A SIMPLIFIED MAGNETIC FIELD TAPERING AND TARGET OPTIMISATION FOR THE NEUTRINO FACTORY CAPTURE SYSTEM

I. Efthymiopoulos, S. Gilardoni, O. M. Hansen*, G. Prior †, CERN, Geneva, Switzerland.

Abstract

In a Neutrino Factory, a 4 MW proton beam with a kinetic energy between 5 and 15 GeV interacts with a free floating liquid mercury jet target in order to produce pions which after capturing are let to decay forming a muon beam, input to the front-end accelerator system of the facility. The baseline capturing layout consists of a series of normal and superconducting solenoids producing a tapered magnetic field from 20 T, near the target, down to 1.5 T at the entrance of the drift pion decay section. An alternative layout is studied, where the magnetic field is rapidly squeezed from 20 T to 1.5 T using only three solenoids. This new layout showed to produce similar, and even slightly better performance than the baseline, having the additional advantage of being simpler and could potentially be made more robust to radiation. In this paper we report on further optimisation studies taking into account the beam interaction path length in the mercury jet and shape fluctuations of the jet.

INTRODUCTION

The Neutrino Factory (NF) [1] is designed to provide intense high-energy neutrino and anti-neutrino beams, ν_e, $\overline{\nu}_\mu$ ($\overline{\nu}_e$, ν_μ) from the decay of stored μ^+ (or μ^-). To probe the very sensitive oscillation parameters, the neutrino mass hierarchy and CP-violation, a high flux of neutrinos, and therefore muons is required. In the baseline design of the NF a total of 10^{21} muon decays per year is envisaged. The muons are produced as tertiary particles from pion decays, in turn produced in a sufficiently heavy target bombarded by an intense 4 MW proton beam. In the baseline design the target is a free-floating liquid-mercury jet target operating in a solenoid-focusing pion-capture channel. This is followed by a solenoidal transport channel in which the pions decay to muons. The emerging muon beam is then bunched, and rotated in phase space to produce a beam with small energy spread. In the last stage of the front-end systems the muon beam is "cooled", i.e. reduced in the transverse dimensions, to match the injection parameters of the accelerators.

The pion-capture channel consists of a series of superconducting solenoids with varying strength starting from 20 T around the target centre to 1.5 T in the constant-field transport decay channel about 15 m downstream. The smooth changing strength of the solenoids or "tapering", each at slightly lower field than the previous, exchanges transverse for longitudinal momentum thus gradually focus the pions and produce a small divergence beam, input to the decay pipe and front-end systems [2]. The design of these solenoid magnets presents severe engineering challenges as most of the 4 MW beam power is dissipated in this region around the target. An internal shield composed of high-Z material is included around the target to protect the superconducting solenoids that extends all the way down to the muon front-end.

THE 3-SOL LAYOUT

The 3 solenoid layout and magnetic field tapering that was proposed [3] showed to preserve and even give slightly better muon yield than the baseline design. In this, the magnetic field rapidly decreases from 20 T around the target to 1.5 T in two steps using two sets of solenoids - therefore the naming 3SOL.

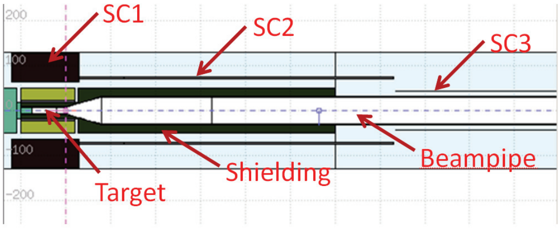

Figure 1: The 3SOL layout around the NF target. SC1, SC2 and SC3 are superconducting solenoids. The beampipe is the white region in the center, the radius is $r_{b1} = 75$ mm in the 20 T region around the target, then in the conical region increases to $r_{b2} = 274$ mm.

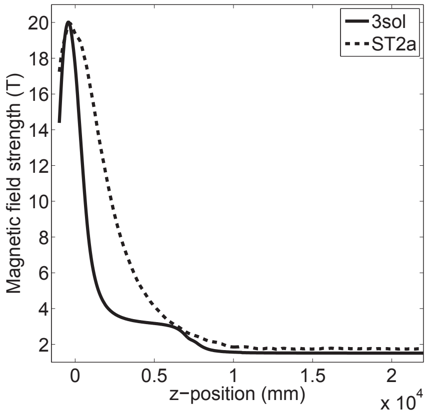

Figure 2: The magnetic field variation in the 3SOL and standard layout.

Compared to the baseline layout, the 3SOL offers the advantage of having the solenoids at much lower current in

---

[*] o.hansen@cern.ch, also at University of Oslo, Norway

[†] presently at University of Canterbury, Christchurch, New Zealand

particular for the region just downstream the target where most of the energy is deposited. The low current for SC2 would potentially allow a larger radius solenoid thus reducing the effect of radiation. From initial studies the performance of the new layout seems comparable and better than the baseline ST2a design [3]. A complete engineering study needs to be done to fully validate this solution and quantify potential cost and complexity savings.

OPTIMISATION STUDIES

The interaction region of the target where the secondary pions are produced can be considered as the particle source therefore the optics of the focusing system with the solenoids should match to the entrance of the decay volume and the accelerator front-end. The effective interaction region is determined by the entry and exit points and directions of the primary beam and the mercury jet both affected by the high magnetic field of the 20 T solenoid. The trajectory of the beam can be chosen to vary the proton path-length inside the target, and therefore the secondary particle production yield, or make the interaction region close to the central axis, i.e. closer to the focal point of the optics system of the solenoids. From hydrodynamics studies of the mercury jet as it traverses the high gradient magnetic field of the central solenoid a quadrupole effect may be present [4] that can distort the jet to an elliptical shape. In the next section the result on further optimisation studies addressing these effects for the 3SOL layout are reported. The studies are done using the G4beamline (G4BL) simulation tool [5]. The input proton beam has a kinetic energy of 8 GeV and $\sigma = 1.5$ mm.

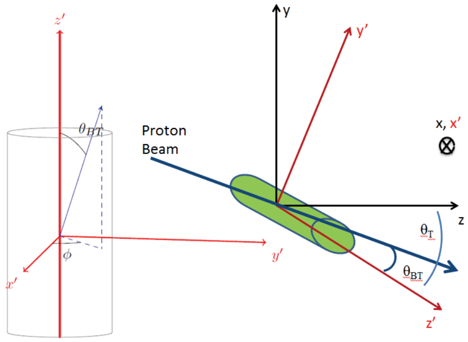

Figure 3: Target and beam. Left: the angle definitions of θ_{BT} and ϕ in the target reference frame. Right:the target reference frame rotation of θ_T around the x-axis. The centre of the target is defined to be in the (0,0,-375) mm.

Elliptical Hg-jet

The distorted jet was simulated by increasing the height and squeezing the width, compared to the circular jet with radius $r = 5$ mm, to form an elliptically shaped jet. The jet height increase has been reported to be $\sim 1.15 \times r$ in a 15 T magnetic field [4]. Here it's assumed that the height increases to $1.2 \times r$ when in a 20 T field. The major semi-axis of the ellipse should be $a = 6$ mm, therefore and from conservation of mass for the jet, the minor semi-axis is calculated to be $b \sim 4.2$ mm.

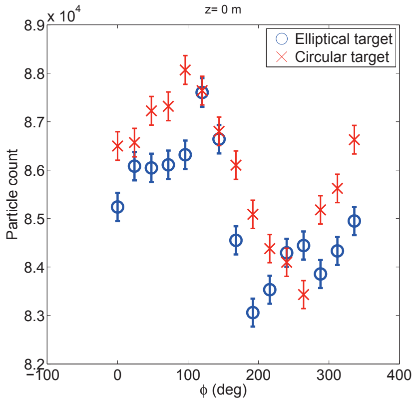

Figure 4: Muon and pion count vs. the azimuth angle ϕ.

To approximate the elliptically shaped jet in G4BL, three cylinders were used: one at the center with radius $r_1 = b$ mm and two placed at $y \pm 2$ mm with $r_2 = 3.8$ mm. The cylinders were then tilted by $\theta_T = 96.68$ mrad. The polar angle between the beam and target is fixed to $\theta_{BT} = 30$ mrad while the azimuth angle is varied from $\phi \in [0, 360]$ degrees, in steps of 24, using the target reference frame, see Fig. 3. The results are presented in Fig. 4 where the maximum particle count variation is 5.5 % for both cases and the elliptical jet has a lower count, on average. The comparisons of particle count are done downstream of the jet in the plane at position $z = 0$ mm, or at +37.5 cm from its centre. The error bars are only statistical.

Particle production center

The jet is now circular. Figure 5 shows the distribution of the y-position of each individual proton interaction point in the jet. The black dashed line shows the case for $\phi = 0$ from the previous section, for the circular jet. The distribution peak, or the particle production center, is off-centered in the positive y-direction. The secondary particles are therefore produced in the upper part of the beampipe, i.e. out of the focal centre therefore more particles will be lost from scraping in the shielding. The distribution peak was therefore shifted towards the center by making the proton beam enter the jet at a lower y-position. Then the secondary particles will have a smaller radial distribution, thus potentially increasing the muon yield at the front-end. In addition it makes the spreading of the energy deposition more even such that the upper part of the shielding doesn't get the peak of the radiation.

In Fig. 5 the y-distribution is skewed and non-gaussian, the median was therefore chosen over the mean to indicate the central tendency. The results are shown in Fig. 6, where the highest count is found when the beam's median is -4mm.

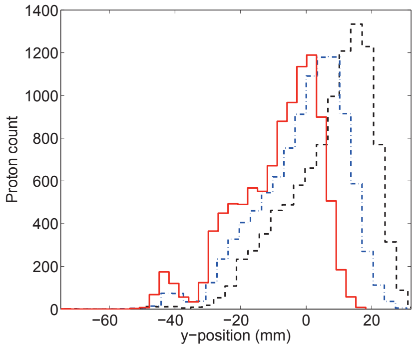

Figure 5: The y-distribution of the interaction between the proton beam and the jet. The black dashed line has median 8.6 mm, the blue dash-dotted line has median 1.25 mm and the red line median -6.1 mm which can be found in Fig. 6.

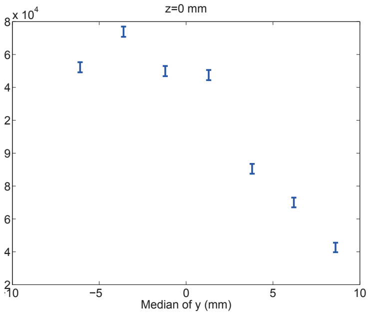

Figure 6: Median of y vs. particle production.

Interaction region length

To increase the interaction region length (pathlength) the angle θ_{BT} is varied from 20 to 35 mrad, while keeping the optimal median value ≈ -4 mm, found in the previous section. The particle count increases for a longer pathlength, the highest average pathlength found was 100.8 mm and the particle count is then increased another 6.8 % giving a total increase of 17.3 % compared to the maximum from Fig. 4.

In summary the production of the secondary particles has been centered in the beampipe and the pathlength was increased. The particle flux has this far been found in the plane at $z = 0$ mm. To make sure the optimisation increases the output of the front-end, the particle flux is now found at $z = 50$ m, where acceptance cuts are applied as described in [3]. The results are shown in Fig. 8 and compared to the ST2a layout [6]. The non-optimised 3SOL and ST2a both used the the maximum value from Fig. 4.

CONCLUSION

Optimisation studies of the proton beam interaction with the mercury jet target have been performed in the 3SOL layout. Changing the jet shape from a cylinder to an ellipse alters the particle production slightly, a decrease of a few percent is expected.

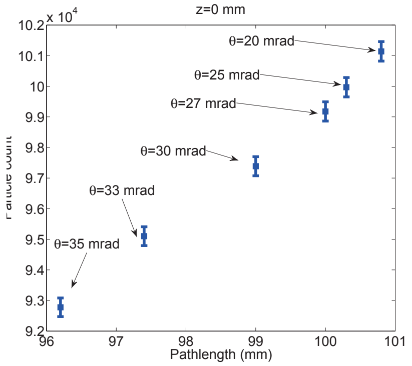

Figure 7: Pathlength vs. particle production.

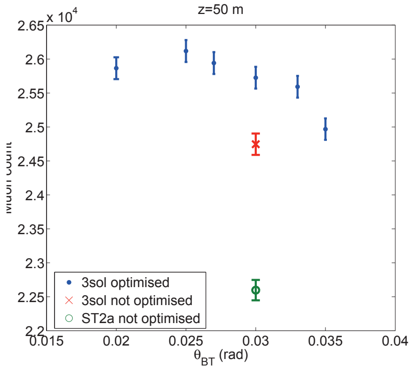

Figure 8: The optimised angle, θ_{BT}, compared to the non-optimised 3SOL and the non-optimised ST2a.

It is found that the muon yield could be maximised if the secondary particles a produced in the center of the beampipe. The optimal angle between beam and target was found to be $\theta_{BT} = 25$ mrad to get the longest path-length and therefore the highest particle flux. Combining these optimisations give an increased muon count of 5.5% (16%) compared to the non-optimised 3SOL (ST2a).

REFERENCES

[1] S. Choubey, et al. (2011), BNL-96453-2011, CERN-ATS-2011-216, FERMILAB-PUB-11-581-APC, RAL-TR-2011-018.

[2] M. Green *et al.*, ICFA workshop on beam dynamics, vol 372, AIP conference proceedings, AIP, 1996.

[3] O. M. Hansen, I. Efthymiopoulos, (2012), "Optimizing the capture section of the Neutrino factory", NuFact12 conference preceedings, AIP.

[4] H. J. Park, (2009), Experimental Investigation of Magnetohydrodynamic Flow for An Intense Proton Target, Dissertation presentation, Stony Brook University.

[5] T. Roberts (2012), G4beamline, http://g4beamline.muonsinc-.com.

[6] R. Fernow, et al. (2004), MUC-NOTE-COOL_THEORY-296.