Improved design and construction of an ionization chamber for the CSNS beam loss monitor (BLM)*

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Abstract: Based on the first ionization chamber (IC) prototype, the structure, working gas component and electrode material of the IC are improved. The test of the improved IC shows that the plateau length is about 2000 V, the plateau slope is less than 0.2%/100 V, the sensitivity is 19.6 pA/rad·h^{-1}, the up-limitation of the linearity can be up to 3.6×10^5 rad/h, and the applied voltage can be operated to 3500 V. The test results show that the performance of the improved IC meets the requirements of the beam loss monitor.

Key words: CSNS BLM detector, ionization chamber, plateau curve

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1 Introduction

The China Spallation Neutron Source (CSNS) [1] is composed of an accelerator, which consists of an H$^-$ ion linac and a proton rapid cycling synchrotron, beam transportations, a target station, spectrometers, and also the necessary service facilities for them. The facility is designed to accelerate the proton beam kinetic energy to 1.6 GeV at a 25 Hz repetition rate and the accelerator is designed to deliver a beam power of 100 kW. One of the key difficulties existing in theory and also in technology for the high intensity beam proton accelerator is beam loss, which is the bottleneck factor determining the final power level of this kind of accelerator. In order to reach the designed power, the beam loss must be limited to 1 W/m.

Beam loss monitors (BLMs) are required to measure the radiation and their locations exactly at a certain time in an area close to the beam pipe to realize machine protection and beam commission. So it is necessary to mount a certain amount of BLMs in the right positions on the H$^-$ ion linac and rapid cycling synchrotron pipe, and also on the beam transport pipes.

The ionization chamber (IC) is one of the most important detectors in a BLM system. The first prototype IC, whose working gas was 100% Ar, applied voltage was 1000 V, linearity range was up to 200 Roentgen/h, and the plateau length was about 800 V, has been reported [2]. The IC working as the BLM during the period of CSNS operation can operate stably, but its performance is still required to be improved when it is used during the period of construction and commission.

2 The improved IC design

According to the requirement of the CSNS , the IC used as a BLM should have a long plateau (≈2000 V) with the plateau slope less than 0.2%/100 V, high sensitivity (15–20 pA/rad·h^{-1}), good linearity (dynamic range $\geqslant10^5$ rad/h), and the ion collection time at negative 3 kV bias would be around 70–80 μs. These specifications can be achieved by increasing the ap-

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plied voltage and optimizing the working gas component. The applied voltage can be increased component. The applied voltage can be increased through optimizing the geometric design and choosing an appropriate electrode material.

2.1 Optimization of the working gas

The response speed of the cylindrical ionization chamber depends on the positive ion transit time T, which is expressed as [3]:

$$T=\frac{d^2}{\mu_0 V_0\left(\frac{p_0}{p}\right)},$$

where μ_0 [$\text{cm}^2/(\text{V}\cdot\text{s})$] is the ion mobility at standard temperature and atmospheric pressure, p is the working pressure, p_0 is the standard atmospheric pressure (equals 760 mmHg), V_0 [V] is the applied voltage, and d is the effective electrode separation [cm] for cylindrical geometry, which is expressed as:

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

where a is the outer electrode radius and b is the inner electrode radius, respectively.

The BLM requires a positive ion transit time, which is proportional to the working pressure and inversely proportional to the applied voltage, and as fast as possible. The positive ion transit time of the first prototype IC equals 72 μs when the applied voltage is −1500 V and the working pressure is 0.95 atm. Increasing the applied voltage and decreasing the working pressure are favorable for reducing T.

Adding some polyatomic molecule to the pure Ar, which is the working gas of the first prototype IC, can not only enhance the applied voltage but also increase the response speed. According to the GEANT4 [4] simulation results, under the radiation of 100 R/h, different working gases lead to different output currents: Ar is 1354 pA, N_2 is 1273 pA, Xe is 4097 pA, Kr is 2578 pA and He is 196.2 pA, respectively. Considering the output current and also the factor of price (Xe and Kr as noble gases are expensive), N_2 is the most suitable gas as the component of mixed gas.

The IC's applied voltage was tested by using the high current breakdown test method, and the result shows that different proportions between Ar and N_2 lead to different applied voltages, which are listed in Table 1.

Table 1. The comparison of applied voltages between different gas mixtures.

gas mixture	anode to ground/V	negative to ground/V	anode to negative/V
pure Ar	1200	1400	1600
Ar(90%)+ N_2 (10%)	1800	2400	2400
Ar(80%)+ N_2 (20%)	2200	3200	2800
Ar(70%)+ N_2 (30%)	2500	3600	3200

Increasing the working pressure leads to the reduction of particle drift speed and then leads to the increase of T. It also contributes to the increase of output current through increasing ion pairs in unit volume and then leads to the increase of sensitivity. The transit time of the positive ions is calculated to be 80 μs if 760 mmHg is adopted in the IC, which is very close to 72 μs, where the working pressure is 725 mmHg, so 760 mmHg is adopted as the working pressure because it is easy to operate and it is favorable for increasing sensitivity.

2.2 The improved electrode design

The electrode itself plays the role of the solid radiator when the type of cylindrical IC measures γ radiation. With the outer electrode biased at negative voltages as incident γ enters into IC, the majority of ions will be generated in the vicinity of the outer electrode. So, the way that most of the positive ions drift to the outer electrode, which biases at negative voltage, before being collected is significantly shorter than the one that the positive ions drift to the inner electrode when the outer electrode biases at positive voltage. This will reduce the opportunities of positive ions and electrons combined to improve saturation characters. In addition, the IC will have stronger anti-interference ability when the signal electrode is on the ground potential.

The two electrodes of the first prototype IC are aligned in a cross section direction. So the high field points at the tip of the two electrodes are easy to break down when the voltage is raised. To increase the IC's applied voltage on the condition that the IC maintains the same size like the prototype where the inner electrode diameter Φ_{in}=2.54 cm and the outer electrode diameter Φ_{out}=3.81 cm, 10 mm are retracted at both ends of the inner electrode. So the effective length is shortened from 17.4 cm to 15.4 cm,

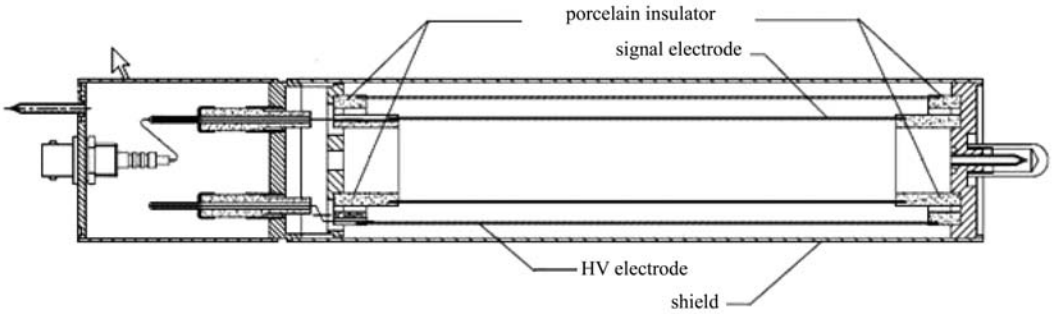

Fig. 1. The schematic diagram of the improved IC.

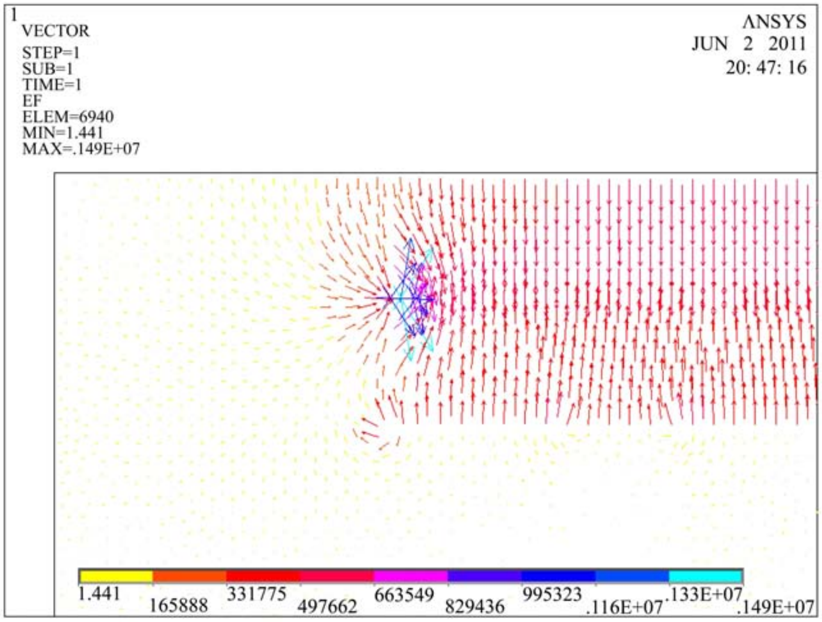

Fig. 2. The map of electric field for the cylindrical electrode in the vertical section (3000 V).

and the effective volume is reduced from 110 cm^3 to 98 cm^3. Fig. 1 shows the structure of the improved IC. The creeping distance of the improved IC is increased and also the applied voltage is improved. However, the new structure also makes the IC need more time to reach the saturate zone because of the uniformity in the edge of the electric field. From the ANSYS simulation result, as shown in Fig. 2, one can more intuitively see the relative situation of the two electrodes.

2.3 The choice of the electrode material

According to the GEANT4 simulation, the output current of aluminum, stainless steel and nickel under radiation of 100 R/h is 731.8 pA, 1355 pA and 1354 pA, respectively [5]. The effect of aluminum is inferior to the effect of the other two materials. Nickel was chosen as the electrode material of the first prototype IC, and it was rolled into a cylinder. As the welding seam is not smooth, it is easy to lead to the pointed end discharge. We chose the seamless stainless steel tube as the electrode material.

3 Performance test of the improved ionization chamber

Based on the aforementioned improvements, the improved prototype IC was constructed and its performance was tested with a radiation source.

3.1 Plateau curve measurement

A 4300 Ci ^{60}Co radiation source was used for the test, and the test setup is shown in Fig. 3. The radiation intensity can be adjusted through changing the distance between the chamber and the ^{60}Co source.

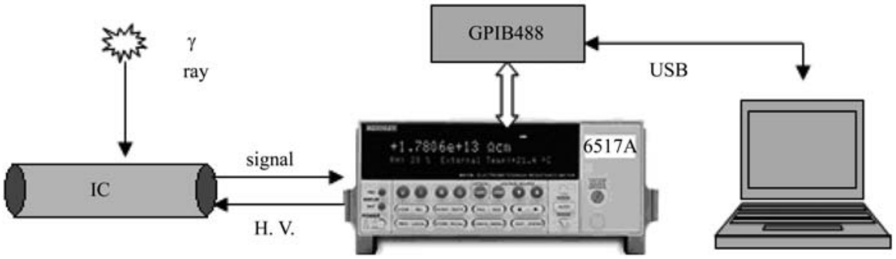

Fig. 3. Setup of the IC's plateau curve measurement.

The signal current of the chamber is first fed into a Keithley 6517A high-impedance electrometer through low noise cable, then it passes sequentially through GPIB-488 and USB interfaces, and finally it is read out by an online computer. The program running for readout is implemented by LABVIEW. The measured plateau curve is shown in Fig. 4 and Fig. 5, respectively. As shown in Fig. 4 and Fig. 5, for the improved IC, the plateau appears from 50 V after irradiation with low radiation dose; while for higher radiation dose, the plateau has a slightly larger starting voltage. However, in both cases the plateau length is more than 2000 V. The plateau slope is equal to or less than 0.2%/100 V. The IC after improvement can work at a rather high applied voltage up to −3500 V even under a very large radiation dose of 3.6×10^5 rad/h.

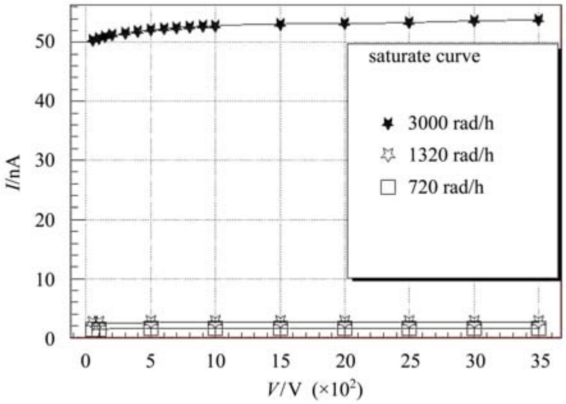

Fig. 4. The plateau curve of the improved IC (for a low radiation dose).

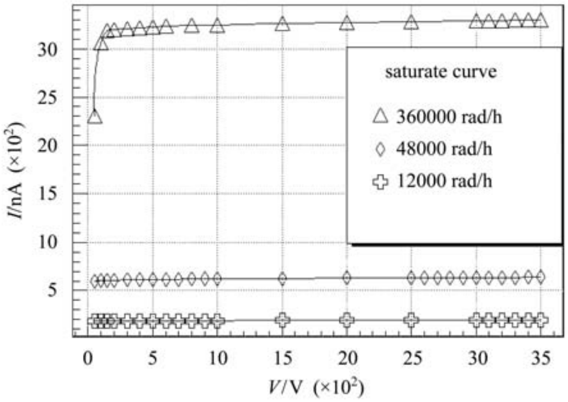

Fig. 5. The plateau curve of the improved IC (for a high radiation dose).

3.2 Linearity

Figure 6 shows the linearity of the improved IC. The Y coordinate means saturation current and the X coordinate means radiation dose. From the fitting, one can see that the improved IC has good linearity.

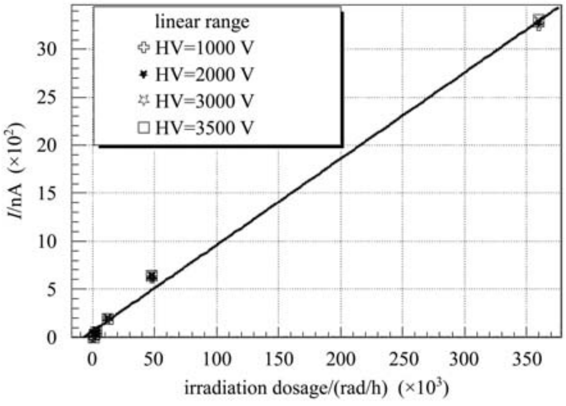

Fig. 6. The linearity response of the improved IC.

3.3 Sensitivity

The sensitivity of IC is defined as the output current for a unit radiation dose. The current here is the one when the IC operates in the saturation region. Table 2 shows the sensitivity for the γ ray under different radiation doses.

Table 2. The sensitivity on the γ source for the improved IC.

radiation dose/(rad·h^{-1})	720	1320	3000	12000	48000	360000
γ sensitivity/(pA/rad·h^{-1})	21.3	19.6	17.7	15.8	13.0	9.1

Compared with the sensitivity of the first prototype (12.0 pA/rad/h under −600 V high voltage and 200 rad/h radiation dose), the improved IC prototype has a much better sensitivity for γ ray detection. It must be pointed out that the sensitivity of the improved IC at the largest dose of 3.6×10^5 rad/h is smaller than the low dose because: (1) the probability of the recombination of ions during drift is much larger due to the large amount of produced ions in the case of high radiation dose; (2) due to the limitation on test, the IC can not be fully irradiated, which leads to a smaller output current.

4 Conclusion

Based on an improved design of the ionization chamber, the structure of the chamber was optimized, and the electrode design was improved. An appropriate working gas was chosen and a proper material was used to make the electrode. The performance of the IC was significantly improved compared with the first prototype IC. The test results show that the improved IC has reached the requirements of CSNS beam loss monitoring.

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