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# IMPACT OF THE ENERGY OF THE PROTON DRIVER ON MUON PRODUCTION

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*Abstract*

Simulations studies have been carried out to examine the impact of the energy of the proton driver on muon production. The muon flux is calculated as a function of proton energy over a wide range, which covers the energies at the existing muon and neutron facilities worldwide. The muon and higher energy pion yields are normalised per beam current and accelerator power. The case of a higher energy of the proton driver at the ISIS muon facility is also examined.

## INTRODUCTION

The first generation of proton accelerators capable of providing intense beams of muons became available in 1957. A great advance in muon research was achieved with these early accelerators, however they were followed by a second generation of accelerators in 1974 which had more than two orders of magnitude in intensity. One such accelerator is at Paul Scherrer Institute (PSI) in Switzerland and it's the world's most intense continuous muon beam source. The PSI cyclotron operates at 590 MeV with a proton current of 2200 mA and the proton beam hits two graphite targets which have attached seven beamlines for muon extraction. The continuous source muon facilities generation was followed in 1987 by the world's most intense pulsed facility ISIS which was built in the UK. ISIS is designed as a spallation neutron source and the muon facility runs in parallel with the neutron facility. Negatively charged hydride ions are injected from the linear accelerator into the synchrotron where they are stripped off their electrons and accelerated to 800 MeV. The nominal beam current is 200 $\mu$A and the proton beam is double pulsed at 50 Hz. The two pulses are directed along the proton beam channel to the intermediate muon target and then to the spallation neutron target. A new facility J-PARC was built in Japan in 2001 and it's designed for a proton energy of 3 GeV and an average current of 333 $\mu$A. The objective of the current paper is to determine the optimum energy for surface muon production in graphite targets and to study the rate of surface muons with respect to both the accelerator power and the beam current.

## SURFACE MUONS

The muon experiments conducted at proton accelerator facilities require reasonably intense muon beams of high quality. Muons are obtained through the decay of the pions produced in nuclear interactions between accelerated protons and target nuclei. There exists a significant fraction of low-energy pions generated inside the target which stop at the target surface layer after losing their momentum. These pions decay at rest producing surface muons with a high polarisation. Another fraction of pions decay in flight in free space close to the production target but the muons produced have a small polarisation.

## GEANT4 SIMULATIONS

Simulations with the Monte Carlo code Geant4 [1] were performed using the ISIS target geometry (Fig. 1). The target is a graphite plate with dimensions (5x5x0.7) cm oriented at 45 degrees to the proton beam giving an effective length of 1 cm along the beam. The muon beam is extracted at 90 degrees to the proton beam. The muons are collected using a thin aluminium beam window situated at 15 cm from the target centre and having a diameter of 8 cm.

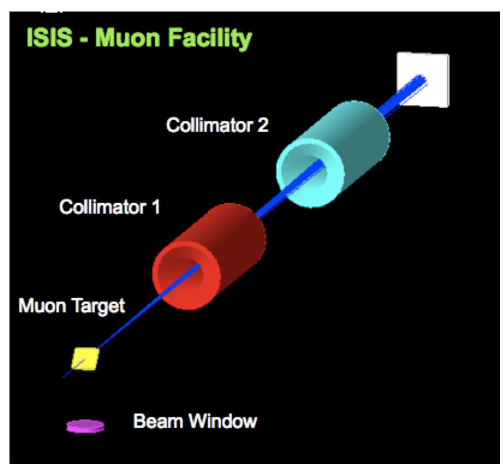


Figure 1: Geant4 modelling of the ISIS muon facility. The muon beam passes through the aluminium beam window. The transmitted proton beam passes through the collimators (hosted in the beam pipe in this Geant4 modelling) and hits the neutron target.

Because the muon facility at ISIS runs in parallel with the neutron facility, the proton transmission through the target is an important parameter which has to be taken into account. The proton transmission is defined as the fraction of protons passing through the collimation system and must be kept at a reasonable level (usually above 96%) to prevent the loss in neutron intensity at the neutron target situated 20 m downstream the muon target. The collimation system was implemented in the Geant4 geometry model. The collimation system consists of two angled cones of Cu each 40 m long. The first collimator has an inner radius of 37.5 mm and an outer radius of 54.15 mm and intercepts protons scattered beyond 41.6 mrad. The second collimator has an inner radius of 51.0 mm and an outer radius of 61.4 mm and intercepts protons at angles grater than 28.8 mrad. Geant4 modelling of the ISIS collimators are shown in Fig. 2 and Fig. 3.

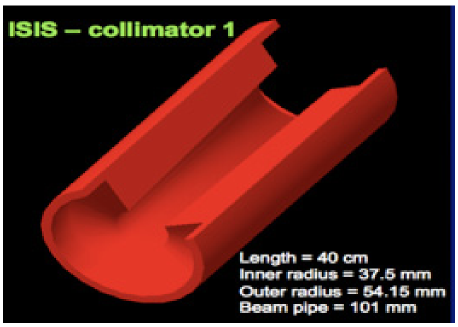


Figure 2: Geant4 modelling of the first collimator inside the beam pipe at the ISIS muon facility.

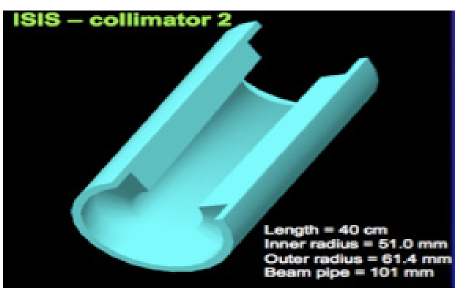


Figure 3: Geant4 modelling of the second collimator inside the beam pipe at the ISIS muon facility.

## PROTON TRANSMISSION

Figure 4 shows that at higher energies the proton transmission through the muon target is increasing, and, as a consequence, we would be able to use thicker targets at higher energies. If we aim for a transmission of 96.7% at ISIS and we increase the energy, the target thickness will vary from the current value 0.7 cm at 800 MeV to 0.9 cm at 3 GeV (Fig. 5). However, for the current study the fixed target thickness was considered in all simulations.

## PION PRODUCTION

The proton-nucleon interaction inside the target produces pions and the energy threshold for these reactions is typically 280 MeV in the laboratory frame. The pion production cross-section in such reactions increases rapidly with energy, as shown in Fig. 6).

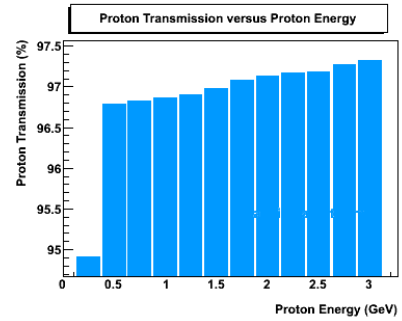


Figure 4: Proton transmission through the muon target as a function of the proton beam energy.

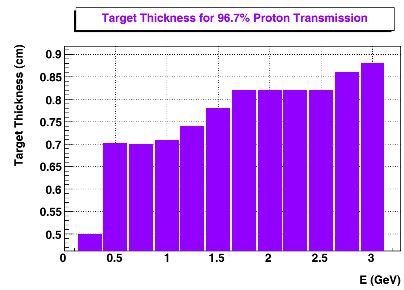


Figure 5: Target thickness for 96.7% proton transmission through the ISIS muon target as a function of proton beam energy.

Single pion production reactions are typical for proton energies up to 800 MeV. Double pion production reactions occur only when there is sufficient energy in the collision, and are typical for proton energies beyond 1 GeV. Momentum and energy spectra of the pions produced by various energy protons incident on a graphite target show the onset of the double pion production at 750 MeV (Fig. 7). However, the double pion production peak can be seen clearly on pion momentum and energy spectra from 1 GeV proton energy onwards (Fig. 8).

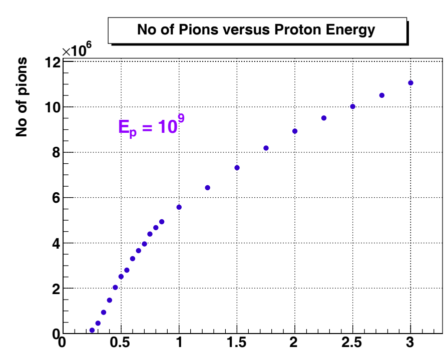


Figure 6: Variation of pion yield with proton energy.

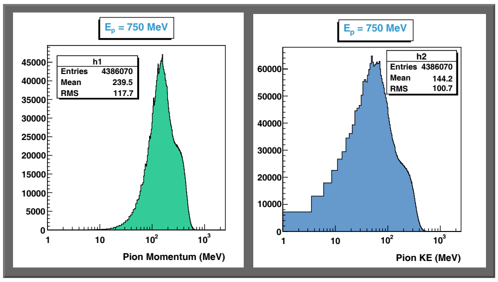


Figure 7: Pion momentum and energy spectra for incident proton energy of 750 MeV.

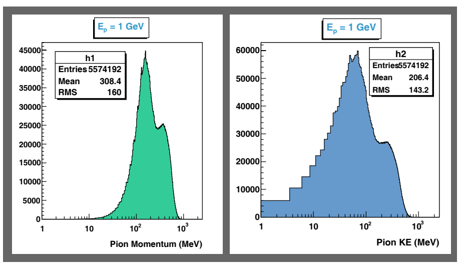


Figure 8: Pion momentum and energy spectra for incident proton energy of 1 GeV.

## MUON PRODUCTION

A beam of $10^9$ protons was sent on a graphite target and the muons produced by pions at rest and by pions in flight were detected in a sperical shell detector surrounding the target. Figure 9 shows a muon production peak at about 500 MeV proton energy, therefore in a dedicated muon facility one should aim for this proton beam energy.

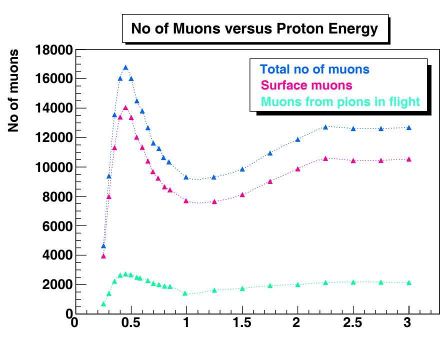


Figure 9: Variation of muon yield with proton energy.

Increasing the proton energy above this value merely produces more high momentum pions in the forward direction, mostly well outside the momentum range likely to be used by a decay beam, though there is a small increase in the useful range. At higher proton beam energies, most pion have high kinetic energy and escape the target rather than coming to rest and having time to decay to surface muons. Therefore, as surface muon production is concerned, PSI gets a higher muon production at 590 MeV then ISIS at 800 MeV and J-PARC at 3 GeV. A normalisation of the muon production rate to the accelerator power shows also a peak at about 500 MeV (Fig. 10). Since the proton transmission is a function of proton energy, a normalisation to the number of protons interacting in the target was done and it also shows a peak at about 500 MeV (Fig. 11) .

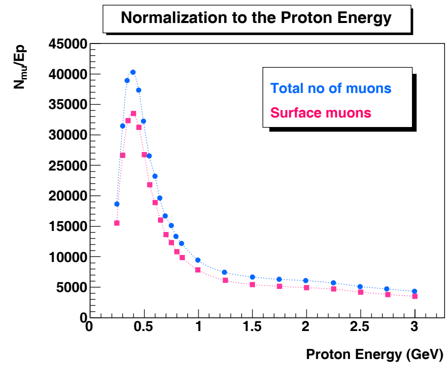


Figure 10: Normalisation of the muon yield to the accelerator power.

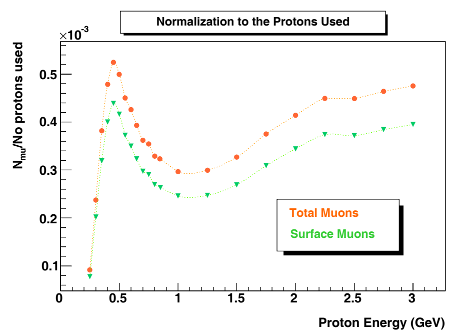


Figure 11: Normalisation to the number of protons interacting in the target.

## CONCLUSION

Muon and pion production as a function of proton beam energy were investigated in this paper. A muon production peak at about 500 MeV incident proton suggests that this is the optimal energy for a muon facility. Momentum and kinetic pion energy spectra show the onset of double pion production from 750 MeV proton energy onwards.

## REFERENCES

[1] Geant4 - a toolkit for simulation of the passage of particles through matter, version 4.9.3.p01, `http://geant4.cern.ch`.