SIGNAL RESPONSE OF THE BEAM LOSS MONITOR AS A FUNCTION OF THE LOST BEAM ENERGY

K. Yamamoto, J-PARC Center, Tokaimura, Japan

Abstract

The 3 GeV rapid cycling synchrotron of the Japan proton accelerator research complex accelerates a proton beam up to 3 GeV and delivers it to the main ring and the material and life science facility. The injection energy of the synchrotron was 181 MeV since 2013, and it was upgraded to 400 MeV in 2014. The main magnets (dipole and quadrupole magnets) of the synchrotron have large aperture, and thickness of yoke is larger than 200 mm. Considering the stopping power of a proton, a shielding effect of the magnets for beam loss monitor strongly depends on the lost beam energy. When the beam loss occurs during injection, the lost proton cannot penetrate the magnet yoke. But when the beam loss occurs after acceleration, lost beam easily pass the magnet. Therefore the signal response of the beam loss monitor is changed even if the number of lost particles is same. To evaluate the beam loss monitor response by the lost beam, we estimated the signal dependence on the lost energy by the simulation.

INTRODUCYTION

The 3 GeV Rapid Cycling Synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC) provides more than 500 kW beam to the material and life science facility and the main ring[1]. In such high intensity hadron accelerator, the lost protons that are a fraction of the beam less than 0.1 % cause many problems. Those particles bring about serious radio-activation and malfunction of the accelerator components. Therefore, the beam loss monitor (BLM) is one of the most important equipment to observe the state of the beam during operation, and to keep steady operation. Moreover, if we set operation parameters of BLM adequately, it can detect the beam loss that is 10^{-6} fraction of the beam. Thus it enables fine-tuning of the accelerator.

In order to increase the beam power of the RCS, the injection energy of the RCS was upgraded from 181 MeV to 400 MeV in 2014[2]. The main magnets (dipole and quadrupole magnets) of the RCS have large aperture, and thickness of yoke is larger than 200 mm. Therefore it works as a shielding to the BLM from the secondary radiation by the beam loss, and its shielding effect strongly depends on the lost beam energy. When the beam loss occurs during injection, the lost proton cannot penetrate the magnet yoke. But when the beam loss occurs after acceleration, lost beam easily pass the magnet. Therefore the signal response of the BLM is changed even if the number of lost particles is same. To evaluate the BLM response by the lost beam, we estimated the signal dependence on the lost energy by the simulation.

BEAM LOSS MONITOR IN RCS

In J-PARC RCS, We use two kind of BLM. One is a plastic scintillator connected on a photo multiplier tube and the other is a proportional counter.

The plastic scintillation counter has good time resolution (FWHM is less than 100ns) and its wave form data is used for a comparison between the experiment and simulation.

The proportional counter is mainly used to the interlock system for machine protection. The filling gas of the proportional counter is Ar-Co2 mixture, and it was purchased from Toshiba Electron Tube Co., Ltd [3]. A total of 90 proportional counters are set up all over the accelerator beam line. These proportional counters are connected with the machine protection interlock system and it is always checking that the integration of the proportional counter signal is not over a preset value. Integration values are also archived at all times and we can check it when some interlock alerted. The typical location of the PBLM is shown in Fig. 1. In this paper, we evaluate the response of the proportional counter.

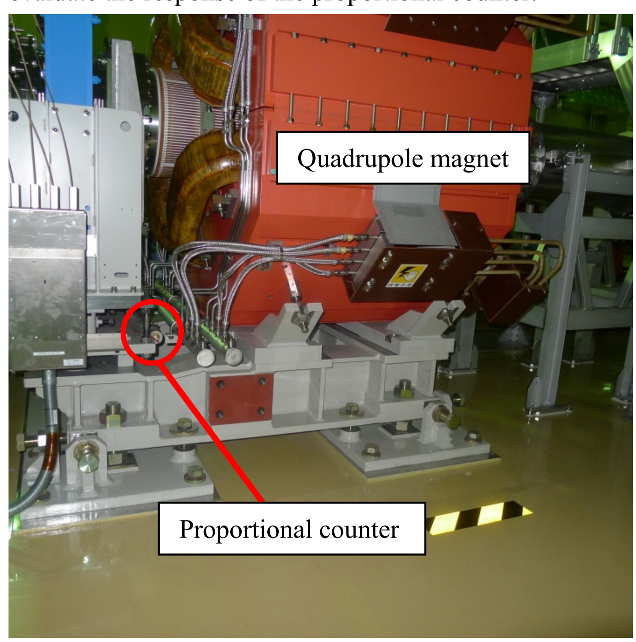

Figure 1: Typical location of the proportional counter.

CALCULATION

The response of BLM would be proportional to the energy deposition by the radiation. Thus we investigated the energy deposition at the monitor as a function of lost beam energy by using the MARS code[4]. The calculation model is shown in Fig. 2. Here, the only quadrupole magnets, proportional counters and vacuum chambers are

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considered. The shape of the quadrupole magnet is regarded as a combination of a cylinder and squares. The cross sections of the actual quadrupole magnet and the model are shown in Fig. 3.

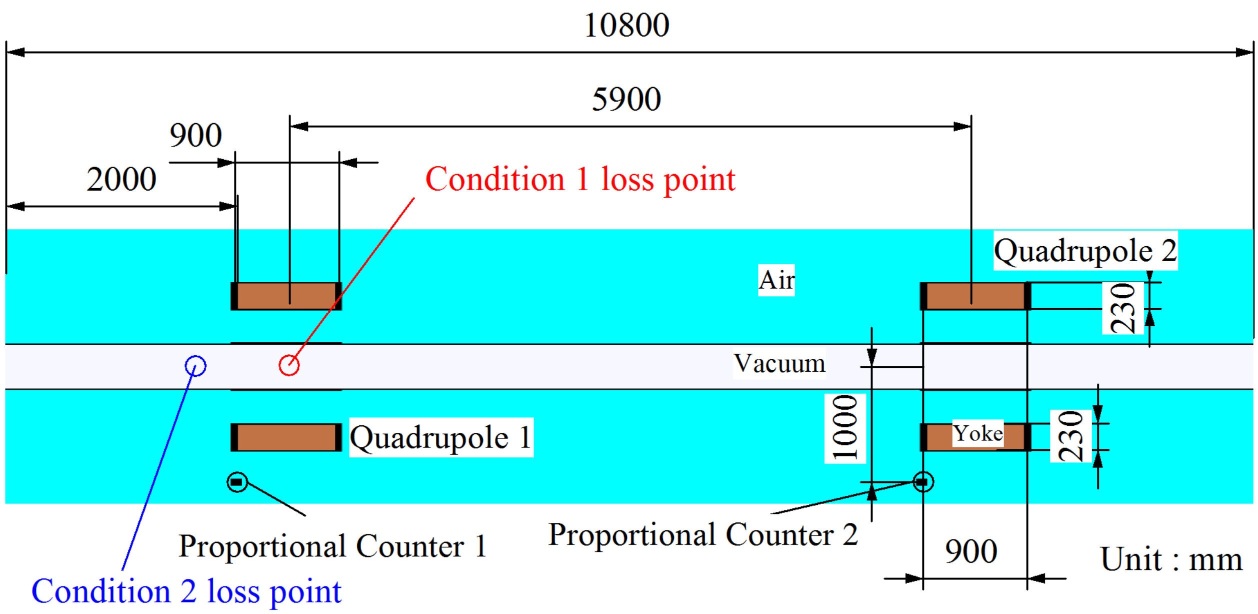

Figure 2: Geometry of the calculation model in MARS code.

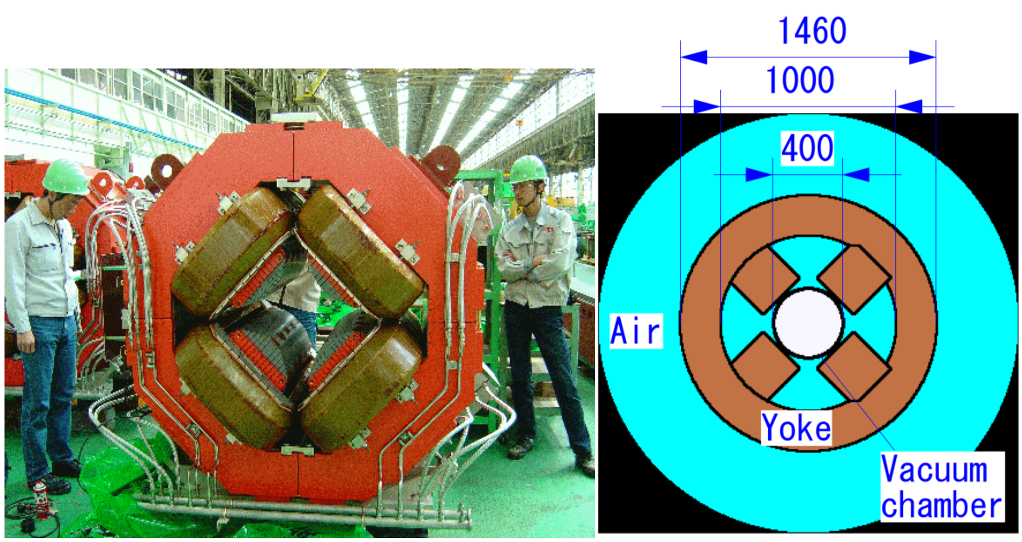

Figure 3: Cross sections of the quadrupole magnet.

The material of the magnets is iron. The vacuum chambers inside of the magnet are ceramic, and the other vacuum chambers are titanium. There is no magnetic field in this calculation. The proportional counters are the iron cylinders in which argon gas is filled. The outer diameter of the proportional counter is 25 mm and thickness of the cylinder is 1.5 mm. Two quadrupole magnets are located in an interval of 5.9m. Each proportional counter is put at the upstream of the magnet's feet.

In this calculation, the beam loss is assumed to be the side of the vacuum chamber. The lost beam shape is a pencil beam with the incident angle of 10 mrad (it has no distribution in the phase space). The number of the test particles is 10^7 in the calculation, and it is considered that those particles corresponded to $2*10^9$ particles per second (corresponded to 1 W loss at 3 GeV energy). In order to evaluate the shielding effect of the quadrupole magnet, we assume two initial conditions. In the first condition, the beam loss occurs in the center of the quadrupole magnet. On the other hand, the beam loss occurs in the 0.3 m upper reaches of the magnet entrance in the second condition (see Fig. 2). The lost beam energy is changed from 181 MeV to 400 MeV, 600 MeV, 800 MeV, 1 GeV, 1.5 GeV, 2 GeV and 3 GeV. We calculated the energy depositions at the argon gases in the proportional counters.

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RESULTS AND DISCUSSION

Result of Condition 1

The energy deposition in the condition 1 as a function of the lost beam energy is shown in Fig. 4, and the trajectories of the protons and secondary particles are shown in Fig. 5.

In this condition, since the beam loss occurred in the middle of the quadrupole magnet, the counter 1 was shielded by that quadrupole magnet. Therefore the energy deposition of the counter 1 was smaller than that of the counter 2 though the distance from the loss point was shorter than the counter 2. When the lost energy was smaller than 1 GeV, the secondary radiation which reaches the counter 1 was so few that the event was too rare (see upper pictures in Fig. 5), and the error bar was very large. The output signals had a tendency to increase in both proportional counters when the lost beam energy became larger due to more production rate of the secondary radiation.

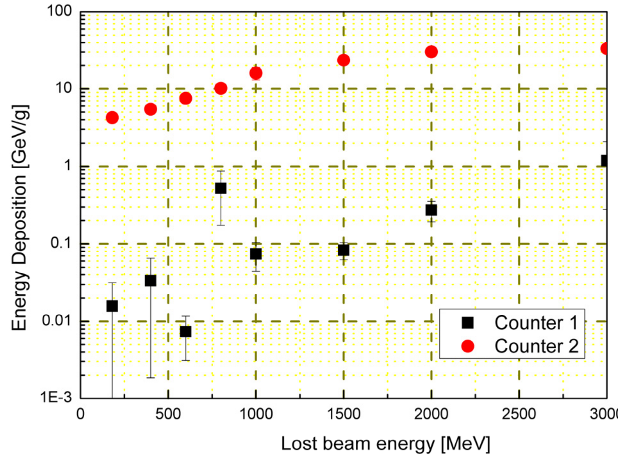

Figure 4: Energy deposition in the condition 1.

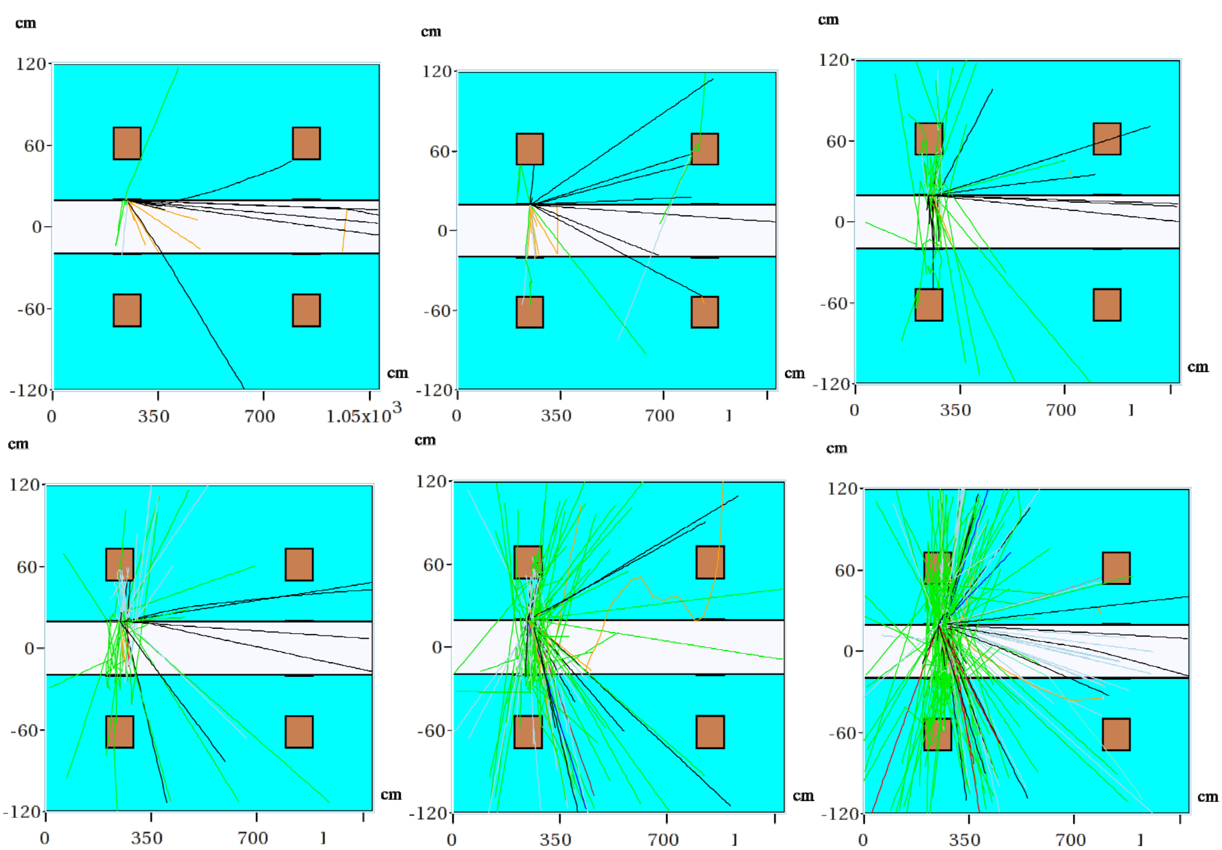

Figure 5: Trajectories of the lost protons and secondary particles in the condition 1.

10 test protons are hit on the vacuum target with the incident angle of 10 mrad at condition 1 lost point. The results are lost proton energy of 181 MeV (upper left), 400 MeV (Upper middle), 600 MeV (Upper right), 1 GeV (Lower left), 2 GeV (Lower middle) and 3 GeV (Lower right). Black lines are protons, green lines are neutrons, light grey lines are gamma-rays, orange lines are electrons, blue lines are pi- and red lines are pi+. Only few deuteron, tritium, alfa-ray, positron and muon from pion are also produced.

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Result of Condition 2

Fig. 6 and 7 show the energy deposition and the trajectories of test particles in the condition 2. Calculation results indicated that the energy deposition of the counter 2 had a minimum at the lost energy of 600 MeV. On the other hand, though the counter 1 was not shielded by the magnet and closer to the loss point, the energy deposition of the counter 1 at 181 MeV was lower than that of the counter2.

The particle trajectories in Fig. 7 revealed this reason. Since the major interaction of 181 MeV proton is the coulomb multiple scattering, the secondary particles were not so generated at the loss point and the counter 1 was not able to receive the energy deposition from those secondary particles. This effect led the larger energy deposition of the counter 2. When the lost beam energy rose to above 400 MeV, the production rate of the secondary radiation at the loss point was also increased. Then more energy was spent in the loss point than the vicinity of the counter 2, and the energy deposition of the counter 1 became larger than that of the counter 2.

Even if the same number of protons were lost, the energy deposition at the lost energy of 3 GeV is nearly 100 times larger than that of 181 MeV.

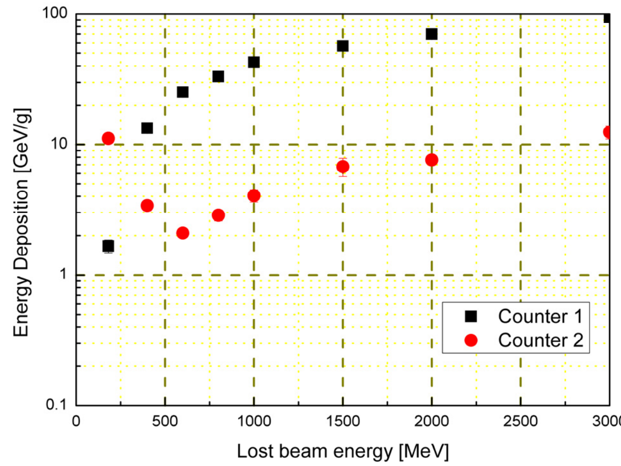

Figure 6: Energy deposition in the condition 2.

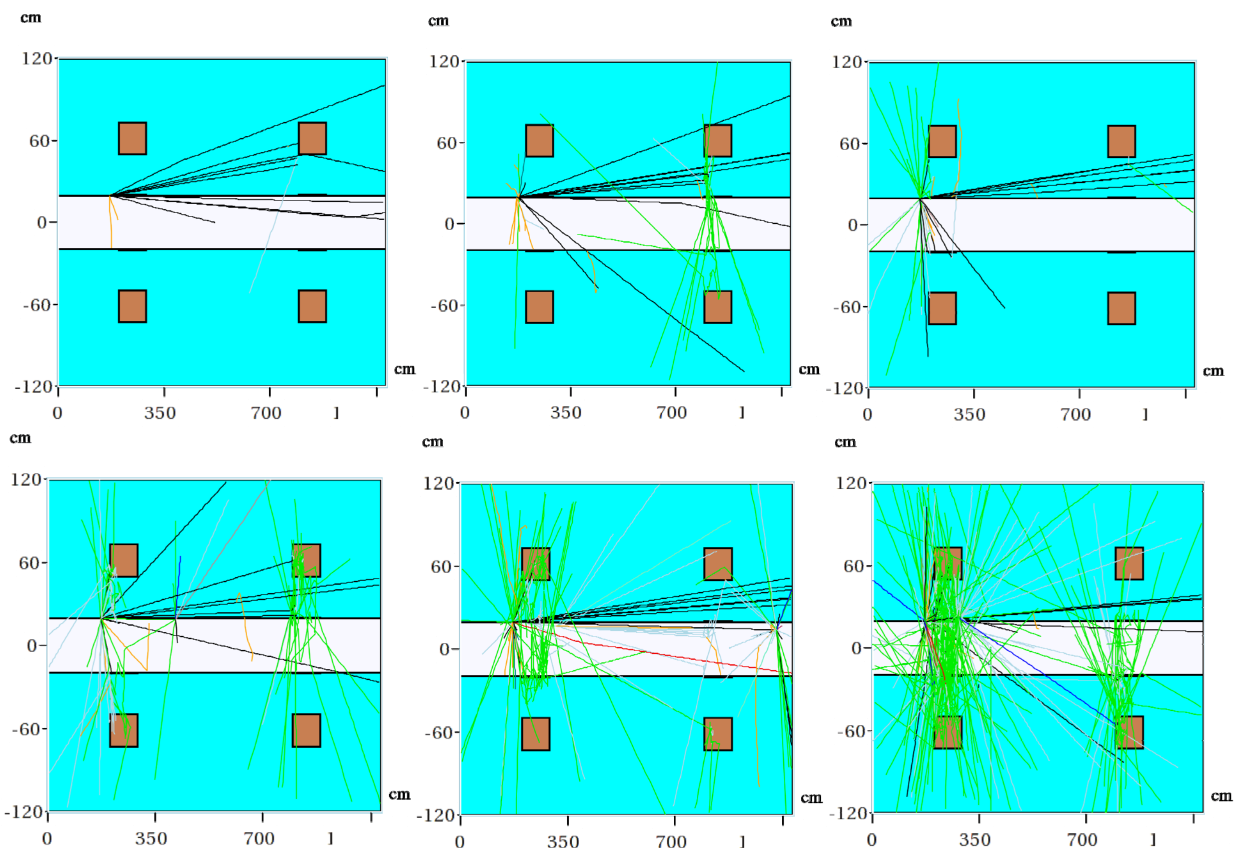

Figure 7: Trajectories of the lost protons and secondary particles in the condition 2.

10 test protons are hit on the vacuum target with the incident angle of 10 mrad at condition 1 lost point. The results are lost proton energy of 181 MeV (upper left), 400 MeV (Upper middle), 600 MeV (Upper right), 1 GeV (Lower left), 2 GeV (Lower middle) and 3 GeV (Lower right). Black lines are protons, green lines are neutrons, light grey lines are gamma-rays, orange lines are electrons, blue lines are pi- and red lines are pi+. Only few deuteron, tritium, alfa-ray, positron and muon from pion are also produced.

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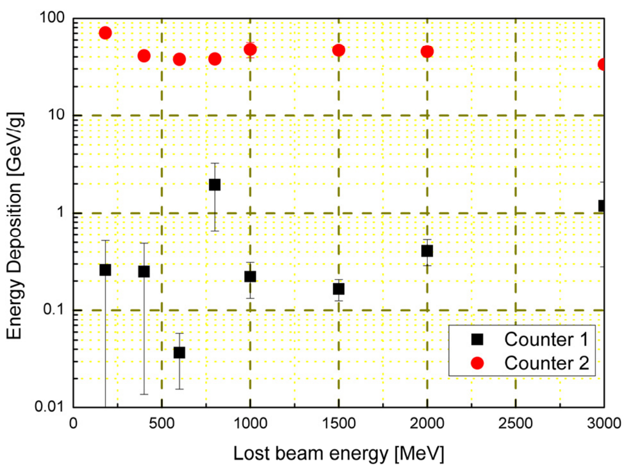
Comparison Between the Condition 1 and 2

From the comparison between the results of the condition 1 and 2, the energy deposition of the counter 1 was different by a factor of one hundred. The difference of the energy deposition of the counter 2 was several times. The large difference of the counter 1 was not only due to the shielding effect of the magnet but also due to the lower density of the hadron cascade at backward direction.

Normalization by the Lost Power

Figure 8 shows the energy depositions normalized by the lost beam power. Except the results of low energy loss and the counter 1 in the condition 1, the energy depositions were almost constant. This indicates that the energy deposition is proportional to the lost power in the energy range of more than 600 MeV.



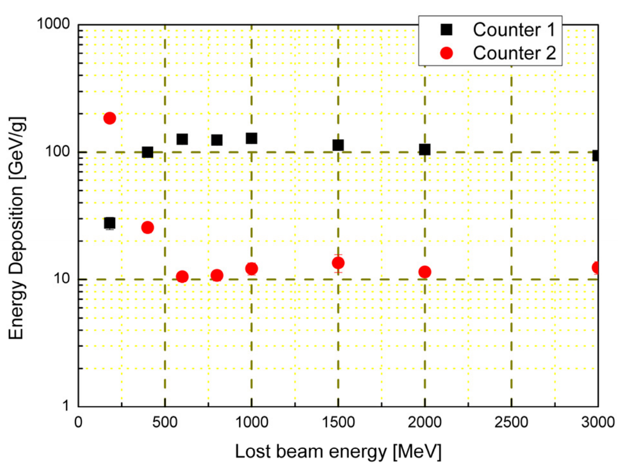


Figure 8: Energy deposition normalized by the lost power.

Results of the condition 1 (upper) and the condition 2 (lower)

CONCLUSION

The J-PARC RCS aims to deliver 1 MW high power proton beam to the downstream facilities. To achieve fine tuning of the accelerator for such high power beam operation, we investigated the response of the BLM with some conditions.

The results of calculation indicated that the response of the beam loss monitor strongly depends on the location of the lost point and lost energy. It is proportional to the lost power except the condition that the magnets become the radiation shielding.

Due to the sensitivity of the monitor response, we have not only to observe the beam loss monitor signals but also to investigate the residual dose distribution. Comparing the monitor signals and residual dose values, we can obtain more precise information of the beam loss.

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