DEVELOPMENT AND OPTIMISATION OF THE MUON TARGET AT THE ISIS-RAL MUON FACILITY

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Abstract

The pulsed muon channel of the ISIS facility at RAL has been successfully commissioned and operated for many years as a tool for μSR studies in condensed matter research. At the present time, the graphite target, of dimensions 50*50*7 mm oriented at 45 degrees to a proton beam of 800 MeV energy, gives 16000 surface muons per double proton pulse passing through the entrance aperture of the aluminium window which separates the muon beamlines from the main proton beam. Potential improvements to the target geometry, and optimisation of the design and estimated performance of the muon target are presented in this paper.

INTRODUCTION

Understanding the physical properties of matter at a microscopic level requires better technologies capable of tackling fundamental problems in condensed matter physics, chemistry, medicine and particle physics. Since these phenomena are at atomic and subatomic level, we must rely on experimental methods like the μSR technique that can probe deep inside materials. Positively charged muons behave as an isotope of hydrogen when implanted in a material, so come to rest and do not undergo any nuclear interactions apart from their natural decay with lifetime 2.2 μs. Muons couple to their local environment via their spin and the spin will precess around the magnetic field at a frequency which depends on the field experienced. Their magnetic moment is three time larger than a proton, thus when implanted in matter this feature makes them an extremely sensitive microscopic probe of magnetism. Like all the experimental techniques, the μSR technique has its own limitations and there is a high demand for μSR science to make available intense beams of polarized muons. The current intensity used in muon facilities at the moment is at the threshold of these experiments and very high intensity muon beams can have an enormous potential for new discoveries over a surprisingly broad range of disciplines. Therefore, a higher muon intensity beam would push the boundaries further and new science is there to be discovered.

THE ISIS MUON FACILITY

ISIS is currently the worlds most intense source of pulsed muons. However the ISIS facility is primarily used for neutron production. Therefore little can be done to modify the proton driver to improve muon beam intensities [1]. Substantial gain in intensity can be achieved through appropriate optimisation of the pion target and muon collection geometries. The specifications of an ideal pion target are firstly a high yield of pions, and hence of muons resulting from the pion decay, and a small production of unwanted particles such as electrons and positrons, neutrons, scattered protons, and gamma rays. Moreover the target should also generate little heat or dissipate heat easily, and have a low residual activity. An added bonus is that the pion target should be small, so that using electromagnetic optics, a small muon beam spot can be tailored to enable raster scanning of μSR samples, or the study of small single crystals.

The Target

The present ISIS target is relatively simple but effective. It is an edge water cooled plate made of graphite with dimensions 50*50*7 mm, oriented at 45 degrees to the proton beam (rotated about a vertical axis) giving an effective length of 10 mm along the beam. The proton beam has an energy of 800 MeV with about 1 MeV energy spread. The nominal beam current is 200 μA, in double pulses at 50 Hz, so $2.5\,10^{13}$ protons per double pulse. The pions and muons are extracted into two beamlines each at 90 degrees with respect to the proton beam and these two beam lines are separated from the main proton beam and target vacuum vessel by a thin aluminium window. Those muons emerging from the target within a vertical acceptance of $\pm$5 mm and a horizontal acceptance of $\pm$30 mm, with divergence of 35 mrad in the horizontal direction and 180 mrad in the vertical direction and momentum in the range 25-27 MeV/c per unit charge are accepted by the muon beamline. The muon production is limited because the geometry is constrained by the accelerators beam line parameters (90 degrees extraction and no worse proton beam losses - the proton beam loss is 96% at the moment) [2].

RESULTS ON MATERIAL TARGET

An understanding of the required target technology is gained through extensive computer simulations using a Monte Carlo code GEANT4 [3] which simulates particle interactions in matter. Computer simulations were run by sending $2.5\,10^{13}$ protons on target and muons having a momentum in the range 25-250 MeV/c were recorded at the aluminium beam window. The window is situated at 15 cm from the target and has a diameter of 8 cm. Two low-Z materials, graphite and beryllium were chosen for the target simulations because they have high melting points and the target is expected to run hot in vacuum (Table 1). We have also considered nickel as a potential high Z target material, but nickel may also be a suitable coating for conventional low Z targets.

Table 1: Material choice

Material	Density	Melting point
Graphite	2.26 g/cm^3	3800 K
Beryllium	1.85 g/cm^3	1560 K
Nickel	8.91 g/cm^3	1728 K

Measurements of the Muon Flux

The muon flux dependence on target thickness was measured for all three materials. The target thickness was chosen to give a proton transmission higher than 86%. Having this constraint, for graphite and beryllium the target thickness can be increased from the current value of 0.7 cm to 2.5 cm while for nickel, which has a higher density than the other two candidates, the thickness can vary from 0.08 cm to 0.22 cm.

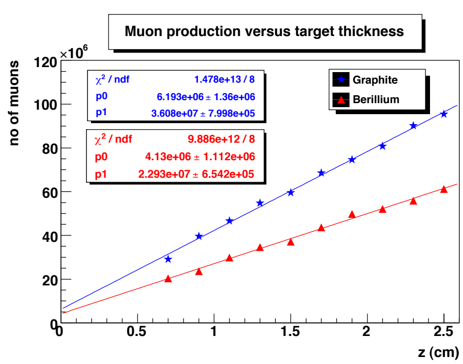

Figure 1: Muon flux dependence on target thickness for graphite and beryllium (momentum is in the range 25-250 MeV/c).

The muon flux is increasing linearly for both graphite and beryllium (Fig. 1) and for thicker targets of 2.5 cm the muon yield given by graphite is much better than for beryllium (about 90 10^6 muons for graphite compared to 60 10^6 muons for beryllium). From the muon production point of view, graphite is a better choice. The muon yield in nickel is much lower than in the other two materials (only 13 10^6 muons produced by a target of 0.22 cm thickness) and the flux is linearly dependant on target width (Fig. 2).

The proton transmission is an important parameter for the ISIS beam. Ideally all the transmitted protons should go through the aperture of the next quadrupole in the proton beamline with a collimator to stop those that are scattered too far. Both transmission and scatter in that transmitted beam together with the heat dissipation in the target itself are limiting factors that should be taken into consideration

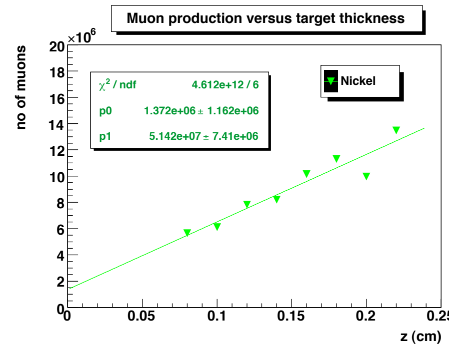

Figure 2: Muon flux dependence on target thickness for nickel (momentum is in the range 25-250 MeV/c).

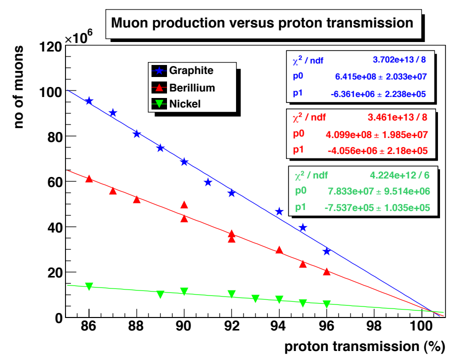

Figure 3: Muon production as a function of proton transmission for graphite, beryllium and nickel targets (momentum is in the range 25-250 MeV/c).

when designing a muon target. In Fig. 3 targets of different materials that have their thicknesses adjusted to give the same proton transmission are compared. The muon yield is increasing while the proton transmission is decreasing therefore in practice the muon production must be balanced against this important parameter.

Momentum Distribution

Regarding the total number of muons recorded at the aluminium beam window, there is a fraction of muons which come from pions decaying in flight and a fraction of surface muons produced at the target surface layer from pions at rest. The surface muons have excellent features, they are almost 100% spin polarised and give a small beam at the experimental target making them excellent tools in material studies. The momentum distribution plots show clearly the separation between the surface muons coming from pions at rest with momentum below 29.7 MeV/c and muons produced by pions in flight with a wide momentum distribution (Fig. 4, Fig. 5, Fig. 6). The ratio between muons coming from pions at rest and muons coming from pions in flight is higher in nickel than in the other two materials. The histograms seem to indicate that thinner targets have relatively more surface muons as a fraction of the total yield - this may be both a thickness effect and a variation with density or with Z. Therefore, although the overall muon production in nickel is lower than in graphite and beryllium, materials such as nickel (and perhaps other high Z elements such as Ti, W, Mo) may be good choice if the surface muon production has to be optimised.

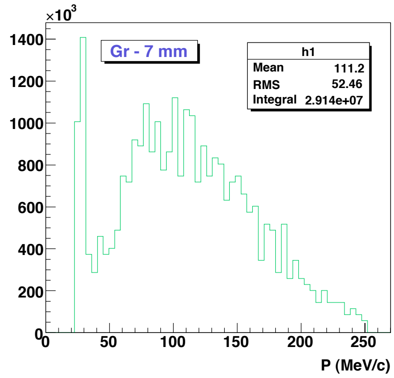

Figure 4: Momentum distribution for muons produced by a 7 mm graphite target.

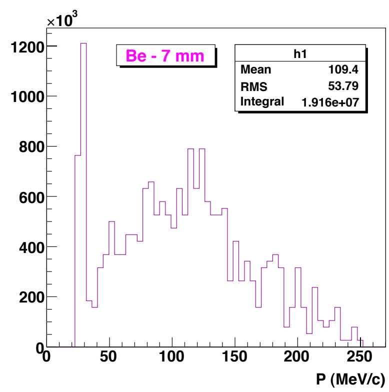

Figure 5: Momentum distribution for muons produced by a 7 mm beryllium target.

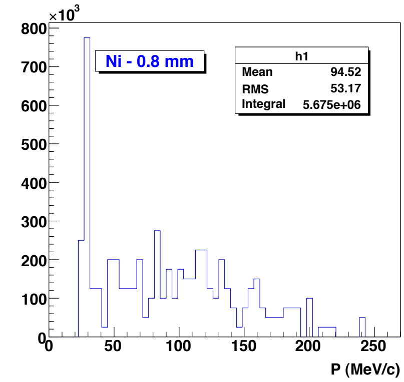

Figure 6: Momentum distribution formuons produced by a 0.8 mm nickel target.

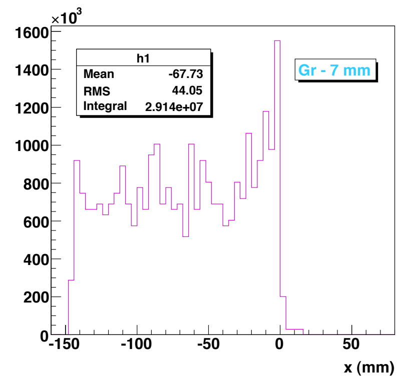

Figure 7: Histogram of the x-coordinate of the pion decay for muons extracted from the graphite target. The muon beamline window is at x=-150 mm. The peak around x=0 corresponds to pions decaying at rest in the target.

Muon Spot Profile

These features are better illustrated by the profile hystograms which show a pronounced peak which corresponds to surface muons and long tails that are mainly pions escaping the target and then decaying in flight. Figure 7 shows these characteristics in the case of a 7 mm thick graphite target.

CONCLUSION

Target simulations were performed by sending protons into three different materials, graphite, beryllium and nickel. The target thickness was adjusted to give the same proton transmission in all three cases. It was found that the muon production is increasing linearly with the target thickness, graphite being the best candidate for the overall muon production. As the muon production is increasing with target thickness, the proton transmission is decreasing accordingly. Momentum distribution studies showed that the ratio between the surface muons and the muons coming from pions in flight is greater in nickel than in the other two materials, which makes nickel a good candidate if the surface muon production needs to be optimised.

REFERENCES

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