# PARTICLE PRODUCTION SIMULATIONS FOR THE NEUTRINO FACTORY TARGET

J.J. Back*, University of Warwick, Coventry, UK
H.G. Kirk, N. Souchlas, BNL, Upton, NY, USA
I. Efthymiopoulos, S. Gilardoni, O.M. Hansen, G. Prior, CERN, Geneva, Switzerland
R.J. Weggel, Particle Beam Lasers, Inc., Northridge, CA, USA
X. Ding, UCLA, Los Angeles, CA, USA

*Abstract*

In the International Design Study for the Neutrino Factory (IDS-NF), a proton beam interacts with a liquid mercury jet target in order to produce pions that will decay to muons, which in turn decay to neutrinos. The target is situated in a solenoidal field tapering from 20 T down to below 2 T over a length of several metres, allowing for an optimised capture of pions in order to produce a useful muon beam for the machine. We present results of target particle production calculations using the FLUKA simulation code.

## INTRODUCTION

The baseline option for the Neutrino Factory is to use a 4 MW proton beam interacting with a free-flowing mercury jet to create copious amounts of pions that are captured in a high magnetic field ($\sim$ 20 T). These pions are transported through a tapered solenoid decay channel where the muons resulting from pion decay are collected, accelerated and stored until they decay to neutrinos. Previous work based on MARS simulations [1, 2], using the Study 2 geometry [3], has shown that the number of useful muons is maximised when the proton beam has a kinetic energy in the range of 5-15 GeV for a mercury jet target that has a radius of 0.4 cm, with a target-beam crossing angle between 20 and 30 mrad. In this paper, we present FLUKA [4] calculations of the accepted number of pions and muons as a function of the proton beam kinetic energy, using the optimised proton beam and mercury jet parameters from the MARS study [2]. We also present a preliminary analysis of the accepted pion and muon yields for a new target geometry that has increased shielding in order to protect the superconducting magnets of the solenoid capture system from high radiation doses [5].

## SIMULATION METHOD

The FLUKA simulation software package is used to calculate the production of low-energy pions from the interaction between the mercury jet target and the proton beam at different initial kinetic energies. This is done by first implementing the geometry and material description of the whole target station, such as the Study 2a design shown in Fig. 1. The mercury jet target is represented as a simple cylinder of radius 4 mm, tilted at 100 mrad with respect to the magnetic $z$ axis. The proton beam has a Gaussian profile with a root mean square radius of 1.2 mm, and its initial position and direction are chosen such that it intersects the mercury jet target at $z = -37.5$ cm with a crossing angle between 20 and 30 mrad, depending on the initial kinetic energy [2]. The extended PEANUT (pre-equilibrium approach to nuclear thermalisation) model is enabled in order to calculate detailed hadron-nuclear particle interactions throughout the whole target station geometry. Particles are tracked using a field map to describe the magnetic field distribution $\underline{B}$ from the normal conducting ($|\underline{B}| \sim 6$ T) and superconducting ($|\underline{B}| \sim 14$ T) coils. For each simulation run, the total number of pions and muons (of both signs) that cross a transverse plane 50 metres downstream from the beam-jet interaction are counted within the decay channel aperture that has a bore radius of 30 cm. We additionally require that these particles have kinetic energies in the range of 40 to 180 MeV in order to calculate the approximate number of useful muons for the Neutrino Factory that pass through the cooling channel. These yields are normalised to the total number of generated protons as well as the initial beam kinetic energy.

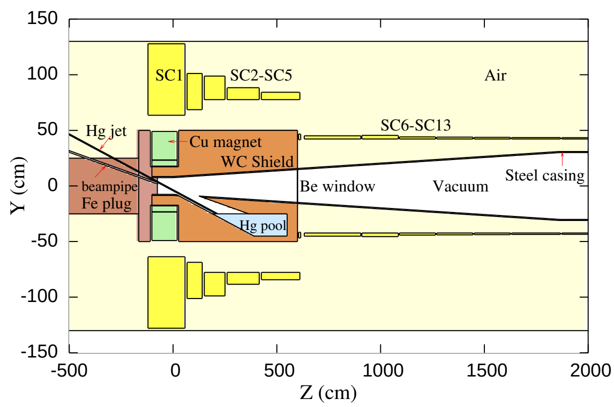


Figure 1: Schematic of the Study 2a target station geometry for the Neutrino Factory. The superconducting magnets are labelled SCn, where n = 1 to 13. The shielding consists of 80% tungsten-carbide and 20% water.

* J.J.Back@warwick.ac.uk

## STUDY 2A GEOMETRY YIELDS

Figure 2 shows the accepted yields as a function of the initial beam kinetic energy for the Study 2a geometry. The yield distribution increases dramatically as the proton beam energy increases from 2 GeV up to 5 GeV, and then remains almost constant up to an energy of 12 GeV. The yields then start to decrease as the beam energy increases. These results imply that the optimal yield is obtained for an input beam energy between 5 and 12 GeV, which is consistent with the conclusions reached by other studies [2, 6]. The relative variation of the yield between the positively and negatively charged species can be as much as 5% in this energy range, according to results obtained from the PEANUT model.

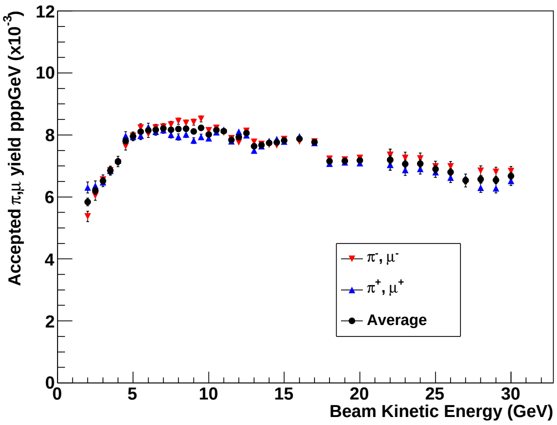


Figure 2: The accepted pion and muon yields (per proton per GeV) for the Study 2a target geometry as a function of the initial kinetic energy of the proton beam.

## INCREASED SHIELDING GEOMETRY YIELDS

Studies have shown that the superconducting magnets in the Study 2a geometry experience a radiation dose that is too high for their safe operation [5]. This can be mitigated by effectively doubling the outer radius of the shielding protecting the inner bore of the superconducting coils. Figure 3 shows the new increased shielding target geometry, which reduces the radiation dose of the superconducting coils to more manageable levels. The tungsten-carbide shielding for this geometry has a larger fraction of cooling water (40%), while the iron plug behind the normal conducting magnets has been removed to increase the space available for the mercury jet return flow system. The size and arrangement of the coils have changed in order to both accommodate the increased shielding as well as to keep the solenoidal magnetic field of 20 T in the beam-jet interaction region. Figure 4 shows a comparison of the axial magnetic field profile along the $z$ axis between the old Study 2a geometry and the new increased shielding configuration. The new magnetic field distribution has a much broader central peak, which will help to significantly improve the capture of useful low energy pions and muons from the target.

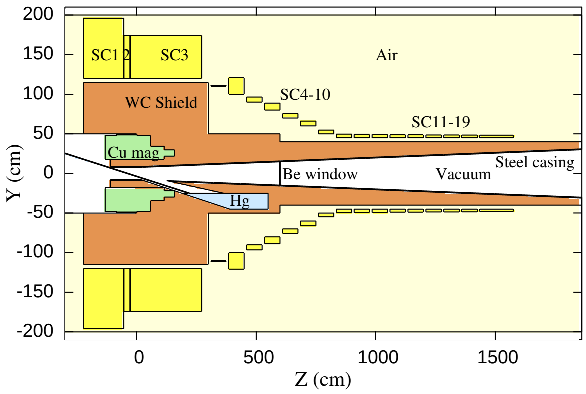


Figure 3: Schematic of the target station geometry with increased shielding to protect the superconducting coils (SC) from high radiation doses.

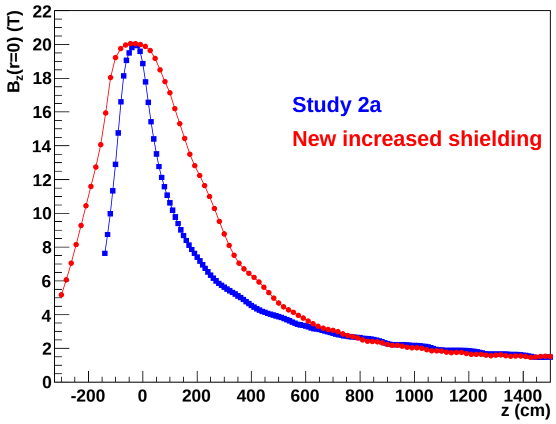


Figure 4: Comparison of the $B_z$ magnetic field profile along the $z$ axis for the Study 2a (blue squares) and the increased shielding (red circles) geometries.

Figures 5 and 6 show a preliminary analysis of the accepted (normalised) yields as a function of the initial beam kinetic energy for the increased shielding geometry. Here, the initial proton beam position and direction are chosen such that the beam-jet crossing angle, at their intersection at $z = -37.5$ cm, is between 20 and 30 mrad, depending on the beam energy. The yields for beam energies between 2 and 5 GeV increase quite sharply, analogous to the results for the Study 2a geometry. The yield is roughly constant over the larger energy range between 6 and 17 GeV, before decreasing again at higher energies. All of the yields are higher than those for the Study 2a geometry, with the optimal yield approximately 30% higher, owing to the wider peak in the magnetic field distribution which improves the capture of particles produced from the target. As before,

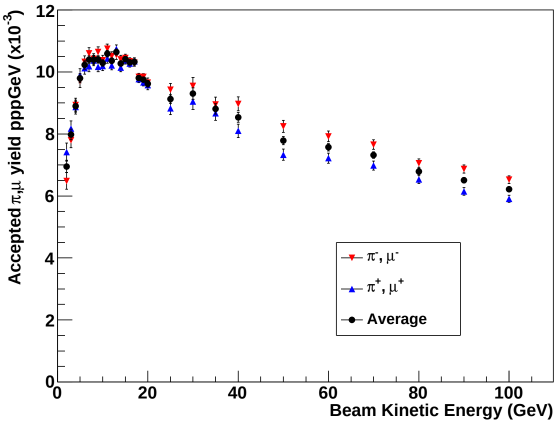


Figure 5: The accepted pion and muon yields (per proton per GeV) for the new increased shielding target geometry for a wide range of proton beam kinetic energies between 2 and 100 GeV.

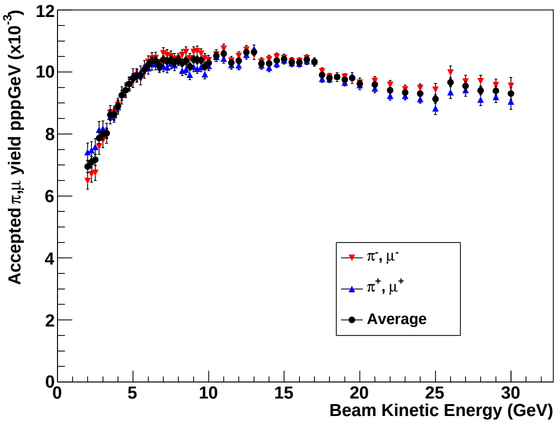


Figure 6: Close-up of the distribution of the accepted pion and muon yields (per proton per GeV) for the new increased shielding target geometry for proton beam kinetic energies between 2 and 30 GeV.

the relative variation of the yields between negatively and positively charged pions and muons can be as much as 5%. It is possible to improve the yields in the energy range between 5-20 GeV further by re-optimising the radius and tilt of the mercury jet, as well as the beam-jet crossing angle at their intersection. However, this has not been done for this study.

## SUMMARY

We have presented a FLUKA simulation study of the accepted pion and muon yields for the Neutrino Factory target station. The calculated yields for the Study 2a geometry are optimal for proton beam energies between 5 and 12 GeV, in agreement with other studies [2, 6]. Also presented are preliminary yield results for a new target geometry that incorporates a substantial increase to the shielding volume in order to protect the superconducting coils from high radiation doses that are expected for the 4 MW proton driver. The optimal yield for this new geometry, for a proton beam energy approximately equal to 13 GeV, is about 30% higher than the optimal yield for the Study 2a arrangement, owing to the broader peak in the magnetic field distribution. The doubling of the aperture size of the magnet coils in the new geometry imply that the forces between the coils increase by a factor of four, causing additional difficulties for the overall magnet support structure. However, it is possible that reducing the magnetic field downstream of the target, to help alleviate this problem, may give yields that are comparable to those obtained for the Study 2a geometry. Therefore, further optimisation of the yields in the new target station geometry, in conjuction with modifications to the magnetic field profile, needs to be investigated.


## ACKNOWLEDGEMENTS

We acknowledge the financial support of the European Community under the European Commission Framework Programme 7 Design Study: EUROnu, Project Number 212372. The EC is not liable for any use that may be made of the information contained herein.


## REFERENCES


[1] N. V. Mokhov, "The MARS code system user's guide", Fermilab-FN-628 (1995); N. V. Mokhov et al., "Recent enhancements to the MARS15 code", Fermilab-Conf-04/053 (2004); `http://www-ap.fnal.gov/MARS`.

[2] X. Ding et al., "Optimized parameters for a mercury jet target", PAC'09, Vancouver, Canada, May 2009, WE6PFP102, p. 2748, `http://www.JACoW.org`.

[3] C. Albright et al., "Neutrino Factory and beta beam experiments and development (feasibility study IIa)", S. Geer and M. Zisman eds., Technical Report, BNL-72369-2004 (2004) [physics/0411123].

[4] G. Battistoni et al., "The FLUKA code: description and benchmarking", in proceedings of *Hadronic Shower Simulation Workshop 2006*, Fermilab, Batavia U.S.A., September 2006, AIP Conf. Proc. **896** (2007) 31; A. Fasso, A. Ferrari, J. Ranft and P.R. Sala, "FLUKA: a multi-particle transport code", CERN-2005-10 (2005) [SLAC-R-773]; `http://www.fluka.org/fluka.php`.

[5] J.J.Back, "Energy deposition studies for the Neutrino Factory target station", JINST **6** (2011) P06002.

[6] J. Strait, N. V. Mokhov and S. I. Striganov, "Towards the optimal energy of the proton driver for a neutrino factory and muon collider", Phys. Rev. ST Accel. Beams **13** (2010) 111001.