the circular and elliptical jet, respectively. The errorbars are statistical.

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jet in G4BL, three cylinders were used. One in the center with radius $r_1 = b$ mm and two cylinders placed at $y \pm 2$ mm with $r_2 = 3.8$ mm, using the G4BL coordinate system. The jet is tilted $\theta_T = 96.68$ mrad with repect to the z-axis, pointing downstream. The polar angle between the beam

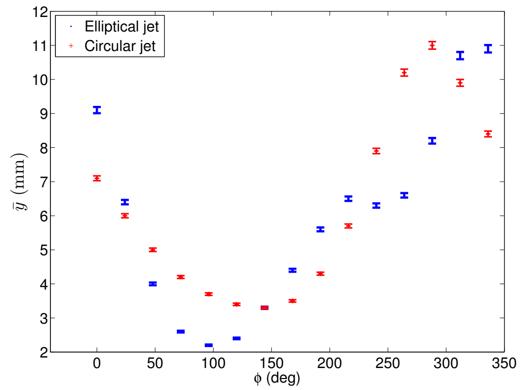

Figure 3: The mean interaction or exit position for a proton in the jet. The beam enters the jet earlier than wanted, the majority of the particles are therefore produced in the upper part of the beampipe. Errorbars are statistical.

and target is fixed to $\theta_{BT} = 30$ mrad while we vary the azimute angle from $\phi \in [0, 360]$ degrees, in steps of 24, using the target reference frame. The target reference frame has its center in (0,0,-375) mm. The results are presented in figure 2, the particle count varies with 5.5 % for both cases and the elliptical jet has a slightly lower count, on average.

Figure 3 shows the *particle production center*, $\bar{y}$, calculated from the mean of the proton/Hg interaction y-position (or the y-position where the proton exits the target if no interaction), the further away from the beampipe center it is the lower the particle count.

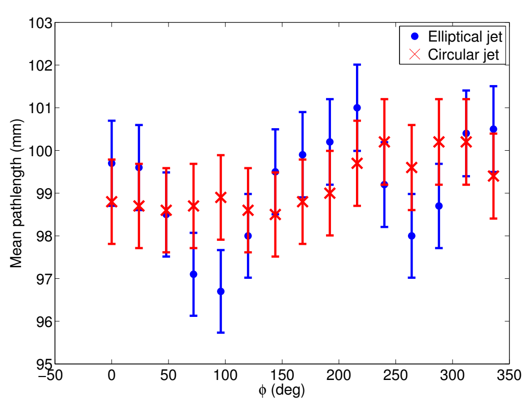

Figure 4: The average pathlength for a proton when varying ϕ. Errorbars are statistical.

Comparing the particle count with the particle production center a correlation can be seen. The region with the lower $\bar{y}$-values coincides with the maximum for the particle count. For the elliptical jet the picture is more complicated since the pathlength varies much more, see figure 4. E.g. the minimum value of the interaction center and the minimum value of the pathlength are both at $\phi = 96$ deg, but still the particle count is the third highest.

MOVING THE PARTICLE PRODUCTION CENTER

Hg-jet is now circular. In figure 5 the black dashed line shows the case with $\phi = 0$ from the previous section, for the circular jet. The distribution peak is clearly at a too high y-position. The production peak was therefore moved closer to the center by making the proton beam enter the target further downstream and the distribution peak moves closer to the center.

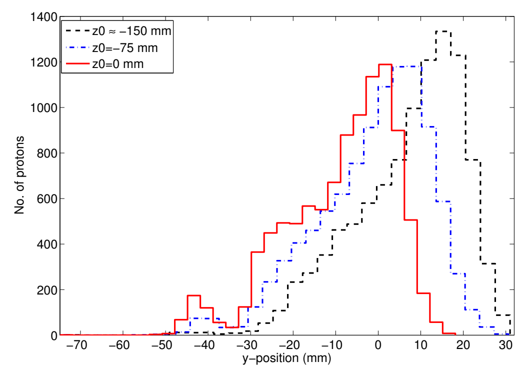

Figure 5: The particle production center is moved closer to the center of the beampipe.

When moving the *particle production* center closer to the *beampipe* center, the previous beam definition had to be corrected slightly. The angle definitions still applies, but now the beam is shifted from the center of the target (0, 0, -375) mm to some chosen point on the edge of the target $(0 + x_0, 0 + y_0, -375 + z_0)$.

The results are shown in figure 6. Finding the maximum when the beam's mean entry z-position is $\bar{z} = -375 + z_0 = -400$ mm, comparing with the highest count from the previous section we get an increased particle count of 10.5%.

INCREASING THE PATHLENGTH

To increase the pathlength the angle θ_{BT} is varied from 15 mrad to 35 mrad, while trying to keep the production center at the same place. The maximum pathlength found was 100.3 mm. The particle count is then increased another 6.8 % giving a total increase of 17.3 % compared to the max from figure 2.

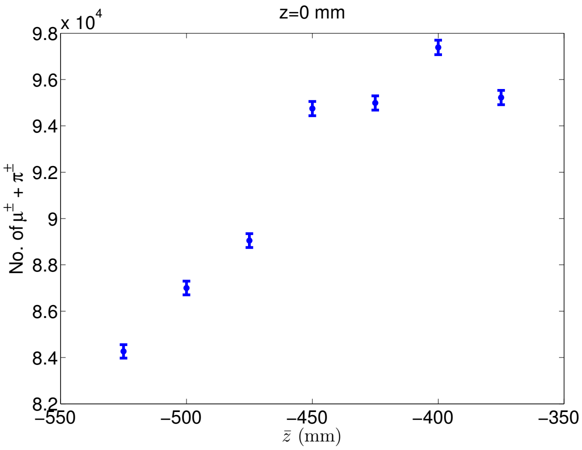

Figure 6: Moving the production center further downstream increases the particle count and centers the particle production.

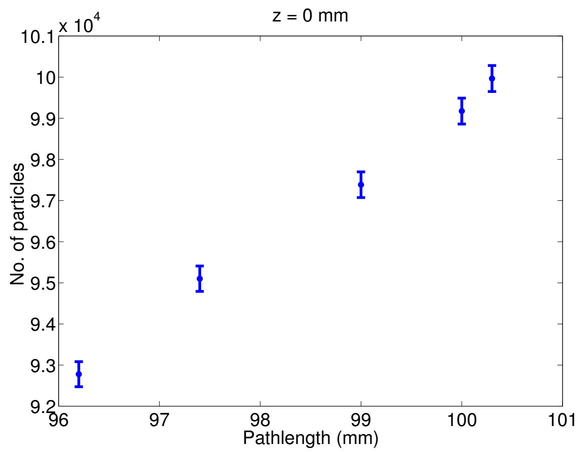

Figure 7: The increased pathlength increases the particle production.

PERFORMANCE OF THE SIMPLIFIED TAPERING SECTION.

The particle flux is found at $z = 50$ m, where acceptance cuts are applied as described in [2]. Therefore the beam has to be transported through the capture region to check if the increased particle count at $z = 0$ m also increases the output at $z = 50$ m. The results are shown in figure 8. The optimised beam parameters increases the muons flux at 50 m.

CONCLUSION

It is important that the beam enters the target with the right angle for both the elliptical,$\phi = 120$ deg, and the circular target, $\phi = 96$ deg. The main explanation is that the particle production center is shifted off the beampipe center, and therefore more particles interact with the shielding in the upper part of the beampipe, if the beam enters the target too early. Changing the target shape to an ellipse

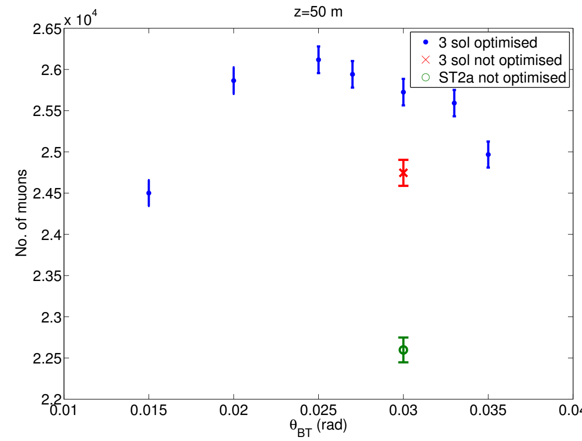

Figure 8: The optimised angle, θ_{BT}, for particle production, compared to the non-optimised 3 sol and the non-optimised ST2a.

doesn't drastically alter the particle production.

To maximise the particle flux it is important to have the particle production center in the center of the beampipe, this will probably also spread the energy deposition out more evenly such that the upper part of the shielding doesn't get the peak of the radiation. The optimal angle between beam and target should be, $\theta_{BT} = 25$ deg, to get a centered particle production, the longest pathlength and therefore the highest particle flux.

ACKNOWLEDGMENT

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