Performance of connected GSO bars

Elsevier Editorial System(tm) for Nuclear Inst. and Methods in Physics Research, A

Manuscript Draft

Manuscript Number:

Title: Performance of connected GSO bars

Article Type: Research Paper

Section/Category: High Energy Physics Detectors

Keywords: Rare decay, Detector, GSO, Scintillator, Resolution, Gamma ray

Corresponding Author: Mr. Yoichi Tamagawa,

Corresponding Author's Institution: Fukui University

First Author: Yoichi Tamagawa

Order of Authors: Yoichi Tamagawa

Manuscript Region of Origin:

Abstract: The performance of connected GSO (Gd_2SiO_5:Ce) bars was investigated using a proton beam of 0.6 - 1.0 GeV/c. Single crystals of 20 cm-long GSO with different Ce concentrations (1.5 mol%, 0.5 mol%) and cross sections (1 cm × 1 cm , 2 cm × 2 cm) were prepared. Long GSO bars were constructed by connecting two crystals of the same type with or without a 10 cm-long plastic scintillator between the crystals. The position dependences of the pulse height, energy resolution and time resolution were investigated. At a typical proton momentum, 1.0 GeV/c, the best energy resolution was 4.8% for 2 cm × 2 cm × 20 cm GSO crystals doped with 0.5 mol% Ce due to the larger light yield, and the best position resolution was 0.55 cm for 1.5 mol% Ce due to the shorter attenuation length.

Manuscript

Performance of connected GSO bars

Y. Tamagawa[a], H. Shirasaka[a], M. Kobayashi[b], T. K. Komatsubara[b], K. Mimori[b], K. Omata[b], T. Sekiguchi[b], S. Sugimoto[b], T. Tsunemi[b], T. Yoshioka[b], Y. Yoshimura[b] and T. Fujiwara[c]

[a] Department of Applied Physics, Fukui University, Fukui 910-8507, Japan
[b] High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan
[c] Physics Department, Kyoto University, Kyoto 606-8317, Japan

Abstract

The performance of connected GSO (Gd_2SiO_5:Ce) bars was investigated using a proton beam of 0.6 – 1.0 GeV/c. Single crystals of 20 cm-long GSO with different Ce concentrations (1.5 mol%, 0.5 mol%) and cross sections (1 cm × 1 cm , 2 cm × 2 cm) were prepared. Long GSO bars were constructed by connecting two crystals of the same type with or without a 10 cm-long plastic scintillator between the crystals.

The position dependences of the pulse height, energy resolution and time resolution were investigated. At a typical proton momentum, 1.0 GeV/c, the best energy resolution was 4.8% for 2 cm × 2 cm × 20 cm GSO crystals doped with 0.5 mol% Ce due to the larger light yield, and the best position resolution was 0.55 cm for 1.5 mol% Ce due to the shorter attenuation length.

Keywords: Rare decay, Detector, GSO, Scintillator, Resolution, Gamma ray.

*Corresponding author.
Tel.: +81776278764; fax: +81776278494; e-mail: tamagawa@apphy.fukui-u.ac.jp

1. **Introduction**

Experimental studies of rare K-meson decays, such as $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, are very interested in searching for any clear evidence of new physics beyond the standard theory. Such experiments have usually been carried out using a large-scale magnetic spectrometer implemented with a precision EM calorimeter, as is used in BNL-E787/E949 experiments [1]. In the E787/E949 experiments, $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay was found in 1997 [2] for the first time after many years of improving the detector system, and additional events have been observed in recent years [3]. It is indispensable to make further improvements in the detector, especially in the detection acceptance and the background rejection. If a non-magnetic detector is feasible, the acceptance could be substantially increased. Moreover, the detector without a magnet would become compact in size, thereby making various improvements more feasible. One of the possible configurations for a non-magnetic, compact, 4π detector for rare K^+ decay experiments needs a stack of high-quality fast-response scintillators surrounding the decay vertex for detecting both charged particles ($\pi^{\pm}, \mu^{\pm}, e^{\pm}$) and γ-rays, all below 250 MeV/c.

The scintillators should be fine-segmented so as to measure the position, the range and the total energy of each decay particle. Besides the K-meson experiment, a detector of this type would also be useful for any other experiments that require precision detection of both low-energy charged particles and γ-rays emitted from the target with 4π coverage, as shown in Fig.1.

The required scintillator should be heavy enough to measure both charged particles and γ-rays, efficient in scintillation light yield to obtain good energy resolution, and radiation-resistant. Cerium-doped gadolinium silicate, GSO:Ce [4], may be a promising candidate, as shown in Table 1. From the energy of charged particles and γ-rays in the decay products, GSO bars with ~40 cm length are required. To study the feasibility of the above-mentioned idea for a compact, non-magnetic, 4π-str spectrometer for rare K-meson decays, we tested bars of GSO:Ce crystal with respect to the position, energy and time resolutions.

GSO crystals are now available with a diameter and length as large as 105 mm and 290 mm, respectively [5,6,7]. Two crystals have to be connected to obtain a 40 cm-long crystal. At the center of the detector system, a plastic scintillator may be useful for the stopping target due to better time resolution. We have tested GSO bars with a configuration of a GSO-plastic scintillator-GSO as well as GSO-GSO. The present paper describes the performance of the connected GSO detector bars studied with a proton beam.

2. Experimental Setup

Three types of GSO single-crystals were grown by Hitach Chemical co.:

1. 1.5 mol% Ce-doped crystal of cross section 1 cm × 1 cm,
2. 1.5 mol% Ce-doped crystal of cross section 2 cm × 2 cm,
3. 0.5 mol% Ce doped crystal of cross section 1 cm × 1 cm

The length of each crystal was 20 cm. As sketched in Fig. 2, we connected two crystals of the same type with silicone grease to make a 40 cm-long bar. It was viewed by two PMTs (Hamamatsu H3171-R1398 [8]) on both ends. The output signals of the PMT were fed to ADC and TDC CAMAC modules.

The proton beam from the T1 line of KEK-PS was defined to 3 mm × 3 mm by using 4-fold coincidence of plastic scintillators placed upstream and downstream of the GSO bar. The beam momentum was set to 0.6 GeV/c, 0.8 GeV/c and 1.0 GeV/c. Measurements on each GSO bar were performed by changing the beam position at a step of 1 or 2 cm by moving the bar and the PMT assembly sideways. Two plastic scintillators for TOF were set apart by 5.83 m in front of the GSO sample to identify the incident beam particle. The data taking was done using an IBM PC and the KODAQ data-acquisition program [9].

A typical ADC histogram of GSO signals is shown in Fig. 3, where the two peaks indicate the energy absorption of incident protons and π 's in the GSO bar.

3. Results

3.1. GSO-GSO bar

We studied the performance of the connected bar of two GSO crystals, as sketched in Fig. 2. We measured the pulse-height distribution, energy resolution and time distribution for 0.6 – 1.0 GeV/c protons. The position resolution was estimated from the pulse height and the time distributions.

3.1.1 Pulse height and energy resolution

As shown in Fig.4, the pulse height of each PMT (A0, A1) decreased exponentially with respect to the beam position. At the center of the GSO bar, where the connection plane was located, the pulse height showed a sudden decrease because of the reflection of light at the connection plane. The total pulse height, which is the sum of both PMT's output (A0+A1) , is not constant with respect to the beam position due to light attenuation in the scintillator. It became about 20% smaller at the center of the GSO bar compared to that at the endpoints. The obtained attenuation spectrum could be used to correct the pulse height when GSO bars were assembled in a detector system. On the other hand, the energy resolution calculated from the width of the proton peak in the distribution of the total pulse height (Fig. 5) was almost constant with respect to the position, except for the endpoints (Fig. 4). The obtained energy resolution is given in Table 2 for different crystal pairs.

The energy resolution of the connected GSO bar with the larger cross section (2 cm $\times$ 2 cm) was better than that of the smaller one (1 cm $\times$ 1 cm); it became better at a lower beam momentum because of a larger energy deposit in the crystal. The energy resolution did not depend so much on the Ce concentration in the crystal, while the pulse height was typically by 27% larger for 0.5 mol% than for 1.5 mol%. The best energy resolution was 3.4% obtained by a 0.5 mol% Ce 2 cm $\times$ 2 cm sample for a 0.6 GeV/c proton beam, whose deposited energy in the GSO crystal was 44.3 MeV, calculated by GEANT3 simulations [10].

3.1.2 Position resolution estimated from the pulse height

The position dependence of the pulse-height ratio (A0/A1) is plotted in Fig. 6 as a function of the beam position (x). After the position dependence is calibrated, we can estimate the beam position from the pulse-height ratio. For a simple estimation, the ratio is fit as $A0/A1 = a \cdot \exp(-2x/b)$ independently in $x>0$ and $x<0$. The effective attenuation length (b) and the estimated position resolution of these crystals for the case of 1.0 GeV/c proton were calculated, and are listed in Table 3. A 0.5 mol% Ce doped GSO-bar has a longer attenuation length owing to its good transparency compared with a 1.5 mol% Ce bar. While the former is superior to the latter in the light yield and energy resolution, as shown in the previous section, the latter gives a better position resolution (0.64 cm) due to the larger position dependence of the pulse-height ratio.

3.1.3 Position resolution estimated from signal time

The pulse from each PMT has a different time according to the beam position in a long connected GSO bar. The time difference between both ends of the GSO bar gives beam-position information, similarly to the pulse-height ratio.

The typical linear relation between the signal time and the beam position is plotted in Fig. 7. At the center of the connected GSO bar, we see a slight deviation from the linear dependence. The deviation is explained in terms of the reflection of light for the events which occurred probably near to the connection plane. The effective light speed in these connected crystal systems and the position resolutions estimated from the time difference for 1.0 GeV/c proton are listed in Table 4. The effective light speed is inversely proportional to the slope of the time difference versus the position, and depends on the cross section of the crystal. The 2 cm square crystals have a faster effective light speed owing to the faster contribution of a direct pass from the event position to the PMTs.

The mean time of both PMTs is plotted versus the beam position in Fig.7. It is constant within ±0.1ns, as expected.

3.2. GSO-Plastic-GSO bar

As a prototype of a 4π detector with a central stopping target, shown in Fig. 1, a connected GSO-Plastic-GSO was tested; two 1.5 mol% Ce-doped GSO (1 cm × 1 cm × 20 cm) crystals and a NE102A plastic scintillator (1 cm × 1 cm × 10 cm) were connected to form a 50 cm-long bar.

The total pulse height and energy resolution are plotted in Fig. 8. In the GSO region the signal intensity slowly decreased with increasing distance from the PMT. When the beam hit the plastic scintillator, the signal intensity was small because of the small energy deposit in the plastic scintillator. The energy resolution was better than 10% in the GSO crystal and 16% in the plastic scintillator for a 1.0 GeV/c proton beam. However, the pulse-height ratio (Fig. 9) of both ends maintained the exponential relation separately in both the GSO and plastic scintillator regions similarly, as shown in the previous GSO-GSO configuration. The signal time difference for the present configuration also shows a linear dependence on the beam position (Fig. 9). We can also estimate the event position using both the pulse-height ratio and the time difference. The obtained position resolution is compared in the next section with the GSO-GSO configuration.

4. Conclusion

For a feasibility test for using GSO crystals as a hermetic stopping K decay detector, the performance of a 40 cm-long GSO bar consisting of two 20 cm-long GSO crystals connected to each other was investigated using a proton beam. The pulse height registered on one end had a finite change at the connection plane, but the total pulse height from both ends had no gap at the plane.

The best energy resolution achieved from the total pulse height was 3.8% (rms) in the 0.5 mol% Ce doped GSO with a cross section of 2 cm × 2 cm for a 0.8 GeV/c proton beam. This good energy resolution makes the connected crystal bar a promising candidate for use not only in a high-energy calorimeter, but also in a detector system containing a central stopping target.

The position resolutions estimated from the pulse-height ratio and time difference are listed in Table 5.

The best position resolution was obtained in 1.5 mol% Ce doped GSO (2 cm × 2 cm in cross section) crystal : 0.64 cm from pulse height ratio, 1.1 cm from pulse time, and 0.55 cm for the combined resolution using 1.0 GeV/c proton beam. Through this beam test, for a same 2 cm × 2 cm cross section crystal, the 1.5 mol% Ce doped GSO crystal was better than a 0.5 mol% Ce doped crystal from the point of view of position resolution.

A GSO bar of 1 cm × 1 cm cross section gave a poorer energy/position resolution than that of 2 cm × 2 cm cross section. However, when the fine segmentation is required, a stack of many 1 cm × 1 cm cross section bars may be promising, since it would give almost the same dE/dx and longitudinal position resolution from independent information obtained in comparison with the 2 cm × 2 cm case.

The GSO-Plastic-GSO configuration with the total length of 50 cm was also investigated for the actual stopping module, and showed a good performance in the energy and position resolution. We found that the combined position resolutions were kept below 0.9 cm in both of the GSO and the plastic scintillator regions.

We confirmed that the connected GSO bar had a good energy resolution and position resolution. The GSO stacking detector may be used as a compact detector to measure the energy, position and time of both charged particles and photons for rare K-meson decay experiments, while tracking the charged particle path and finding its range in such a detector remain to be studied. If we combine this GSO bar detector with some position-sensitive detector, i.e., straw chamber or plastic fiber scintillator detector, we could even improve the capability of the detector system.

5. Acknowledgements

This research was supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan under Grant-in-Aid for Scientific Research on Priority Areas.

References

[1] I-H.Chiang et al., IEEE Trans.Nucl. Sci. NS-42(1995) 394.

[2] S.Adler, et al, Phys. Rev. Lett. 79 (1997) 2204-2207.

[3] S.Adler, et al, Phys. Rev. Lett. 88 (2002) 041803.;
V.V.Anisimovsky, et al. Phys. Rev. Lett. 93 (2004) 031801.

[4] M. Ishii and M. Kobayashi, Prog. Crystal Growth and Charact. Vol.23 (1991) 245.

[5] M. Tanaka et al., Nucl. Instr. and Meth. A404 (198) 283-294.

[6] H.Ishibashi et al., IEEE Trans. Nucl. Sci. NS-45 (1998) 518.

[7] H.Ishibashi et al., Proceedings of KEK-RCNP International School and Mini Workshop for scintillating crystals. KEK Proceedings 2004-4 (2004) 41-50.

[8] The catalog of Hamamatsu Photonics K.K. Potomultiplier Tubes And Related Products.

[9] K.Omata et al., IEEE Trans. Nucl. Sci. NS-39 (1992)143.

[10] GEANT Detector Description and Simulation Tool, Cern Program Library, Long Writeup W5013, October 1994

Figure caption

Fig. 1. Conceptual sketch of a compact 4π detector.

Fig. 2. Experimental setup. Two 20 cm-long GSO crystals connected to each other is mounted in a test beam line. The signal is read by two PMTs (A0 and A1) from both ends. A set of time-of-flight counter is used to separate protons from pions. Plastic detectors P1 and P2 (3mm×3mm) define the beam.

Fig. 3. Typical ADC histogram of a GSO signal. The solid (dash) line is the near (far)-end PMT's output with respect to the beam position.

Fig. 4. Position dependence obtained from a 0.5 mol% Ce doped crystal (2 cm × 2 cm cross section) using a 1.0 GeV/c proton beam. (left) Each PMT output (square) exponentially decreases with the distance between the PMT and the beam position. The total pulse height (solid circle) slowly goes down toward the center. (right) The energy resolution (rms) derived from the total pulse height is constant within 1% over the whole region, except for the endpoints.

Fig. 5. Proton peak in the distribution of the total pulse height.

Fig. 6. Signal intensity ratio (A0/A1) versus the beam position in a 0.5 mol% Ce doped GSO-GSO bar (2cm×2cm cross section) for a 1.0 GeV/c proton beam.

Fig. 7. (left) Signal time difference (2 cm × 2 cm 0.5 mol%Ce, proton 1.0 GeV/c). (right) The mean time of the two PMT outputs keeps constant within ±0.1 ns.

Fig. 8. Total pulse height (●) and energy resolution (□) (GSO-Plastic-GSO).

Fig. 9. (left) Pulse-height ratio A0/A1 (GSO-Plastic-GSO). (right) Signal time difference (GSO-Plastic-GSO)

Table

Table 1.

Characteristics of GSO [3].

Density	6.71 g/cm^3
Radiation length	1.38 cm
Light yield	about 20 % of NaI:Tl
Peak emission	440 nm
Decay time	30 ns (1.5 mol%Ce) - 60 ns (0.5 mol%Ce)
Hygroscopicity	No
Radiation hardness	Over 10^6 Gy (1Gy = 100 rad)

Table 2.

Energy resolution (rms) estimated from the sum of each pulse height of both ends. The energy deposit in the crystal and the energy resolution calculated by GEANT3 are listed in the brackets.

	Incident proton beam		
GSO crystal	0.6 GeV/c	0.8 GeV/c	1.0 GeV/c
0.5mol%Ce 2cm×2cm	3.4%	3.8%	4.8%
1.5mol%Ce 2cm×2cm	-	4.0%	5.2%
GEANT3 estimation	(2.4%)	(3.5%)	(4.7%)
Energy deposit	(44.3MeV)	(29.6MeV)	(24.1MeV)
1.5mol%Ce 1cm×1cm	-	5.6%	6.7%
GEANT3 estimation		(5.3%)	(6.2%)
Energy deposit		(14.2MeV)	(11.8MeV)

Table 3.

The attenuation length (b) and position resolution for a 1.0 GeV/c proton estimated from the pulse-height ratio.

GSO crystal	Attenuation length (cm)			Position resolution (cm)		
	x < 0	x > 0	average	x < 0	x > 0	average
0.5mol%Ce 2cm×2cm	66.0	63.5	64.8	0.98	0.94	0.96
1.5mol%Ce 2cm×2cm	41.5	41.9	41.7	0.64	0.64	0.64
1.5mol%Ce 1cm×1cm	25.0	29.7	27.4	0.59	0.70	0.64

Table 4.

The effective light speed in the crystals and the position resolution estimated from the signal time (1.0 GeV/c proton).

GSO crystal	Effective light speed	Position resolution (1σ)
0.5mol%Ce 2cm×2cm	10.6 cm/ns	1.4 cm
1.5mol%Ce 2cm×2cm	9.9 cm/ns	1.1 cm
1.5mol%Ce 1cm×1cm	5.0 cm/ns	2.0 cm

Table 5.

Comparison of the obtained position resolutions (rms).

For the GSO-Plastic scintillator(NE102A)-GSO configuration, the numbers in the parentheses give the resolutions in the plastic scintillator region.

GSO Crystal	configuration	from pulse height	from signal time	combined resolution
0.5mol%Ce 2cm×2cm	GSO-GSO	0.96 cm	1.4 cm	0.79 cm
1.5mol%Ce 2cm×2cm	GSO-GSO	0.64 cm	1.1 cm	0.55 cm
1.5mol%Ce 2cm×2cm	GSO-GSO	0.95 cm	2.0 cm	0.61 cm
1.5mol%Ce 2cm×2cm	GSO-Plastic-GSO	0.96 cm	2.6 cm	0.89 cm
		(1.30 cm)	(1.1 cm)	(0.75 cm)

Figure(s)

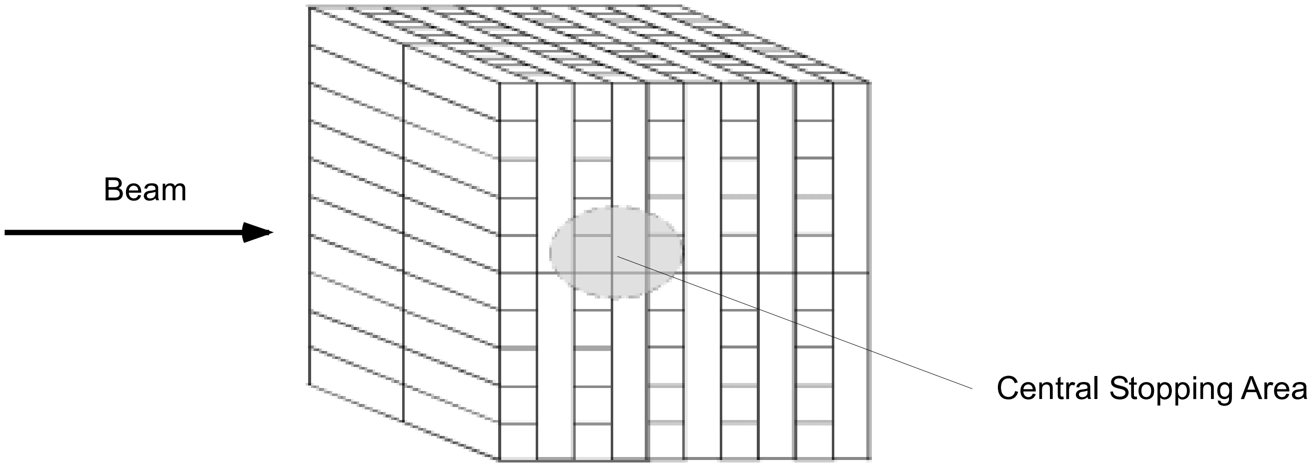

Fig.1

Figure(s)

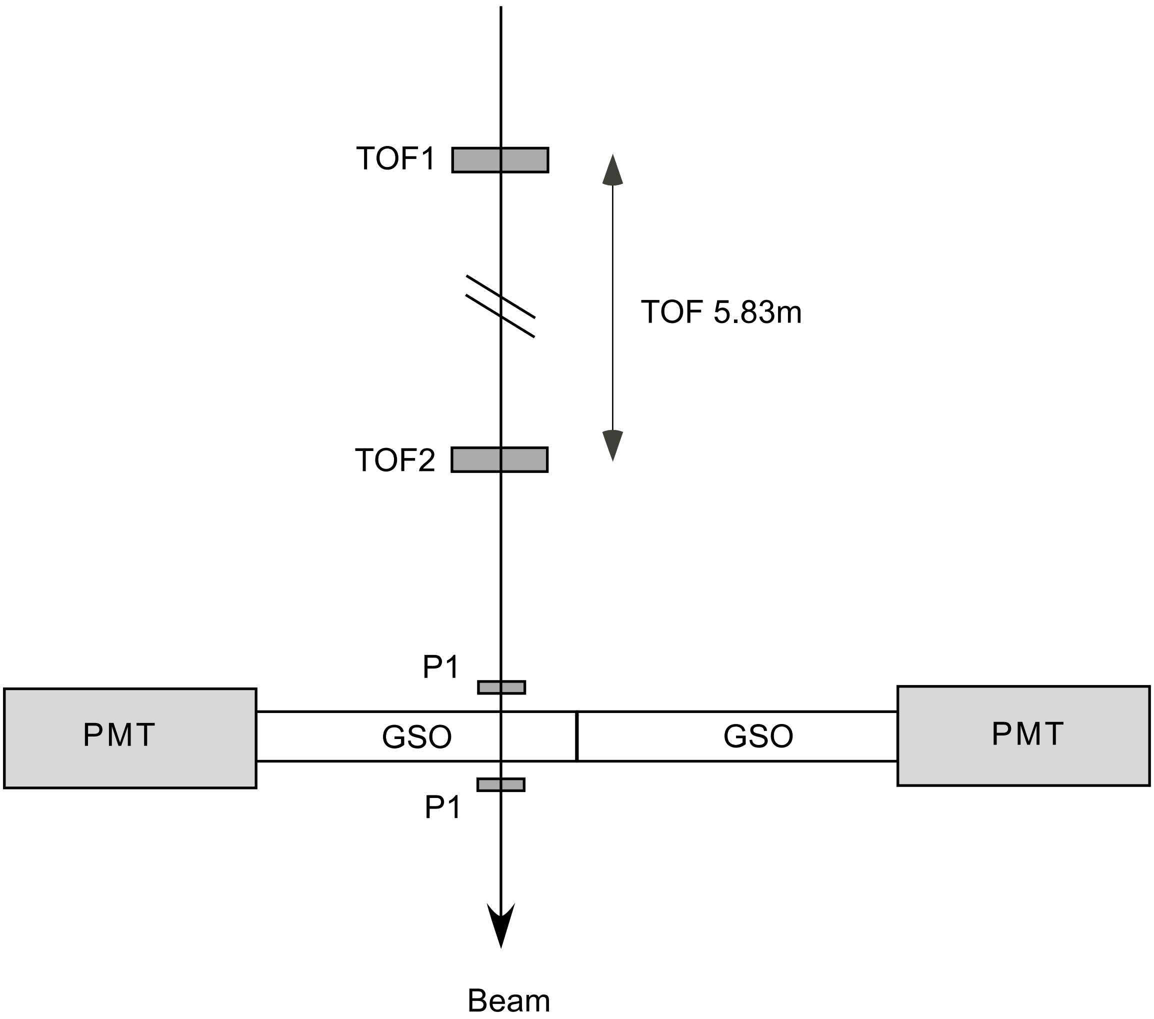

Fig.2

Figure(s)

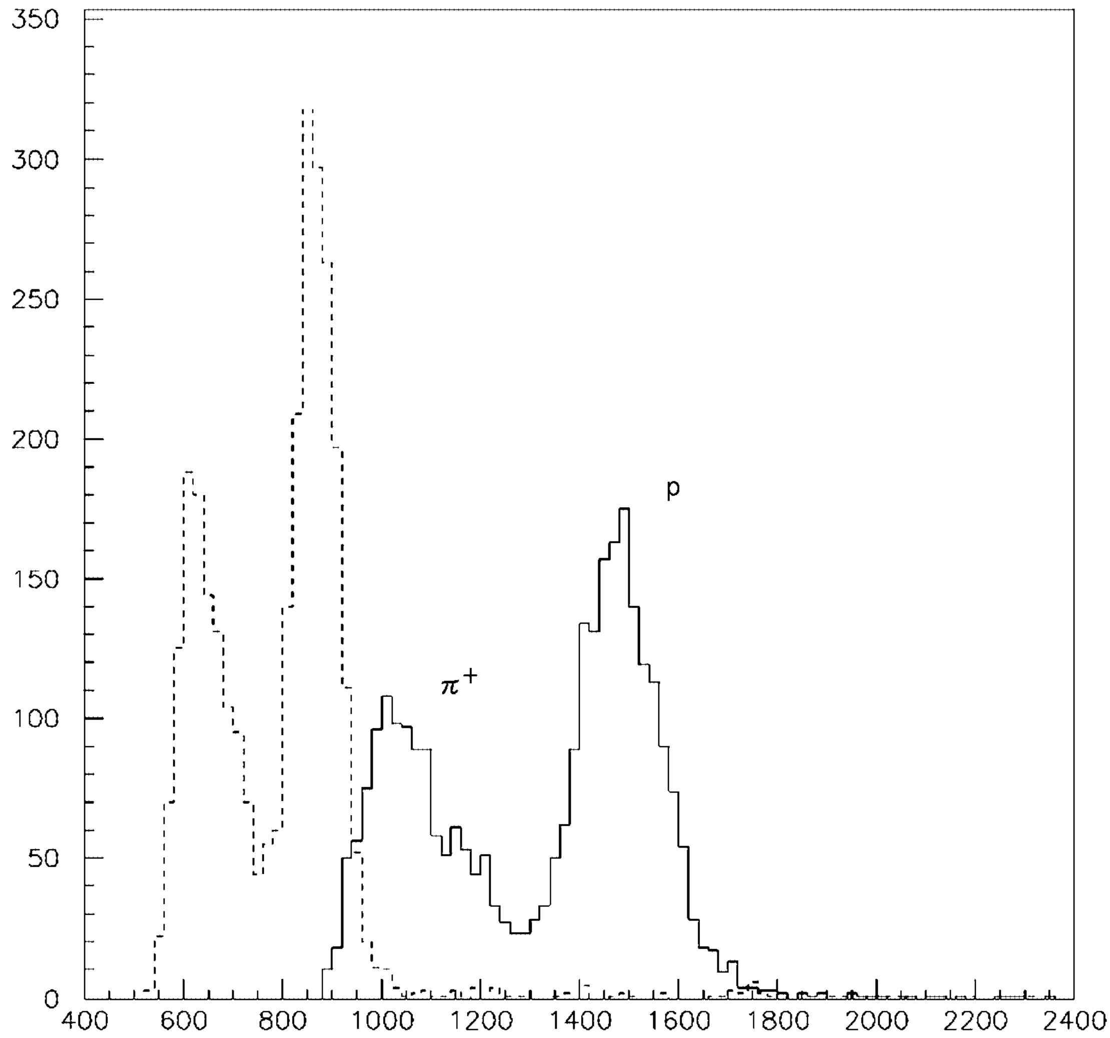

fig.3

Figure(s)

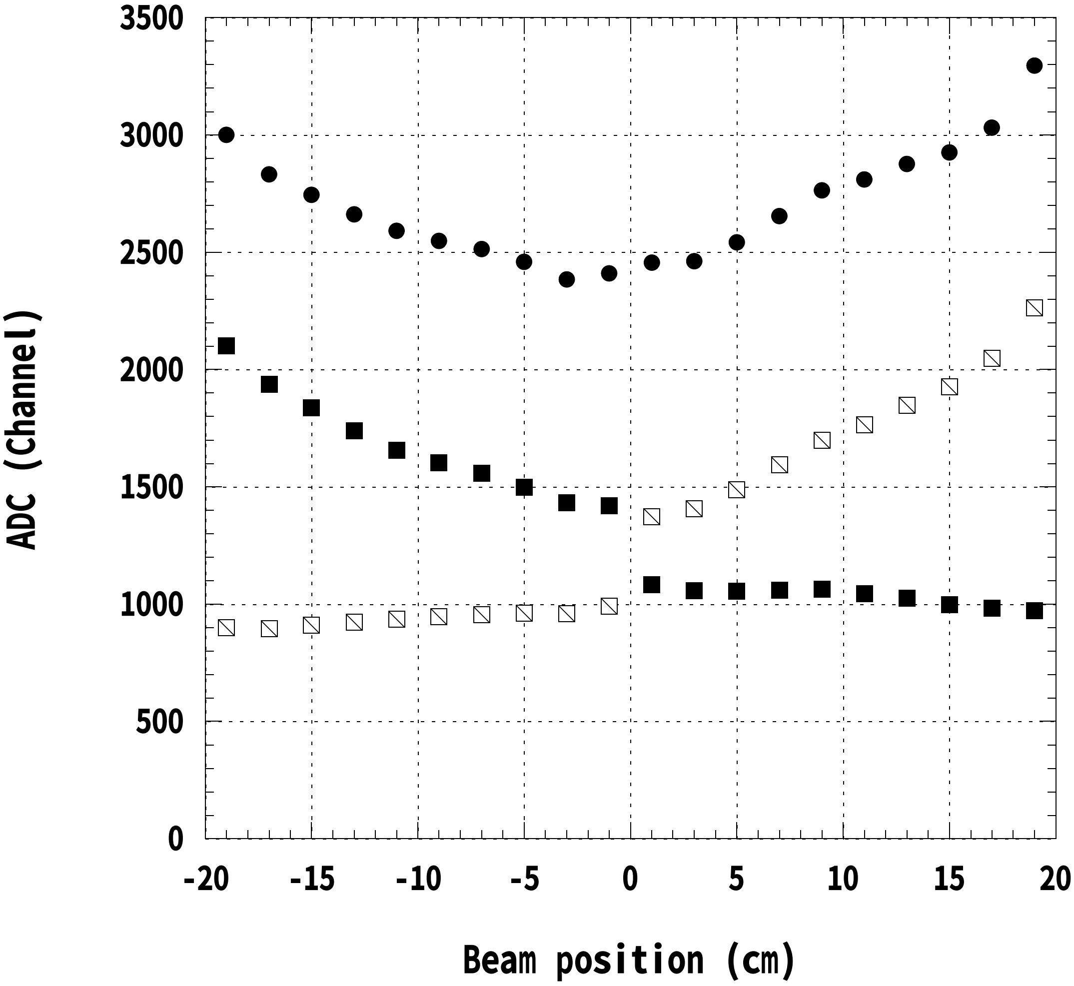

Fig.4 (Left)

Figure(s)

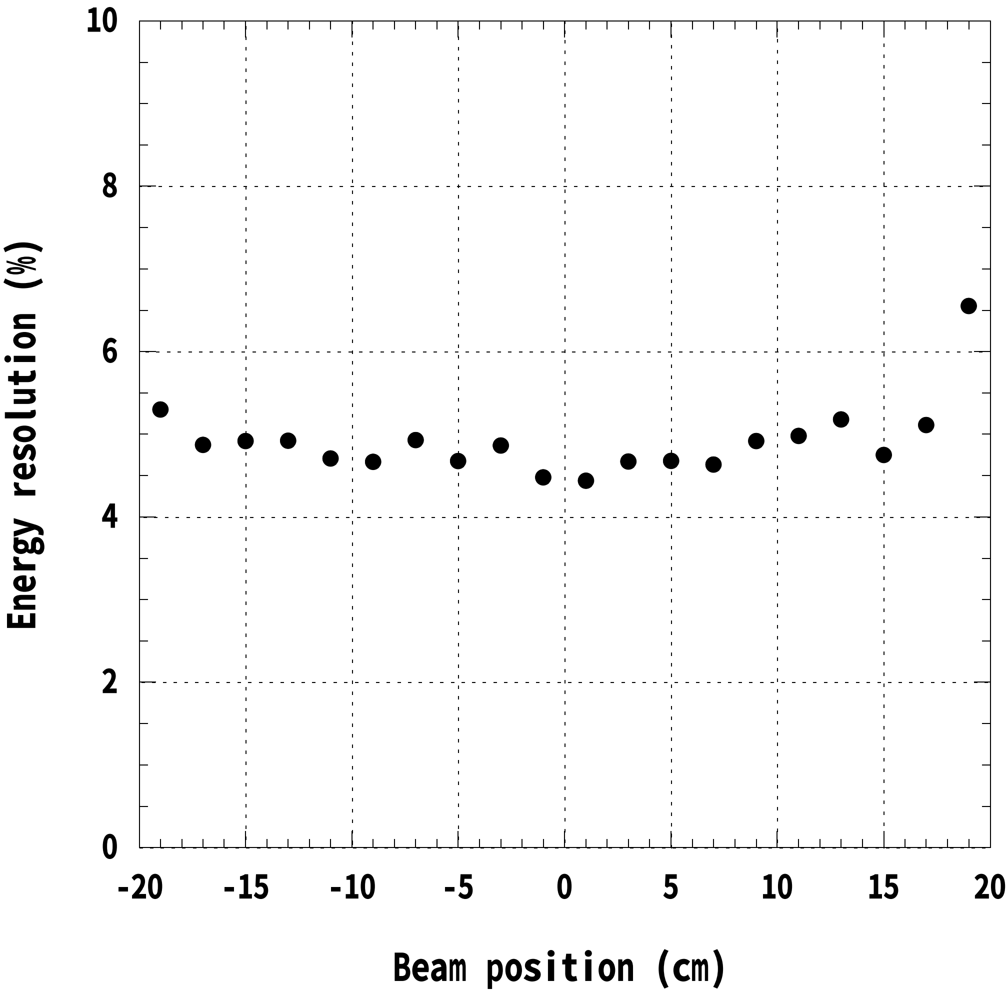

Fig.4 (Right)

Figure(s)

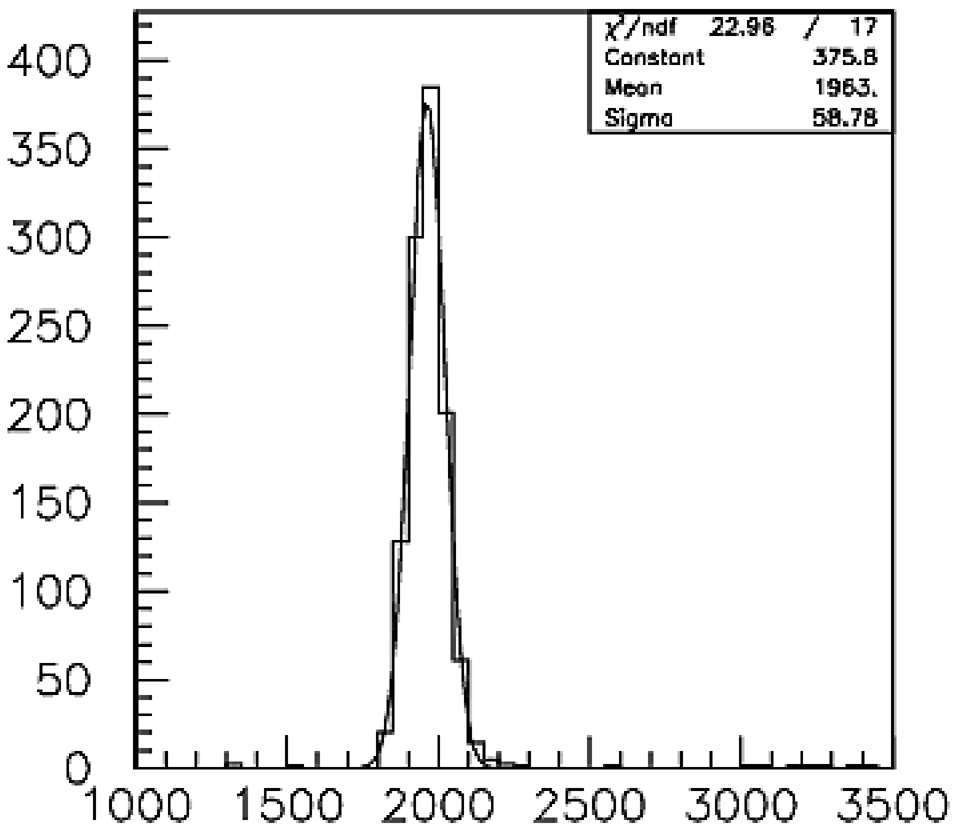

Fig.5

Figure(s)

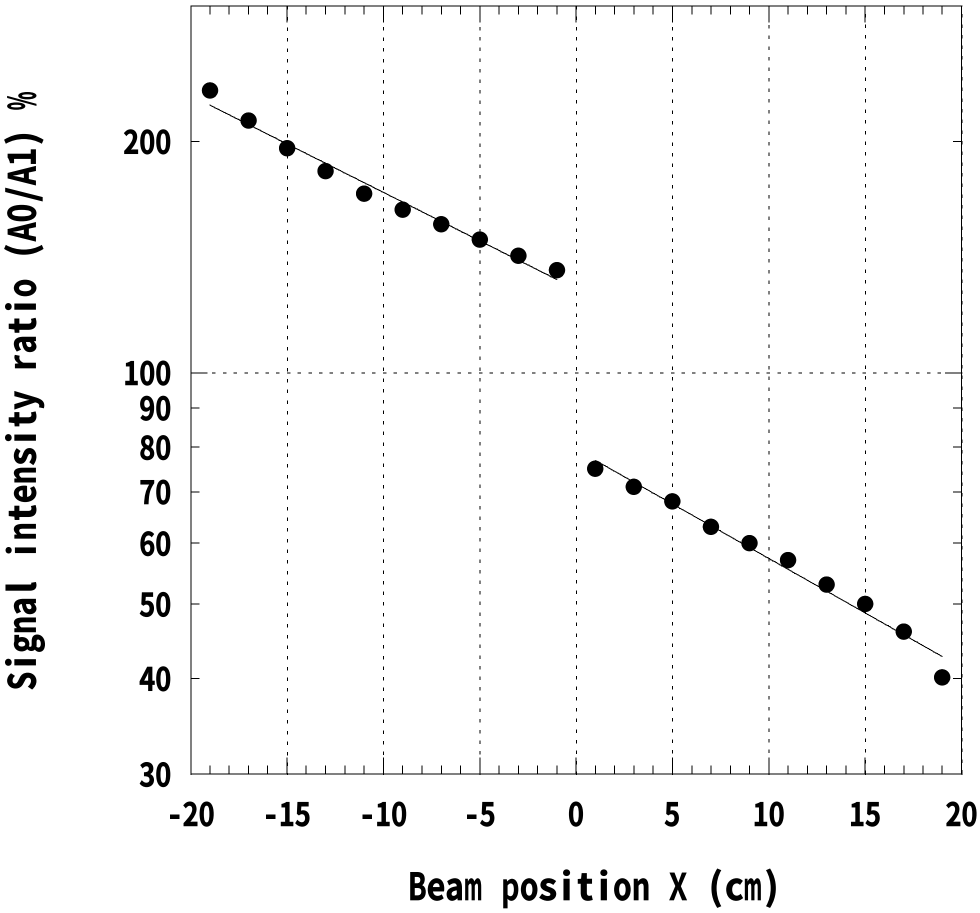

Fig.6

Figure(s)

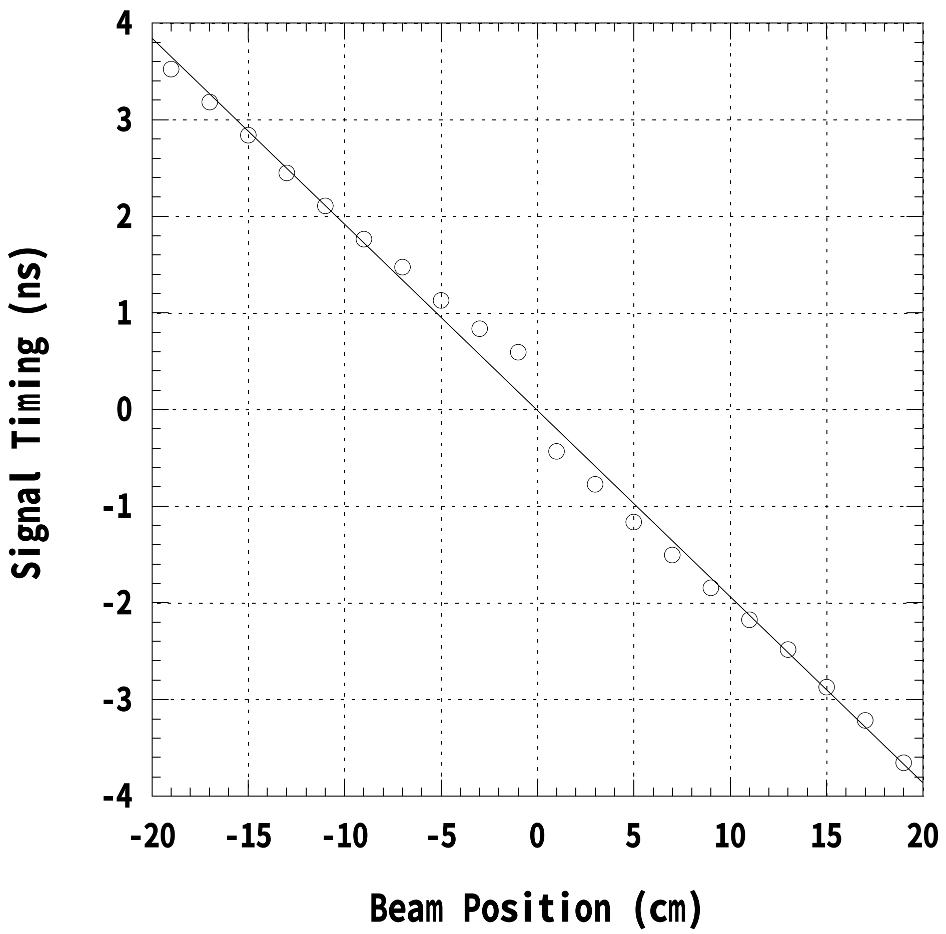

Fig.7 (Left)

Figure(s)

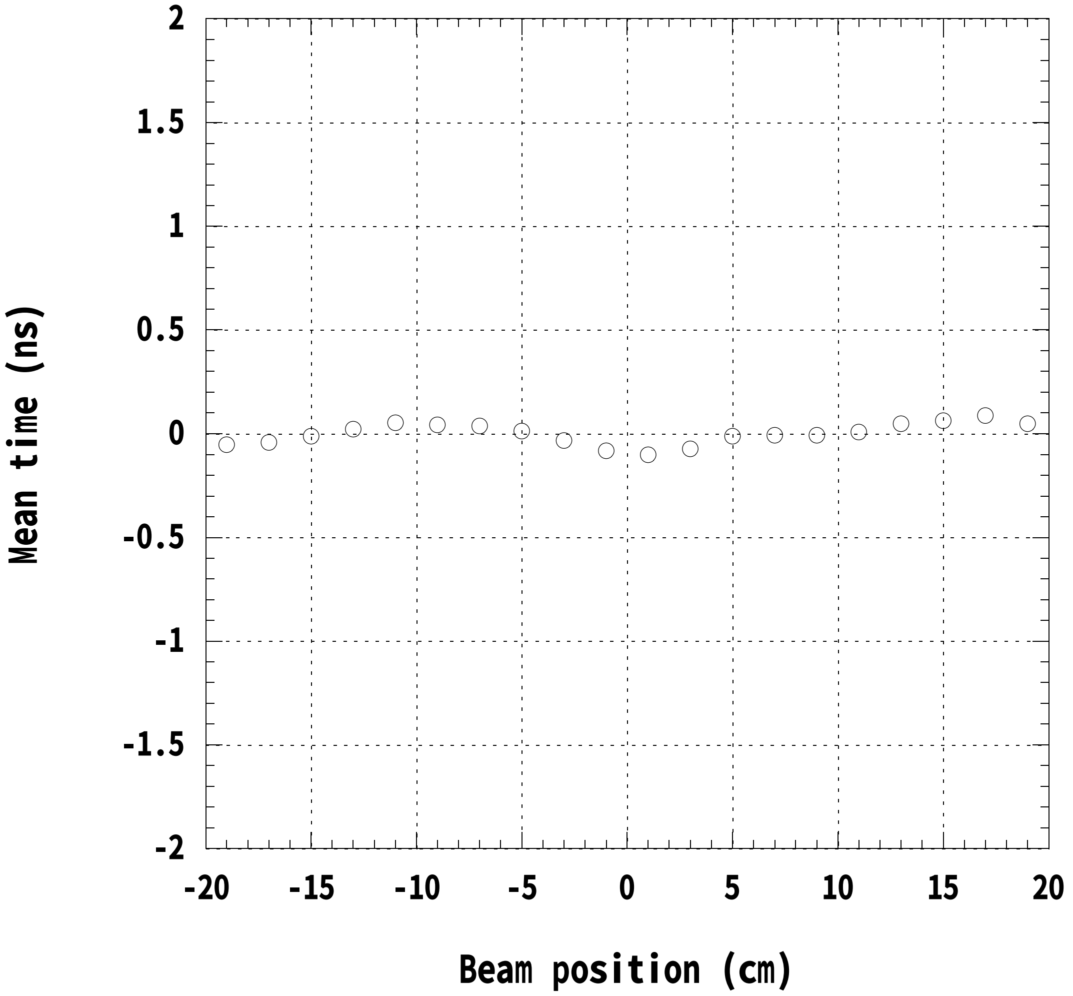

Fig.7 (right)

Figure(s)

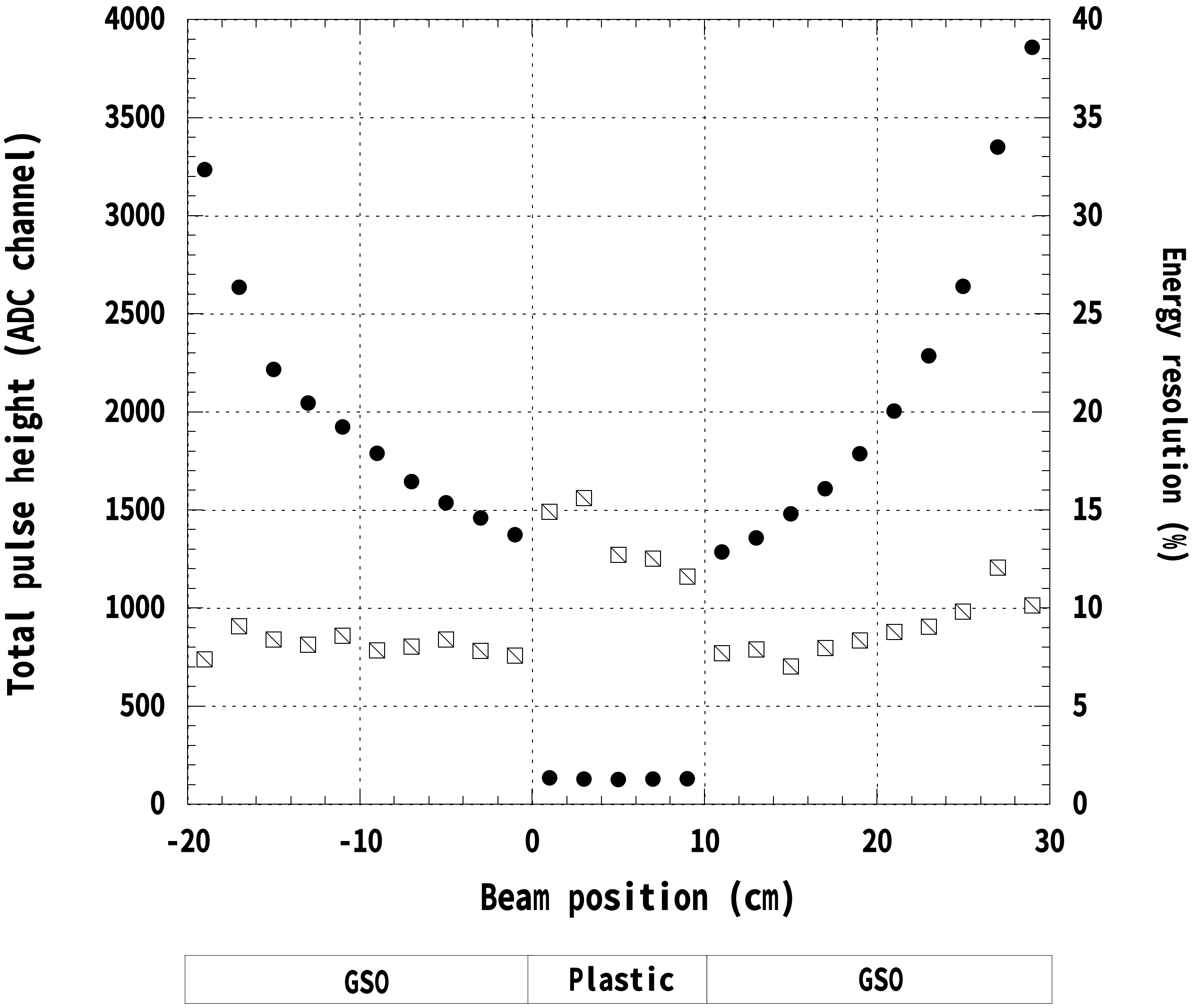

Fig.8

Figure(s)

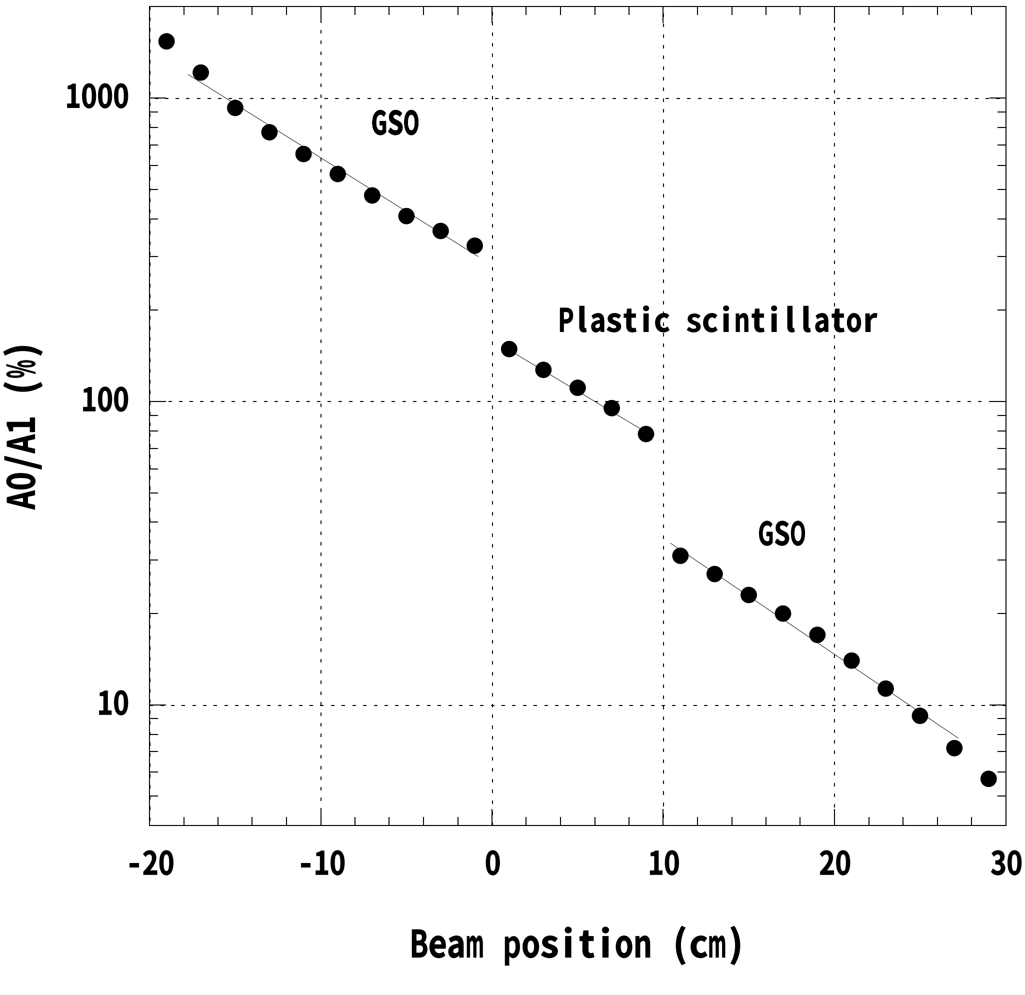

Fig.9 (Left)

Figure(s)

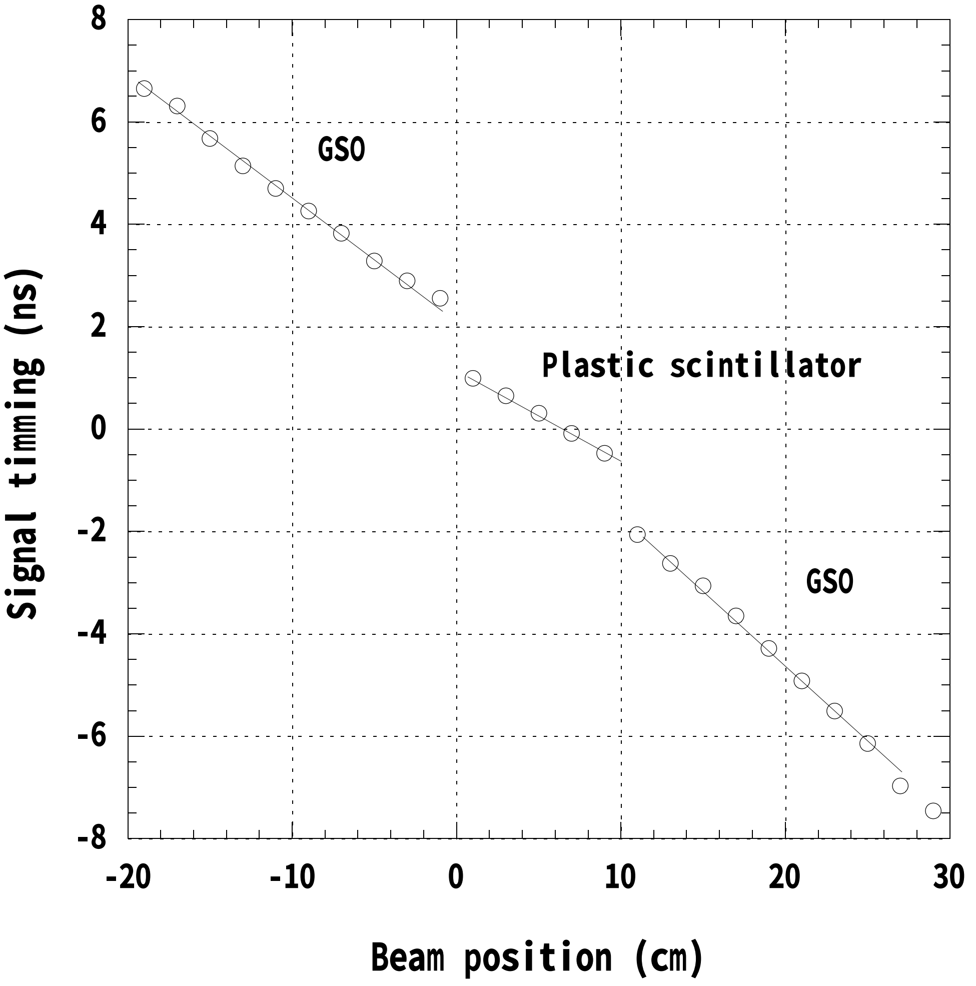

Fig.9 (Right)