Journal of NUCLEAR SCIENCE and TECHNOLOGY, Supplement 4, p. 338–341 (March 2004)

# Design of Ion Chamber for Beam Loss Monitor of PEFP

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A beam loss monitoring system is being designed for PEFP(Proton Engineering Frontier Project) by Korea Atomic Energy Research Institute(KAERI). The beam loss monitoring system is based on the ion chamber and an electrometer. An air-filled ion chamber was designed and fabricated as a prototype detector of beam loss monitor. The radiation response of the ion chamber was simulated by using EGSnrc code. The collection efficiency and stability of the ion chamber with respect to the different radii of inner electrodes is discussed. The proper choice of high voltage bias polarity for the ion chamber is also studied. The test of the ion chamber under high dose rate is under way at KAERI gamma irradiation facility at the exposure rate of $10^6$R/h.

***KEYWORDS: beam loss monitoring system, ion chamber, EGSnrc***

## I. Introduction

The PEFP(Proton Engineering Frontier Project) is to build an 100 MeV, 20 mA proton linear accelerator in Korea. An accelerator facility with such a high intensity beam needs the BLM(Beam Loss Monitor) system for the primary diagnostic tool for tuning and preventing excess activation and equipment damage. The detector of BLM has to satisfy many requirements. The gain of the detector has to be stable with time. The components of it should be tolerant of the radiation. If the detector is replaced with new one, the gain of it can be recalibrated easily. Ion chamber can satisfy such requirements, and a number of accelerator facilities select the ion chamber as the BLM detector.[1)]

We are designing an ion chamber for BLM. The ion chamber is cylindrical shape, and argon is filled inside the chamber. Before the parameters of the ion chamber are determined, we fabricated a prototype ion chamber. Air was filled inside the chamber, and the response of the ion chamber was measured. With these data, we can design the BLM ion chamber specifically.

## II. Prototype Ion Chamber

A prototype ion chambers for the BLM was fabricated, and the saturation curve of the ion chambers was measured. The prototype ion chamber was constructed of two concentric cylinders filled with air as shown in **Fig 1**. The cylinders were 210 mm long and made of 2-mm thick aluminum. The diameter of outer electrode was 38 mm, and three different inner electrodes were made(Type 1 : diameter of 6 mm, Type 2 : 16mm, and Type 3 : 25 mm). The inner electrode was hollow and filled with air inside. Guard electrode, which could reduce the leakage current of the collecting electrode, was made of copper, and it was placed in the middle of the inner electrode and the outer electrode. Teflon insulators were placed between electrodes.

The ion chamber was housed inside the 2-mm thick aluminum cylinder. Two MHV connectors were mounted for signal collection and high voltage biasing. These connector structure could help the easy daisy chaining. **Figure 1** shows the prototype ion chamber.

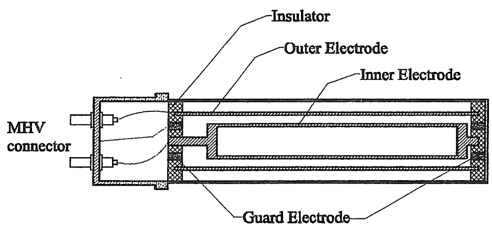


**Fig. 1** Prototype ion chamber.

The saturation curve of the ion chamber was measured. 60 keV $\gamma$-rays from $^{241}$Am incidented perpendicular to the cylinder surface, which make the dose rate of 2 mSv/hr in the center of the ion chamber. High voltage was biased on one connector with ORTEC high voltage supplier Model 660, and the collecting signal was recorded from the other connector with Keithley Electrometer Model 6517A. The high voltage was biased on the outer electrode, and the signal was measured on the inner electrode. After that the high voltage was biased on the inner electrode and the signal was recorded on the outer electrode. The polarity of the bias was also reversed. It could give the influence of the bias polarity on the ion chamber operation. Since we measured the saturation curve with three different types of inner electrodes, we could also determine the adequate diameter of the inner electrode.

### 1. Inner electrode diameter

The collection efficiency $f$ of an ion chamber at a given bias voltage $V$ can be defined as the ratio of the measured current to the ideal saturation current. The equations for describing $f$ have been known since Thomson described them

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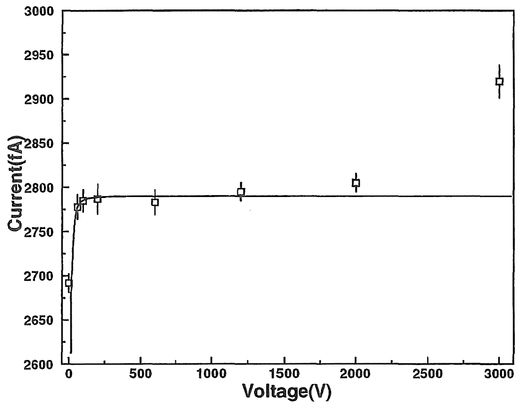


**Fig. 2** The saturation curve of ion chamber type II. The negative voltage was biased on the outer electrode, and the signal was recorded on the inner electrode. The line is from the fitting with the theoretical line.

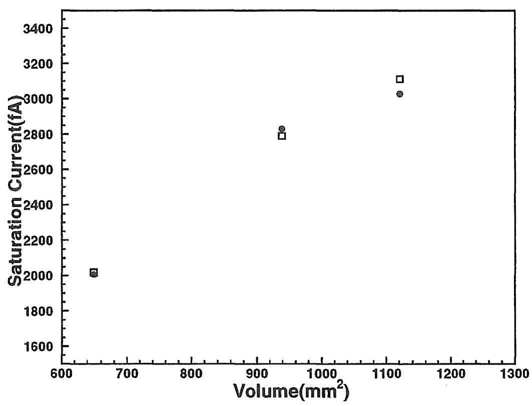


**Fig. 3** The saturation charge($Q_\infty$) vs. volume of the ion chamber. $Q_\infty$, which is expressed in current unit, is from the fitting.

**Table 1** $\beta$'s from the fitting. $\beta$ is defined in the main text, and it should be independent of the collection volume.

| CASE | $\beta$ | Error |
|---|---|---|
| Type I, Neg. Out | 4.86E-05 | 1.64E-04 |
| Type I, Pos. Out | 2.72E-04 | 1.60E-04 |
| Type II, Neg. Out | 4.08E-05 | 3.03E-05 |
| Type II, Pos. Out | 2.04E-05 | 2.67E-05 |
| Type III, Neg. Out. | 7.25E-05 | 3.58E-05 |
| Type III, Pos. Out | 2.25E-05 | 1.12E-05 |

in 1899.[2] However, they have not been solved in closed form. Approximated result, which gives a good fit for $f \geq 0.7$, is[3]

$$f = \frac{1}{1+\xi^2}, \tag{1}$$

where

$$\xi^2 = \left(\frac{\alpha}{6ek_1k_2}\right)\left(\frac{d^4}{V^2}\right)\left(\frac{Q_\infty}{vol}\right). \tag{2}$$

Here, $e$ is the electron charge, $k_1$ the electron mobility, $k_2$ the ion mobility, $d$ the equivalent gap, $Q_\infty$ the saturation charge at infinite applied voltage, $vol$ the collecting volume of the ion chamber, and $\alpha$ is the first Townsend recombination coefficient. $d$ for the cylindrical ion chamber can be expressed as

$$d = (a-b)\left[\frac{a+b\,ln(a/b)}{a-b}\frac{}{2}\right]^{1/2}, \tag{3}$$

where $a$ the radius of outer electrode, and $b$ is the radius of inner electrode. From above equations, we can see that the signal can be saturated easily in lower bias voltage as the distance between the outer electrode and the inner electrode gets closer.

The saturation curve of Type II ion chamber is shown in **Fig. 2**. The curve reaches a flat zone, and the charge multiplication occurs when the voltage is higher than 2000 V. We use three different methods to obtain the voltage, where $f$ reaches 0.999, for each saturation curve.

The first method is the inverse voltage method. There shows a linear relationship between the inverse of the collecting current, $i$, and the inverse of the applied voltage, $V$, in the near saturation region, if the recombinations of the positive and the negative ions form within the track of a single ionizing particle.

$$\frac{1}{i} = \frac{1}{i_0} + \frac{constant}{V}, \tag{4}$$

where $i_0$ is the ultimate saturation current. We can get $i_0$ from extrapolation, and determine the voltage, where $i$ is 99.9 % of $i_0$.

The second method is the two voltage method, which is known to be independent of the shape of the saturation curve.

$$f = \frac{(V_1/V_2)^2 - i_1/i_2}{(V_1/V_2)^2 - 1}. \tag{5}$$

Here applied voltage, $V_i$, and the measured charge, $i_i$, are obtained from different pair of measurement.

The third method follows from Eq. 1. If we set $\eta^2 = f\xi^2$, we can obtain $\eta^2$ from the measurement. Then

$$f = 1 - \eta^2 = 1 - \beta\frac{d^4}{vol}\frac{fQ_\infty}{V^2}, \tag{6}$$

where $\beta = \left(\frac{\alpha}{6ek_1k_2}\right)$.

If we multiply $Q_\infty$ on both sides of Eq. 6,

$$fQ_\infty = Q_\infty\left(1 - \beta\frac{d^4}{vol}\frac{fQ_\infty}{V^2}\right). \tag{7}$$

$fQ_\infty$, $\frac{fQ_\infty}{V^2}$, $d$ and $vol$'s can be obtained from the measurement, and $Q_\infty$ and $\beta$ are varied in the fitting with the measurement.

**Table 1** shows $\beta$ from the fitting result. Except the positive voltage biased on the ion chamber Type I, they are well agreed within error bar, which is consistent with the expectation. $Q_\infty$ from fitting result with respect to the volume is shown in **Fig. 3**. Since the 60 keV $\gamma$-ray source is placed in center of the ion

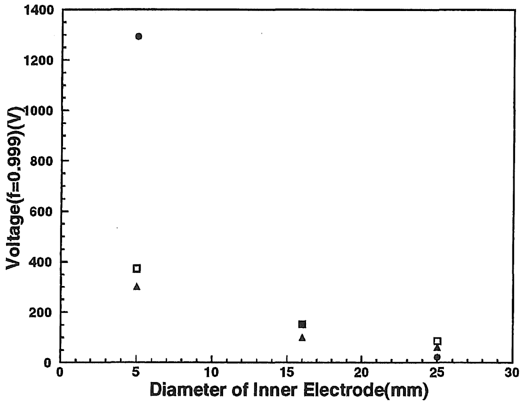


**Fig. 4** $V_{f=0.999}$ as a function of the diameter of the inner electrode. The closed circles are from the inverse voltage method, the closed triangles from the two voltage method, and the open squares are from the fitting method. As the diameter of the inner electrode gets larger, $V_{f=0.999}$ gets smaller.

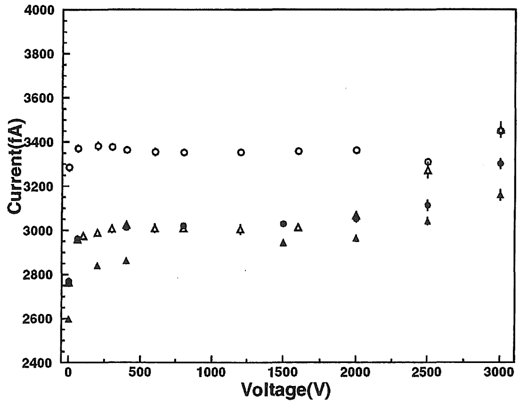


**Fig. 5** The bias polarity effect on the ion chamber operation. The ion chamber is Type I. The open circles are the case of the negative voltage biased on the inner electrode, the closed circles the case of the positive voltage on the outer electrode, the open triangle the case of the negative voltage on the outer electrode, and the closed triangles are the case of the positive voltage biased on the inner electrode.

chamber, the collecting volume can be estimated from $\pi(a^2 - b^2)$. $Q_\infty$ increases almost linearly with the collecting volume, which is also consistent with the expectation.

The line in **Fig. 2** is from Eq. 1, in which the parameters of $Q_\infty$ and $\beta$ are taken from the above fitting result.

The biased voltages $V_{f=0.999}$, where $f = 0.999$, are obtained from above three methods. **Figure 4** shows $V_{f=0.999}$ in the case of the negative voltage biased on the outer electrode. As one can expect, the measured current can be saturated in lower voltage if the distance between the outer electrode and the inner electrode gets closer. Three methods give the similar result except the case of $b = 5$ mm. Since the inverse voltage method assumes that the recombination takes place within the track of single particle ionization, it can not give a reliable result.

Because beam loss monitoring system will be placed in the high dose environment, it is better to get the saturation current with lower biased voltage.

The ion transit time can be expressed as[4)]

$$t = \frac{d^2}{\mu_0 V(P_0/P)}, \tag{8}$$

where $\mu_0$ is the ion mobility, $V$ applied voltage, $P_0$ atmospheric pressure, and $P$ is the working pressure. If $d$ gets smaller, we can collect ions in shorter time.

However, the field becomes unstable when the inner electrode is too close to the outer electrode. In our measurement with ion chamber Type III(Inner electrode diameter: 25 mm), the signal shows fluctuation above $V$ = 2000 V. And, as the inner electrode gets close to the outer electrode, we will get smaller current.

¿From the above consideration, we choose 20 mm for the diameter of inner electrode.

## 2. High voltage Bias polarity

It is known that the current collected from an ion chamber exposed to constant radiation can change in magnitude when the polarity of the collecting potential is reversed. The prototype ion chambers were tested with both positive and negative voltage biased on the inner electrode, and the signal was recorded on the outer electrode. The ion chambers are also tested with high voltage biased on the outer electrode, and the signal measured on the inner electrode. These four configuration can give the influence of high voltage bias polarity on the BLM ion chamber operation. The results are shown in **Fig. 5**. The magnitudes of the measured currents in four cases were different. When high voltage was applied on the outer electrode and the polarity was reversed, the magnitude of the collected current stayed almost the same. However, high voltage was biased on the inner electrode and the polarity was reversed, the magnitude changed quite significantly. It is suggested if the potential of the outer electrode is not the same as the potential of the housing. Then the charge liberated in the volume between the outer electrode and the housing can be collected through the outer electrode. Further investigation is under way. When high voltage is biased on the outer electrode, the shape of the saturation curve does not change much with the change of high voltage polarity, except ion chamber Type I. When the negative high voltage was biased on the outer electrode, the electron multiplication gets bigger in higher voltage region. From the above study, we will bias the positive high voltage on the outer electrode, and the current will be collected on the inner electrode.

## 3. Wall material

Inside the ion chamber the secondary electrons generated from the walls will also ionize the gas. If the walls are sufficiently thick compared with the secondary electron ranges, the secondary electron flux leaving the wall will be independent of the wall thickness. Since the incident radiation will be attenuated through the wall, the walls of ion chamber should

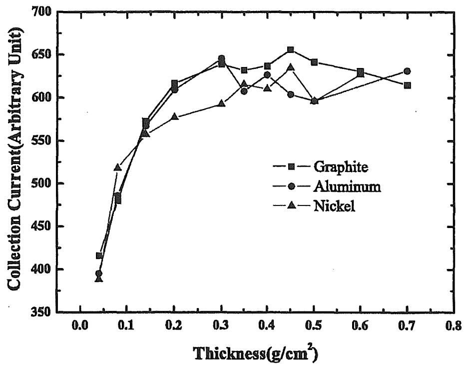


**Fig. 6** The collecting current with respect to the thickness of wall from EGSnrc calculation. The thickness is expressed as $g/cm^2$.

be thin enough to reduce the attenuation of incident radiation. The proportion of wall electrons inside the ion chamber is known to be independent of the nature of wall material if the wall thickness is expressed in gram per square centimeter.[3] However the wall material and thickness has to be more carefully determined.

Monte-Carlo calculation was performed to simulate the response of the ion chamber with respect to the wall material and wall thickness. EGSnrc code is used for the calculation. EGSnrc was recently developed and it is the first Monte Carlo code thought to be able to simulate ion chamber response at the 0.1 % level of accuracy.[5]

In the EGSnrc calculation, the electron cutoff energy(AE) was 512 keV and the photon cutoff energy(AP) was 1 keV. The spin effects in the multiple scattering were off, which will make an effect less than 0.1 %. Graphite, aluminum, and nickel are simulated for the wall material, and argon gas, which will be filled inside our BLM ion chamber, is inside the collecting volume. The thickness of wall material is changed with gram per square cm unit. The response of ion chamber for $\gamma$-ray from $^{60}$Co is simulated.

The result of the simulation is shown in **Fig. 6**. The current show almost similar behavior with respect to the thickness of the wall expressed as $g/cm^2$. The current in nickel wall is smaller than the other ones. We select aluminum as the ion chamber wall, and the thickness is 2 mm, which is for the incident energy of $\gamma$-ray from $^{60}$Co.

## III. Design Parameters and Future Study

The BLM ion chamber parameters are as follows. The BLM ion chamber will be a aluminum cylindrical shape of 210 mm long. The diameter of outer electrode is 38 mm, and the diameter of the inner electrode is 20 mm, which follows from the measurement with prototype chamber. The thickness of aluminum electrode will be 2 mm, which was from EGSnrc calculation. The net internal volume of the detector is 103 cm$^3$. The estimated response will be 12pA/Rad/hr. The insulator is made of ceramic.

We are underway to test the prototype chamber in high dose rate at KAERI gamma irradiation facility. Also the BLM ion chamber is designed and being fabricated.

## IV. Conclusion

In Korea, high current proton accelerator is developed by PEFP. The BLM system is necessary for such an accelerator facility, and the ion chamber can be an adequate choice for BLM detector. The design of the ion chamber for BLM is studied in KAERI. A prototype ion chamber was fabricated. It was the concentric aluminum cylinders and air was filled inside the collecting volume. The effect of the radius of the inner electrode, and the bias polarity on the ion chamber operation were measured with the prototype ion chamber. EGSnrc code was used to simulate the wall material effect on the ion chamber operation.

From these studies, we can determine the specific of the BLM ion chamber.

This work has been carried out under the Nuclear R&D program by Ministry of Science and Technology(MOST) of Korea. The authors also wish to acknowledge the partial support from KOSEF Engineering Research Center program of Innovative Technology Center for Radiation Safety(iTRS) at Hanyang University, Seoul, Korea.

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