Progress in NUCLEAR SCIENCE and TECHNOLOGY, Vol. 1, p.44-47 (2011)

ARTICLE

Shielding Experiments at High Energy Accelerators of Fermilab(I) - Dose Rate Around High Intensity Muon Beam -

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JASMIN - Japanese and American Study of Muon Interaction and Neutron detection - a program for studies of shielding and irradiation effect around high energy accelerators has been started since 2007 using high energy proton accelerators located in Fermi National Accelerator Laboratory (FNAL) as a collaboration of JAPAN and FNAL. The series of the presentations entitled "Shielding experiments at high energy accelerators of Fermilab" describes the part of the results of this collaboration regarding transport of secondary particles, neutron and muon, from 120 GeV proton induced reactions through experimental data and simulation. In this paper, behavior and associated radiation dose of high energy muons in tens of meter thick rock are measured using OSLs, CR39s, TLDs and an ionization chamber. The doses for the same geometrical condition of the experiment are calculated using multi-particle Monte Carlo simulation code, MARS, to check its predictive power for muon transport and the dose. From this comparison, consistency between the experiment and calculation is confirmed in 60 m thick rock. The calculation enables to separate contributions of each particle to the dose. The result shows considerable amount of the contribution to the dose from electrons, photons and neutrons from electro-magnetic cascade due to interaction of high energy muon.

KEYWORDS: muon, radiation dose, transport, 120 GeV, Fermi National Accelerator Laboratory, MARS

I. Introduction

1. JASMIN collaboration.

The Japanese and American Study of Muon Interaction and Neutron detection (JASMIN) collaboration has been organized to study radiation safety issues around high energy accelerators in FNAL[1)]. The collaboration aims to study behaviors of secondary particles generated from beam losses in high energy accelerators. The physical quantities which should be measured for this purpose are particle flux, activities in air, water and materials, damage of instruments and so on. The remarkable efforts for similar experiments have been performed until now[2,3,4,5)], however only a few attempt exist more than 1 GeV energy region[6,7,8)]. At around this energy, most simulation codes switch implemented reaction models from one for intermediate to high energy[9)]. The methodology of the collaboration includes not only taking experimental data but also benchmark and improvement of the reaction models.

The data takings have been performed using two facilities in FNAL, anti proton production (pbar) and neutrino from main injector (NuMI). The pbar is prepared for anti-proton production using 120 GeV, 65 kW proton beam, which is required for FNAL collider experiment, Tevatron. The shielding structure of pbar is suitable for this type of the experiments. The induced activities and neutron flux measured at this facility, and it's simulation will be reported in the successive papers. The induced activities in air are also studied and reported elsewhere. The NuMI is a facility for long distance neutrino oscillation study using 120 GeV, 300 kW proton beam. In this facility, intense muon beam that is generated during neutrino production through hadron decays is available for study. The induced activities due to the beam are reported elsewhere[10)], and radiation dose distribution due to muon beam is the topic of this paper.

2. Muon transport and its interaction.

Muons, which are produced at high altitude through interactions of cosmic-ray, can be observed everywhere on the earth since they penetrate air due to its large penetrability and have relatively long life, 2.19 μs. Recently, the cosmic-ray origin muons are used as a ray for non-destructive inspection of a massive object[11,12,13,14,15)]. Another source of muons is a high energy accelerator having the energy more than double of muon mass, which permits pair creation of muons. For more than 10 GeV accelerator, muons are dominant particle behind the shield since they have large penetrability[16)]. Under this condition, the muon transport, radiation dose and secondary particles become major concern from radiation safety point of view of high energy

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accelerators. The accelerator for free electron laser (FEL) is one of examples to show the importance of muon evaluation for radiation safety design since the facility must have experimental area at the direction of intense electron beam. Thus, most of dose in the area is due to muon when a thick shielding wall is placed at the upstream of the experimental area[17].

Until now, several experimental data for muon transport are published. The transport of muon from 14 and 18 GeV electron induced reaction is studied using two-mile electron accelerator and end-station B in SLAC[18,19,20]. For proton accelerator, the experiments at CERN and FNAL are reported in references[21,22,23]. Based on these experimental data and theoretical models, several empirical models[24,25] and simulation codes have been developed and successfully reproduce the data. Modern multi-particle transport calculation codes that incorporate these fruits can calculate not only muon distribution but also radiation dose distribution due to muon[9,26,27,28], however validation of these results has not been sufficient since there is a few experimental data to pay attention of dose[29].

The scope of this study is to obtain experimental data of transport for high energy muon in 60 m thick of rock using dosimeters. The direct and indirect dose productions associated with the muon are obtained at the same time. Theoretical simulation for this experimental geometry is done to examine the consistency of the results for radiation dose of muon and its secondary particles.

II. Experiment

Figure 1 shows the elevation view (left-bottom) and plan view (right-top) of NuMI and downstream of hadron absorber, respectively. Outline of NuMI facility is described in ref [30]. A graphite target (6 cm diameter and 120 cm long) is bombarded by 120 GeV, 300 kW proton beam. At immediately behind the target, a set of electric horn system is placed to focus pions from the target. The particles produced at the target are led to 670 m long, 2 m diameter decay pipe filled with 1 bar helium gas after the target section. Hadron absorber is located at the end of the decay pipe to absorb remaining hadrons. Thus, only muon and neutrinos enters rock located at the downstream of the hadron absorber. There are four spaces to monitor muons to ensure direction of neutrino. Muon alcove 1 is located just behind the hadron absorber, and muon alcoves 2-3-4 are located in the rock. The muon alcoves 2-3-4 are drilled perpendicular to muon beam axis, and connected to a bypass tunnel which is drilled parallel to the axis. At the connection point of the alcoves and the bypass tunnel, personal protection system (PPS) doors are placed to prohibit access inside the alcoves during beam operation.

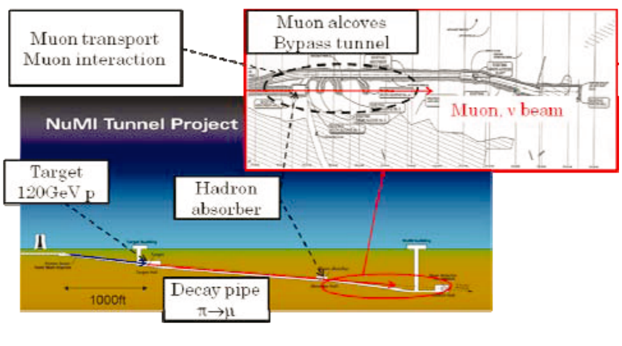

Fig. 1 Schematic view of NuMI facility. The left-bottom shows elevation view from main injector switch yard-target-decay pipe-hadron absorber-muon alcoves-MINOS experimental hall. The right-top shows plan view from hadron absorber-muon alcoves-MINOS experimental hall. Present experiment was carried out using muon alcoves.

To measure the muon transport and its radiation dose, dosimeters of Luxel-budges and TLD-budges are placed in the alcove 2-3-4 as shown in **Fig. 2**. The spacing between dosimeters is 1.5 m to cover the alcoves entirely. The spacing around the beam axis is reduced to 0.5 m to measure more detail. The heights of the positions are determined from the measurement of residual dose rate on the wall of the alcoves. The Luxel-budge consists of OSL dosimeter, CR39 and borated CR39 (CR39(B)), which are sensitive to muon/electron/γ/X, fast and thermal neutron, respectively. The TLD budge (Panasonic 813PQ) has 4 elements, 2 elements of which are for muon/electron/γ/X and the other 2 for thermal neutron measurement. In addition to the dosimeters, measurements using an ionization chamber are also performed in the bypass tunnel.

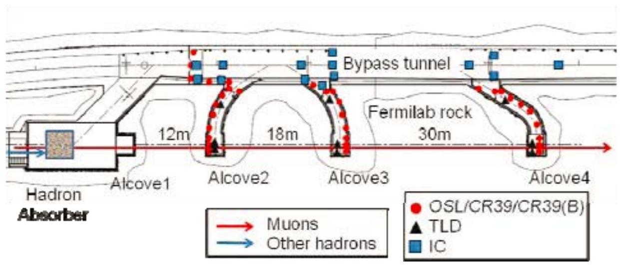

Fig. 2 Locations of dosimeters and detectors to measure muons and secondary particles. The thicknesses of rock between the alcoves are also shown in this figure.

These dosimeters were retrieved after 6 to 24 hours beam irradiation. The numbers of protons were recorded using toroid coil (TOR101) just upstream of the target. The integrated doses obtained from the dosimeters were normalized to number of protons on the target. The dosimeters were put these positions in naturally-occurred beam stop and picked up using ropes through air-ducts, since the beam operation was not dedicated to this experiment. Most of the beam operation was done under normal state except 1/3 of the operation under the second electric horn system off mode due to its failure. The effect from the horn off operation was estimated using a theoretical simulation. The other main error source came from dosimeter reading, 15% for OSL and 5 % for TLD. 40% for CR39s were added due to directionality. The integrated dose obtained from readings of dosimeters (raw numerical values) were distributed from 1.35 mSv to 5 Sv for OSL, from 0.20 mSv to 45.70 mSv for CR39, from 0.20 mSv to 0.50 mSv for CR39(B), from 0.8 mSv to 6.5 Sv for TLD, i.e, all the dosimeters were used within their dynamic ranges.

III. Theoretical calculation

The three dimensional model of entire NuMI facility developed in FNAL was used for calculation of radiation dose distribution in the alcoves. The model includes the graphite target and shield blocks surrounding the target, decay tunnel structure, hadron absorber and room for the absorber, the muon alcoves including their curvature and the bypass tunnel.

MARS code[9] was used for this calculation, since the code is able to handle all muon interaction process as well as generation and transport of the other particles which would affect on radiation dose. The calculations were done for two successive parts to reduce CPU time. The first part calculated the particle production from 120 GeV proton beam and transport from the target to behind the hadron absorber with 1 GeV threshold energy. The energy, coordinate, direction cosine, flight time and weight were written in a file for each particles reaching to behind the hadron absorber. The second part calculated particle transport in the downstream of the hadron absorber, i.e, the rock, muon alcoves and bypass tunnel using the particles in the file as source particles, with 1 meV and 0.2 MeV threshold energy for neutron and the other particles, respectively. The material composition and density of the rock were Ca : O : C : Mg : H = 0.09 : 0.56 : 0.17 : 0.08 : 0.10 by atomic fraction and 2.85 g/cm^3, respectively[9].

IV. Results

Figure 3 shows the calculation result for (b) total dose and (c) muon dose distributions on the plan view of muon alcoves and bypass tunnel as well as (a) calculation geometry for the second part. The color scale stands for dose rate in mSv/hr for 1 proton per second. The plot (c) clearly shows forward peaking distribution of muons. From the plot (b) and (c) the radiation dose in the bypass tunnel is due to secondary particles from muon, i.e, neutron, gamma and electron.

Figure 4 shows the comparison between the experiment and the calculation along the alcove 2 perpendicular to the beam axis. In this figure, DET, DEG, DEM, DEN and DEE stand for dose rate of total, photon, muon, neutron and electron, respectively. The absolute values of the experiment and the calculation are determined from itself without any normalization.

The TLD and OSL data around the beam line are in excellent agreement with DEM data, which indicates most of radiation dose on the beam line due to muon. The second highest component is electrons since plenty of them is produced from the electric-magnetic cascade initiated by high energy muons. Due to difference on directionality

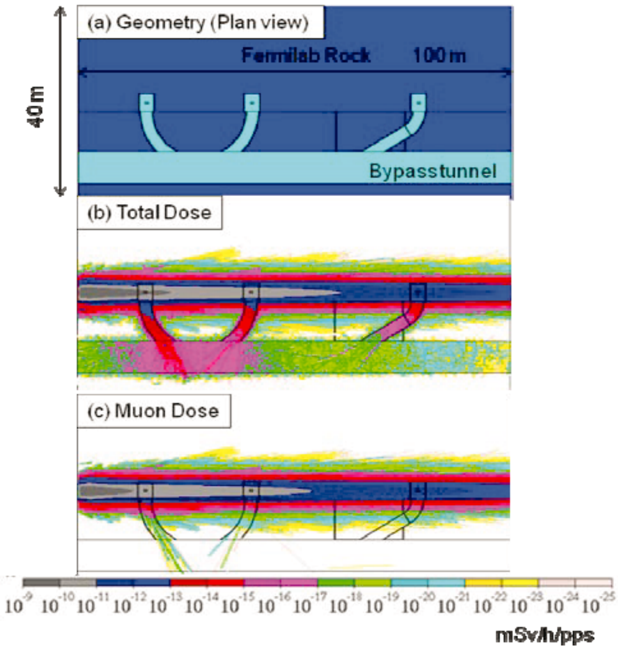

Fig. 3 The results from MARS calculation. (a) The plan view of geometry of the second part calculation, (b) total dose distribution, (c) muon dose distribution. The color scale of the results means mSv/hr for proton per second.

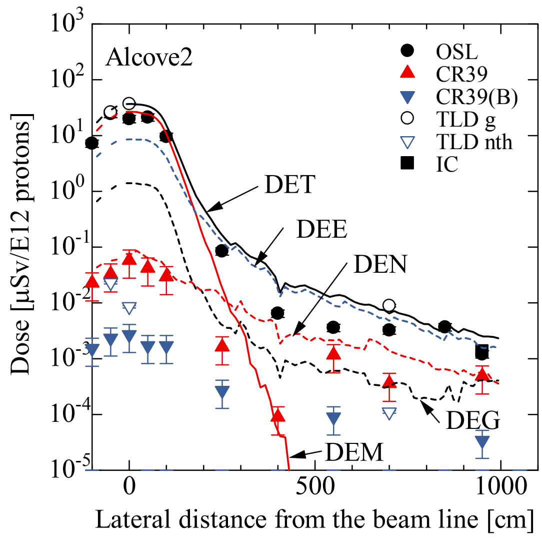

Fig. 4 Experimental and calculation results for dose along alcove 2. DET, DEG, DEM, DEN and DEE stand for dose rate total, photon, muon, neutron and electron, respectively

between muon and electron, contribution from electron becomes dominant with increasing the distance from the beam line. The calculation points out considerable amount of contribution by electron and photons to the total dose, the contributions of which are close to 50 % and 5 % of muon dose, respectively, at around the beam line. Both OSL and TLD are not able to distinguish doses from muon, electron and photon, unfortunately, we only conclude that results of OSL and TLD are in good agreement with sum of muon, electron and photon dose caused from muon and its interaction, at this moment.

According to the calculation results the contribution by muon to the dose rate decreases with increasing the distance from the beam line, and is less than the one by other particles beyond 300 cm from the beam center. In this region, most of the dose is due to electrons, which explain the results of OSLs well.

Both experimental and calculation results show occurrence of neutrons. The results of CR39 are in fairly agreement with calculation results. The difference between experimental data and calculation result on neutron dose indicates presence of high energy neutron. The results for Alcove 3 and 4 shows same tendency.

Figure 5 shows attenuation of dose as a function of thickness of the rock for experimental and calculation results. The calculation results are in good agreement with experimental. At the positions of alcoves, the doses obtained by calculation drop significantly. The behavior clearly indicates these secondary particles are generated in the rock. From the fact, radiation dose around muon beam should be taken in to account for not only muon but also electron, photon and neutron, especially at the certain distance from the beam. It should be noted that the experimental data does not have any information for high energy neutron which could be generated through high energy muon interaction. This has been remaining as an issue should be solved in the next step.

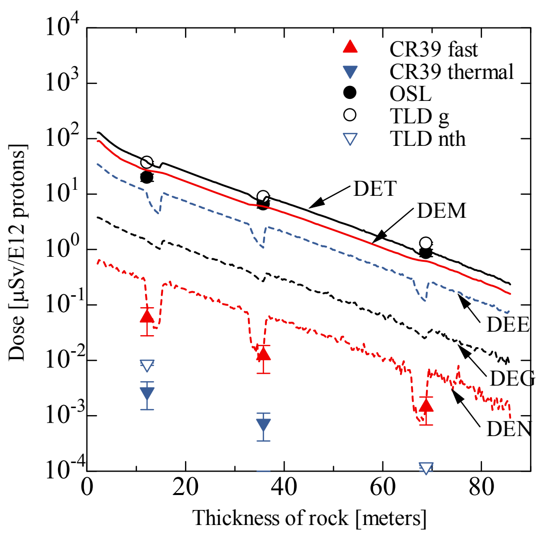

Fig. 5 Experimental and calculation results for attenuation of dose on the beam line as a function of rock thickness.

V. Conclusion

The distributions of radiation dose associated with intense muon beam have been measured in rock using standard dosimeters at NuMI facility in FNAL. The theoretical calculation, MARS, well explains origins of dose rate measured by the dosimeters.

Acknowledgment

The authors wish to thank Mr. H.Nakamura, KEK for his support of TLDs. This work is supported by grand-aid of ministry of education (KAKENHI 19360432) in Japan. Fermilab is a U.S. Department of Energy Laboratory operated under Contract DE-AC02-07CH11359 by the Fermi Research Alliance, LLC.

References

1) H. Nakashima, et.al, Nucl. Technol. 168, 482, (2009)
2) N. Nakao, et al., Nucl.Sci.Eng. 124, 228, (1996).
3) H.Nakashima, et al., Nucl.Sci.Eng. 124, 243, (1996).
4) T.Nunomiya, et al., Nucl.Instrum.Meth. B179, 89, (2001).
5) N.Nakao, et al., Radiat.Prot.Dosim. 116, 553, (2005).
6) M.Awschalom, et al., Nucl.Instrum.Meth. 136, 521 (1976).
7) H.Nakashima, et al., Proc. of the Shielding Aspects on Accelerator, Target and Irradiation Facilities –SATIF6, SLAC, 10-12 Apr. 2002.
8) N.Nakao, et al., Nucl.Instrum.Meth. A 562, 950, (2006).
9) N. V. Mokhov, , FERMILAB-FN-628 (1995), N.V. Mokhov, S.I. Striganov, Fermilab-Conf- 07-008-AD (2007), Hadronic Shower Simulation Workshop AIP Proceedings 896.
10) H. Matsumura, et al., Proc. on Workshop on Environmental Radioactivity (2008).
11) L.W.Alvarez, et.al, Science 167, 832, (1970).
12) K.Nagamine et al., Nucl. Instrum. Meth. A 356, 455 (1995).
13) H.Tanaka et al., Nucl. Instrum. Meth. A356, 585, (1995).
14) K.R.Borozdin, et.al, Nature 422, 277, (2003).
15) S.Pesente, et al, Nucl. Instrum. Meth. A604, 738, (2009).
16) IAEA Technical reports series No.188, Feb.1979.
17) M.Santana et al, Shielding Design for the LCLS BTH and Undulator, AccApp07 – The Eighth International Topical Meeting on Nuclear Applications and Utilization of Accelerators, Pocatello (Idaho, USA).
18) W.R.Nelson, Nucl. Instrum. Meth. 66, 293, (1968)
19) High-Energy (< 18GeV) Muon Transport Calculations and Comparison with Experiment, Nuclear Instruments and Methods 71, 121, (1969)
20) W.R.Nelson, et al, Experimental investigation, Nucl. Instrum. Meth. 120, 413, (1974)
21) W.R.Nelson, et al., Nucl. Instrum. Meth. 215, 385, (1983).
22) J.D.Cossairt, et al., Nucl. Instrum. Meth. A276, 78, (1989).
23) J.D.Cossairt, et al., Nucl. Instrum. Meth. A276, 86, (1989).
24) A.H.Sullivan, Nucl. Instrum. Meth. A239, 197, (1985).
25) B.P.Roe, Nucl. Instrum. Meth. 92, 257, (1971).
26) A.Dementyev, et al., Nucl. Phys. B70, 486, (1999)
27) A.Ferrari, et al., Radiat. Prot. Dosim. 74, 227, (1997)
28) T.Siiskonen, Radiat. Prot. Dosim. 128, 234, (2008)
29) M.Hofert, Rad.Prot.Dosim. 20, 149, (1987)
30) K.Anderson, et al., NuMI facility technical design report, Technical Report, FERMILAB-DESIGN-1998-01, Fermilab, 1998