JAERI-Data/Code
2001-014

JP0150373

MEASUREMENT OF PROFILE AND INTENSITY OF PROTON BEAM BY AN INTEGRATING CURRENT TRANSFORMER AND A SEGMENTED PARALLEL-PLATE ION CHAMBER FOR THE AGS-SPALLATION TARGET EXPERIMENT (ASTE)

March 2001

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編集兼発行　　日本原子力研究所

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Measurement of Profile and Intensity of Proton Beam by an Integrating Current Transformer and a Segmented Parallel-Plate Ion Chamber for the AGS-Spallation Target Experiment (ASTE)

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(Received February 5, 2001)

Profile and intensity of proton beams incident to a mercury target were measured for the experiments under AGS-spallation Target Experiment (ASTE) collaboration. Protons of 1.94, 12 and 24 GeV energy were measured for a temperature, pressure wave and neutronics in the mercury target. For the beam profile measurement, segmented parallel-plate ion chamber (CHIDORI) was used as the online detector. Imaging plates (IP) were also used for the profile measurement with aluminum activation foils as the image converter. An integrating current transformer (ICT) and activation method by Cu foil were used for the measurement of beam intensity.

The beam profile obtained by CHIDORI gives a good agreement with the results with the IP. The beam intensity obtained by ICT agrees with the data obtained by the activation technique within ± 3 % for 12 and 24 GeV cases. Furthermore, these results show in good agreement with those obtained by the monitor of segmented wire ionization chamber (SWIC) and secondary emission chamber (SEC) installed by the AGS team. Therefore, a reliable beam monitor technique was established, so that the analysis of the experiment such as temperature and pressure wave can be normalized by the number of incident protons.

Keywords: Beam Profile, Intensity, 1.94-,12- and 24-GeV Protons, Imaging Plate, Integrating Current Transformer, Segmented Parallel-plate Ion Chamber

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JAERI-Data/Code 2001-014

AGS核破砕ターゲット実験(ASTE)における積分型カレントトランスフォーマー及びセグメント化された平行平板電離箱を用いた陽子ビームのプロファイルと強度の測定

日本原子力研究所東海研究所中性子科学研究センター

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(2001年2月5日受理)

1.94, 12および24 GeV陽子を水銀ターゲットに入射し，ターゲット内の温度，圧力波および中性子特性を測定するAGS核破砕ターゲット実験における入射陽子ビームのプロファイルと強度の測定を行った．入射陽子ビームプロファイルのオンライン検出器としてセグメント化された平行平板電離箱(CHIDORI)を用いた．また，プロファイルはアルミ箔を陽子ビームで放射化し，これから生成するγおよびβ線の強度分布をイメージングプレート(IP)で検出する方法で測定した．ビーム強度の測定には積分型カレントトランスフォーマー(ICT)および銅箔の放射化法を用いた．

CHIDORIおよびIPによるプロファイルの結果は良い一致を示した．また，ICT法と放射化法によるビーム強度の結果は，12および24GeV陽子に対し3%以内で良い一致を示した．さらに，これらの値はAGSのチームが設置したセグメント型ワイヤー電離箱(SWIC)および二次放出電離箱(SEC)による結果と良い一致を示した．以上より，モニター手法を確立し温度および圧力波等の実験解析が入射陽子当りで規格化できるようになった．

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1 Introduction

In the JAERI-KEK Joint project (JKJ), European Spallation Source (ESS) and Spallation Neutron Source (SNS), a mercury target is proposed as the primary of candidate of the target for the intense spallation neutron source. For the engineering design of the target, it is required that precise characteristics of the thermal hydrostatics and neutronics of the mercury target irradiated by the proton beams. However, these characteristics has not been studied well. In order to obtain those data, AGS (Alternating Gradient Synchrotron)-spallation Target Experiment (ASTE) [1, 2, 3, 4] has been started in 1997 by the international collaboration of JAERI, Forschungszentrum Jülich (FZJ), Paul Scherrer Institute (PSI), Oak Ridge National Laboratory (ORNL), and Brookhaven National Laboratory (BNL).

In the experiment, the pressure wave and thermal distribution of the target were measured[2]. From the view point of the validation of the neutronics calculation, a reaction rate distribution on the target[3] and a spectrum of neutrons produced in a water moderator placed by the target[4] was measured. For those measurements, precise intensity and beam profile of proton beams is indispensable because those results completely depend on the beam intensity and profile as an input condition. However, there are the following difficulties for the measurement of the intensity and profile in the AGS experimental condition:

1) Proton energy

The incident energies of protons for each run are varied from 1.94 to 24 GeV. In this energy region, only a few reaction cross sections for monitoring the intensity are known accurately.

2) Beam intensity

The intensity of the beam is expected to be from 8×10^{12} to 5×10^{13} protons per pulse depending on the condition of the accelerator. A counting detector such as a scintillator can not be employed for direct measurement because of the pile up in the output signal. On the other hand, by using the scintillator, the relative intensity can be obtained by the measurements of the secondary particle from the radiator located in the prime beam line. However, the absolute intensity cannot be obtained.

3) Real time measurement

For the diagnostics of the beam, a detector, which can give the information for each proton pulse, is required. For the pressure wave measurement, in particular, such a monitor is crucially required because the profile and intensity of individual beams are necessary in the analysis of such measurements. By using an activation detector, integrated proton intensity and profile can be obtained. The activation detector can not be adopted for the pressure wave and thermal measurement because the data for individual beam can not be observed.

Therefore, a detector using other technique is required.

1.1 Method Chosen for the Measurement of Beam

Concerning above, we chose the following techniques as for the profile measurement, segmented parallel-plate ion chamber, namely CHIDORI[5], and imaging plate technique. By the CHIDORI, the real time profile can be obtained. Precise two-dimensional distribution of profile can be obtained by the imaging plate technique. Integrating Current Transformer (ICT) and the activation techniques using the $^{Nat}Cu(p,x)^{24}Na$ reaction were employed for the measurement of beam intensity. By using the ICT, the real time intensity for each pulse can be measured, while the activation technique gives the integrated proton intensity during one irradiation.

Once the experiment begins, it is difficult to access the beam line even in a short time if the equipment was failed. Thus, it is preferable to use redundant monitors to reduce a risk of an unexpected failure. Other beam monitors were also settled by the AGS team, which was used as back up systems. For the measurement of profiles and intensity of the beam, Segmented Wire Ionization Chamber (SWIC) and Secondary Emission Chamber (SEC) were settled in the beam line.

2 Experiment

The experiment was carried out at a target room of the U-line in the AGS facility. A schematic view of the experimental arrangement is shown in Fig. 1. In this experiment, the mercury was contained in the cylindrical target container (130 cm in length and 20 cm in diameter) with half sphere (20 cm in diameter). Furthermore, the container was covered by the secondary container. The target was covered with the lead reflector except for the pressure wave measurement. The position of the target can be moved by the remote control. For the Time-of-Flight (TOF) measurement of neutrons, the both center of target and incident beam was located at 4 cm higher than the center for the measurement of pressure wave.

For the measurement of beam profile, we employed the segmented parallel-plate ion chamber (CHIDORI) and imaging plate technique. The beam intensity was measured by the Integrating Current Transformer (ICT) and the Cu activation foil technique. The ion chamber of CHIDORI was placed at 1 m up-stream position from the target. Cu and Au foils were attached on the surface of the secondary container where the incident protons penetrate.

In the experiments, the incident beams were delivered by a pulse on demand. For all measurements except the TOF measurement for 1.94-GeV protons, a pulse is consisted of one micro bunch for each macro pulse. In the measurement of TOF for 1.94 GeV, a configuration of 8 micro bunches per macro pulse was employed to carry out the measurement efficiently.

2.1 Measurement of Beam Profile

2.1.1 Segmented Parallel-Plate Ion Chamber (CHIDORI)

To measure the beam profile, a segmented parallel-plate ion chamber CHIDORI †[5]. was employed. When protons pass through a gas, electron/ion pairs are produced in the gas. The number of pairs is proportional to the proton intensity. The electrons move to the anode electrode along an electric field. In the parallel-plate ion chamber, the electric field is given in perpendicular direction to the electrodes. The number of electrons collected in the segmented anode cell represents to the number of protons, which pass the segmented area in the ion chamber. Therefore, the profile can be obtained by the integration of collected charge in segmented anode.

A schematic drawing of CHIDORI is shown in Fig.2. CHIDORI was composed of parallel plates of anode and cathode with active area of 170 x 170 mm^2. Both anode and cathode electrodes were consist of Cu-coated polyimide foil 98.5 and 36 μm^2 in thickness, respectively. The anode consists of 1024 rhomboid cells (5x5 mm^2) which was created by the edging of Cu-coat of the foil. Each cell is electronically connected to the neighbor cells along horizontal and vertical directions at outside and inside of anode plane, respectively. Thus, the projection of the profile was obtained for 32 positions along horizontal and vertical axis. Both electrodes were glued to fiberglass frames by which these electrodes

†CHIDORI means a plover in Japanese. It is given the name because the shape of rhomboid cell of the chamber is similar as a foot mark of a plover.

were separated with distance of 10 mm. The frames were jointed by the screw shown in Fig. 2. As the ionization gas, the helium was employed because the mobility of the electron was fast enough to avoid the recombination of the electron/ion pair. In the chamber, helium gas flowed with a pressure less than 108 kPa. In this condition, the swelling of the CHIDORI was kept less than 0.5 mm.

The electronic circuit is shown in Fig. 3. The cathode was supplied with -900 V for giving the electric field in the chamber. The 64 signals of the anode were transferred to attenuators (GND GNX-020) by the twisted pair cables. The attenuated signals were fed to charge sensitive ADC (REPIC RPC-022) controlled by CAMAC in order to obtain the integration of charge. These digital data from ADCs along with the information of the time, when the protons irradiate, were recorded event by event in a hard disk of personal computer driven by the data acquisition program KODAQ[6].

In order to subtract the background electric noise, a measurement was carried out without beam. After subtraction of the background, the net data for the profile was obtained. Before and after the experiment, calibrations were performed using charge source to confirm the stability and linearity of ADCs. It was found that ADCs kept good stability and linearity throughout measurements.

2.1.2 Imaging Plate Technique

The imaging plate (IP) technique was employed also for monitoring of beam profile. The thin aluminum foil was placed in the proton beam during exposure. After irradiation, the Al foil was attached to an IP. IP was exposed to the radiations emitted by the activated products in the Al foils. The image of IP represented to the intensity distribution of the radio-activities, which corresponded to the incident proton intensity. The profiles for individual pulses can not be measured by this technique because the Al-foil had to stay at the position during irradiation. On the other hand, the two dimensional profiles were clearly obtained, even though it was a result of accumulation of overall pulsed in the measurement.

An aluminum foil in thickness 25 μm was placed at 6 cm in front of the target and had been irradiated by the proton beams during measurement. After about two days cooling, the foil was directly attached with the imagine plate BAS1000 (Fuji Film). As a result, sources of the imaging plate were mainly γ-rays and beta rays from ^{22}Na and ^{7}Be. The image was finally obtained by an imaging plate reader (Fuji Film) which has pixels with size of 200 μm^2

2.2 Measurement of Intensity for Incident Protons

2.2.1 Integrating Current Transformer (ICT)

For the measurement of individual incident proton beam intensity, the integrating current transformer (ICT) of ICT-210-20:1 (Bergoz) was employed. Due to the electromagnetic induction by the beam current passed in ICT, a current is produced as the signal which is proportional to the input beam current. A schematic view of the ICT is shown in Fig. 4. The ICT consists of a troidal coil covered with a copper shell and produces output signal of the integrated charge which is exactly 1/40 of the beam pulse charge. The ICT delivers a pulse with 20 ns rise time irrespective to the beam pulse rise time, because of the integration by the capacity put in the ICT. This ICT can be operated for the pulse widths from less than a picosecond to more than a microsecond. Due to the Ampère law, the ICT does not depend on the position of the beam to the output charge.

A block diagram of the circuit used for the ICT is shown in Fig. 3. The signal of the ICT is carried to a attenuator through a 50 m long cable. After adjustment of the amplitude of signal, the pulse was fed to Bunch Signal Processor (BSP:Bergoz)[7]. In the BSP, the signal of ICT is amplified and shaped, and the charge of the signal is integrated. An external gate signal, provided from a kicker magnet signal of AGS, is applied to BSP prior to the beam arrival time in 6 μs. The output signal of BSP is fed to a current collective CAMAC-ADC (REPIC:RPC-022) via an inverter. For the measurements such as pressure wave and TOF, the amplified signal of BSP was fed to a Constant Fraction Timing Discriminator (CFTD: CANBERRA) and the timing signal of beam arrival was produced.

In order to obtain the absolute current, a calibration is performed before the experiment using the actual cable and ADC. This calibration was performed in the air which was the same condition at the AGS experiment. The block diagram of the electrical circuit for the calibration of ICT is shown in Fig. 5. Relationship between the input current and the output signal was obtained as shown in Fig. 6. A good linearity between the input and output was confirmed.

2.2.2 Copper Activation Foil Technique

To obtain total number of incident protons, the activation method using the $^{Nat}Cu(p,x)^{24}Na$ reaction was used. The reaction was chosen because it has threshold energy about 400 MeV and its cross sections have been relatively well studied[8, 9, 10, 11]. The detail of the method and correction of data for the activation technique is given in Ref. [1], so subjects are expressed briefly here.

A copper foil of 0.1 mm thickness with an area of 200 x 200 mm^2 was put on an aluminum frame along with the Al foil for IP measurement. The purity of copper foil was 99.99%. After irradiation, the foil was removed from the frame and intensity of induced activities in the foils were obtained by the γ-ray spectrum measurement. The copper foil was cut to 100 pieces with a cross section of 20 x 20 mm^2. Ten pieces out of these pieces were stacked in to one, then induced activity of ^{24}Na was measured by a calibrated Ge-detector. The number of incident protons is obtained by the following equation,

$$N_p = Y/N_{Cu}t\sigma, \tag{1}$$

where N_p is the number of protons, N_{Cu} the number density of Cu nuclide, t the thickness of foil, σ the reaction cross section of $Cu(p,x)^{24}Na$, Y the total yield of ^{24}Na nuclide obtained by the measurement of γ-ray. The reaction cross sections for 1.9, 12 and 24 GeV is given as 3.0, 3.5 and 3.5 mb, respectively. These values were obtained by the estimation from the experimental data [8, 9, 10, 11].

3 Results and Discussion

3.1 Result of Beam Profile

3.1.1 CHIDORI

Beam profiles obtained by CHIDORI are shown in Figs. 7 to 9, which are data for TOF measurements. In the figure, the center of the position represents the center of the target. The positive position in the vertical and horizontal distributions stands for the top and right in the beam direction. The background was subtracted from the results as described before. It is found that the width of peak for protons at 12 and 24 GeV is smaller than the result for 1.94 GeV. For 12- and 24-GeV protons, beams were well focused because the emittance of the beam is decreased as increase of the proton energy in the synchrotron. On the other hand, the 1.94-GeV protons were not accelerated in the synchrotron, in other word, the operation of 1.94-GeV is not in the normal condition, so that the width of the peak is larger than those for higher energies.

By the fitting of Gaussian function to the profile, the peak position and the full width at a half maximum(FWHM) are obtained. In Figs. 10 to 12, a trend of the peak position of the beam is shown for 1.94, 12 and 24 GeV in the TOF measurement. It is shown that the peak positions are stable for 12 and 24 GeV. On the other hand, the peak position for 1.94 GeV is scattered during measurement.

It should be noted that CHIDORI and ICT did not operate unfortunately in the pressure wave measurement due to a trouble in a trigger signal device. However, these data were obtained by the another monitors SEC and SWIC, equipped by the AGS team.

3.1.2 Imaging Plate

The two dimensional distributions of the beams obtained by the imaging plate are shown in Figs. 13, 14 and 15, where the incident protons penetrate from the front to back surface. It is found that the beam for 12 and 24 GeV are well focused at the center and there is no local peak in the distribution. On the other hand, the profile for 1.94 GeV beam is uniformly distributed around center. This is ascribed to the large emittance of the beam for low energy protons as described in 3.1.1.

3.1.3 Comparison of the Results of Beam Profile

By the projection of two dimensional data on the vertical and horizontal axis, the profiles in the same manner of the result with CHIDORI were derived from IP data. In Fig. 16, the results with CHIDORI are compared with those by IP for 24 GeV. In this figure, the result of IP is normalized to fit the peak intensity of the CHIDORI. It is found that the width of the peak obtained by the IP is remarkably larger than that of by CHIDORI. This is explained by the fact that the protons and neutrons produced in the target additionally activated the aluminum foil.

In order to suppress the contribution of the background, additionally data analysis for the IP is made by the integration around at the peak. IP data are integrated on the peak area within 15cm width, which are also shown in Figs. 7 to 9 as solid lines. Although it still remains small background, the position and width of peak of IP data show good agreements with the results with CHIDORI except for 1.94 GeV.

Furthermore, the results obtained by SWIC are also compared in Figs. 7 to 9. The peak by SWIC is in good agreement with the result of CHIDORI. The width obtained by SWIC are, however, slightly larger than the results by CHIDORI and IP. This is probably due to the secondary particles of the target, since the SWIC was located closer to the target than the CHIDORI.

3.2 Result of Intensity of Proton Beam

3.2.1 ICT

Intensity of the each protons measured by ICT are shown in Figs. 17 to 19 as a function of elapsed time of the TOF measurement. It is found that the individual pulse intensity for 1.94 GeV is largely fluctuated. This will be mainly caused by the inadequate matching of the beam optics. On the other hand, the individual pulse intensities for 12 and 24 GeV are stable during the measurements.

3.2.2 Cu-foil Activation Technique

In Table. 1, results for the intensity obtained by the activation technique are compared with the results with ICT. For 1.94 GeV, the intensity obtained by the activation technique is 50 % smaller than the result with the ICT. For other energies, the intensities obtained by the activation technique are, however, in good agreement with those by the ICT within 3.5 %. Especially for 24 GeV, the intensities obtained by activation technique shows remarkably good agreement with the results with the ICT within 0.9 %. The small value in the activation method for the 1.94 GeV suggests that the uncertainty of the activation cross section below 2 GeV is rather larger than one in the higher energy region above 10 GeV.

3.2.3 SEC

The beam intensity obtained by the SEC is compared with results with the ICT and the activation foil method. The results are shown in Table 1. Furthermore, the results obtained by the ICT and SEC for TOF measurement are compared in Table 2. It is found that the intensity obtained by the SEC agree within 18 % with data by the ICT in the worst case. For 24-GeV, the results by the SEC show remarkable agreement with the results by the ICT within 1.8 %.

The trend of intensity measured by the SEC is also shown in Figs. 17 to 19. It is shown that both results by the ICT and SEC for individual pulse at 12 GeV is constantly different. On the other hand, the intensity of individual pulse for 24-GeV protons show agreement within 3 %. It shows that the uncertainty of the ICT is less than 3 %.

4 Conclusion

For the measurement for the temperature and pressure wave in the mercury target and the measurement for the time-of-flight of the neutrons, the profile and intensity of incident proton beam are measured in ASTE experiment on March in 1999. A segmented parallel-plate ion chamber (CHIDORI) and SWIC (Segmented Wire Ionization Chamber) and as the online detector and Imaging plates technique were employed to measure the profile of the incident proton beam. An integrating current transformer (ICT) and Secondary Emission Chamber (SEC) were used for the individual beam intensity. Also activation method by Cu foil were used to measure total amount of the protons.

The profile obtained by the CHIDORI shows good agreement with the result with the imaging plate and the SWIC. The shape of the peak by CHIDORI shows much better agreement with the data obtained by the imaging plate than the shape by SWIC. Thus, the final data of individual profile is adopted to the results with CHIDORI.

Beam intensity obtained by the ICT gives good agreement with the results with activation technique and SEC. The intensity obtained by the ICT agrees with the result by the activation technique within 3.5 % except for 1.94 GeV. For 24-GeV protons, the intensities obtained by the ICT are in good agreement with those by the SEC and the activation technique within 1.8 %.

For the measurement of pressure wave, those individual data are adopted to the result of SWIC and SEC, because the CHIDORI and ICT can not be operated. Although there is slightly difference between the results for 1.94 GeV, the data obtained by the different equipment give good agreement each other. Thus, it can be concluded that a reliable data for the proton beam are obtained in this experiment.

Acknowledgments

This work has been carried out in a frame of the ASTE collaboration. The authors would like to thank all the staff members of BNL involved in the ASTE experiment for their help and support. The authors would like to convey their thanks to Professor Tanaka of beam channel group of KEK and Dr. Muto of NML group of KEK for giving a chance to use CHIDORI and valuable discussion about profile monitor. They also appreciate Mr. Suzuki and Ochiai of REPIC and Mr. Miyazawa of GND for rapid preparation of ICT, attenuator and cables. The experimental work at BNL was supported by the U.S. Department of Energy under the contract DE-AC02-98-CH10886 with Brookhaven Science Associates.

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Table 1 Comparison of results for proton intensity obtained by ICT, activation technique and SEC.

Proton energy(GeV)		1.9	12	24
Number of pulses		864	56	18
Proton Intensity	ICT	6.42×10^{14}	4.52×10^{13}	2.07×10^{13}
	Activation technique	4.22×10^{14}	4.37×10^{13}	2.05×10^{13}
	SEC	5.55×10^{14}	4.09×10^{13}	2.05×10^{13}
Ratio of the results	ICT/Activation	1.522	1.035	1.009
	ICT/SEC	1.157	1.105	1.014

Table 2 Results of proton intensity obtained by ICT and SEC for the time-of-flight measurements.

Proton energy(GeV)		1.9	12	24
Number of pulses		40	11	14
Proton Intensity	ICT	6.00×10^{13}	1.07×10^{13}	1.54×10^{13}
	SEC	5.09×10^{13}	9.56×10^{12}	1.51×10^{13}
Ratio of the results	ICT/SEC	1.178	1.120	1.018

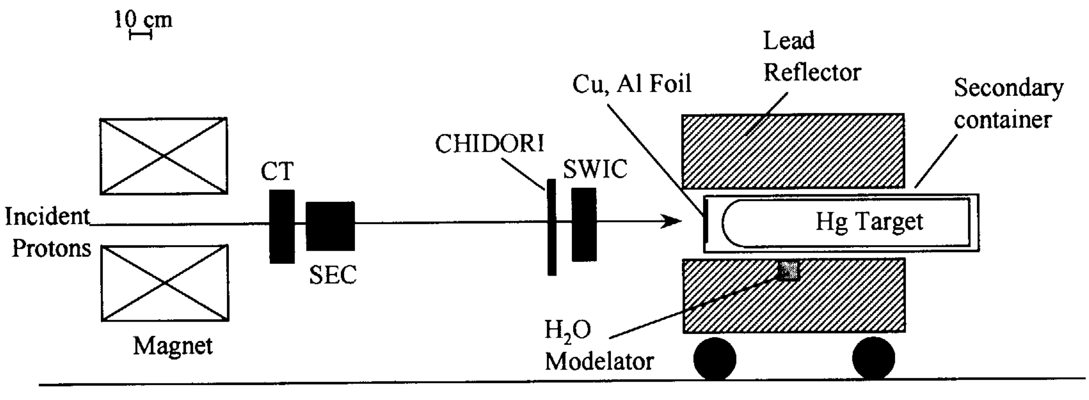

Fig. 1 Schematic view of the experimental arrangement at U-line in the AGS.

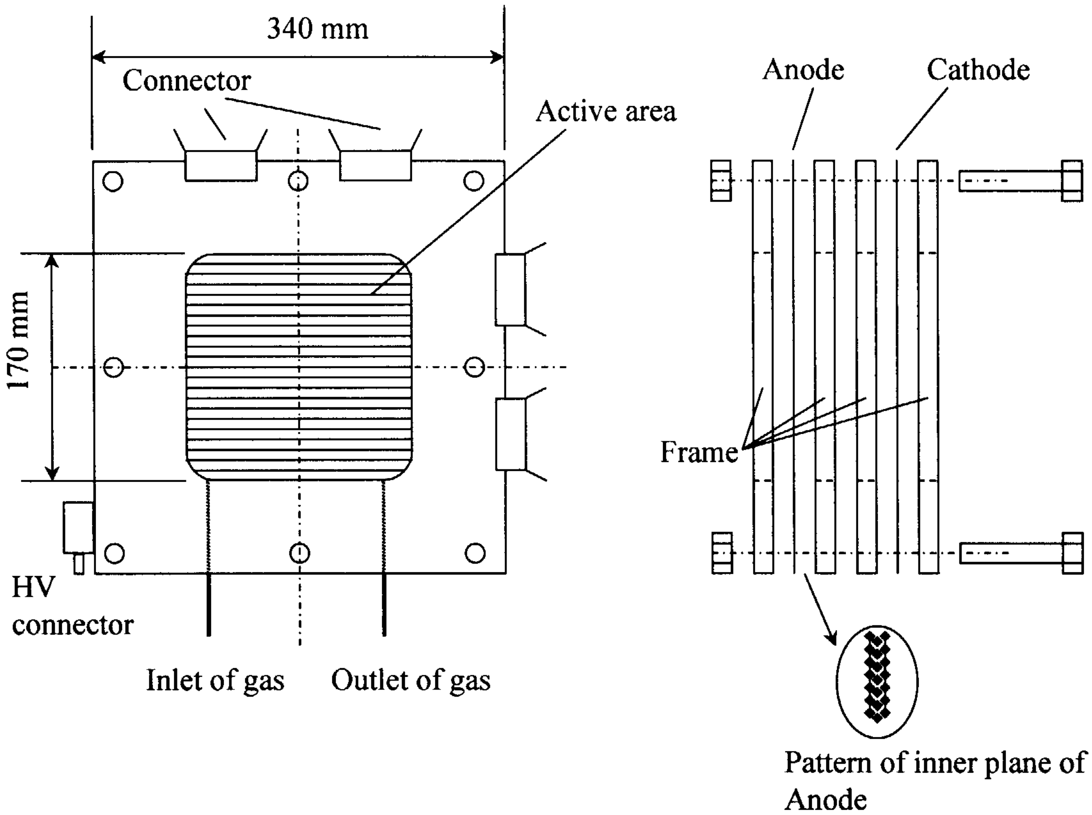

Fig. 2 Schematic view of segmented parallel-plate ion chamber(CHIDORI).

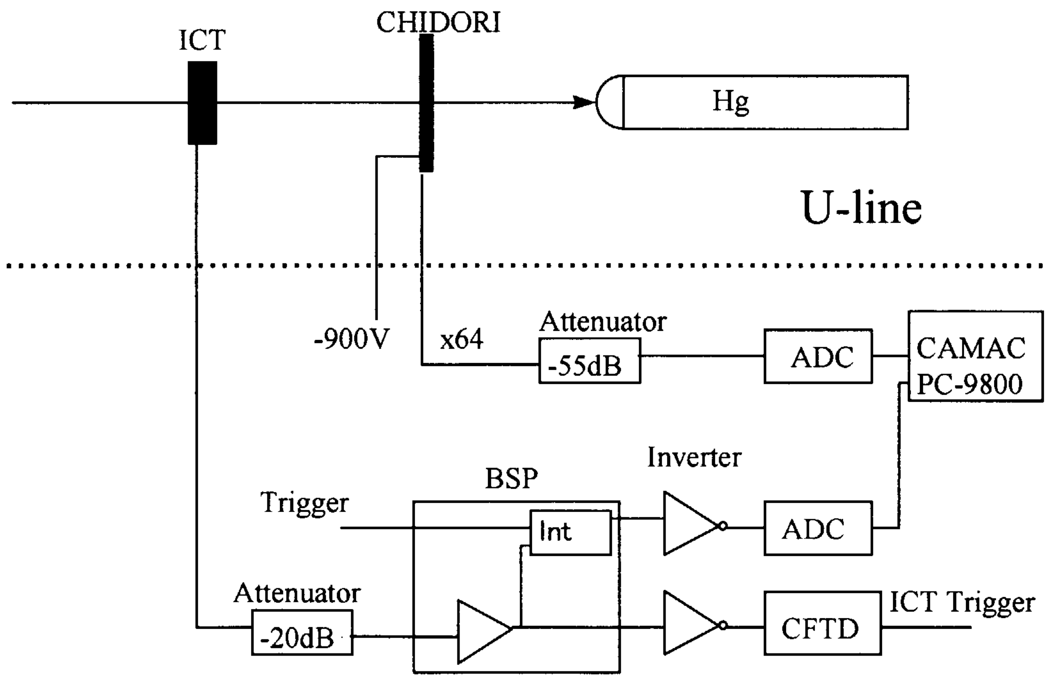

Fig. 3 Block diagram of the electronics used in the measurement for CHIDORI and ICT.

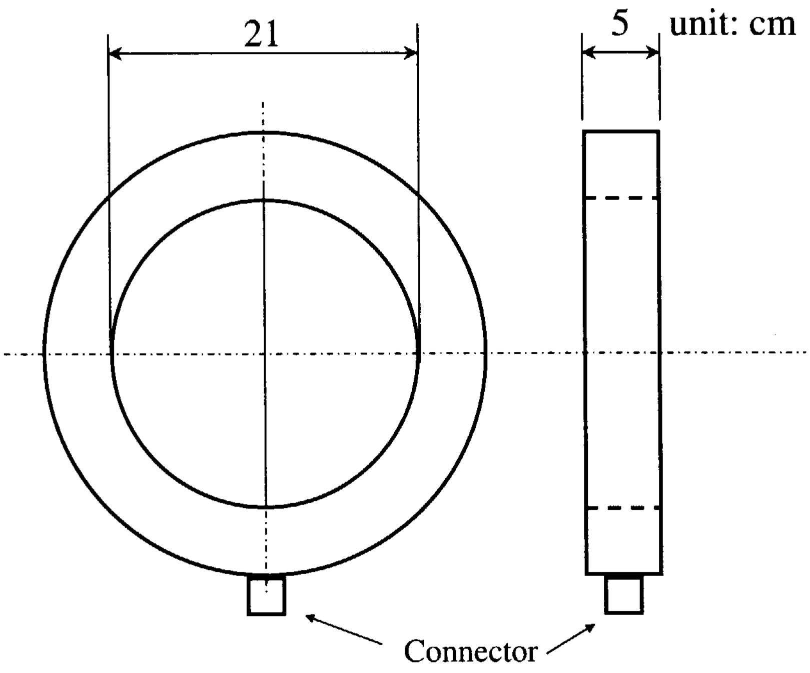

Fig. 4 Schematic view of integrating current transformer(ICT).

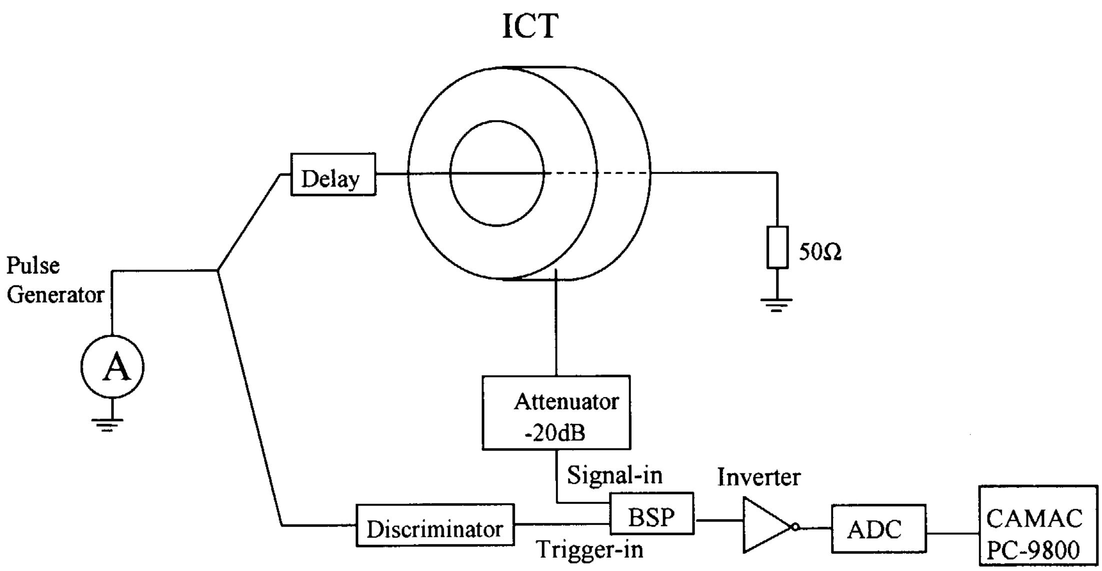

Fig. 5 Block diagram of the electric circuit for the calibration of the ICT.

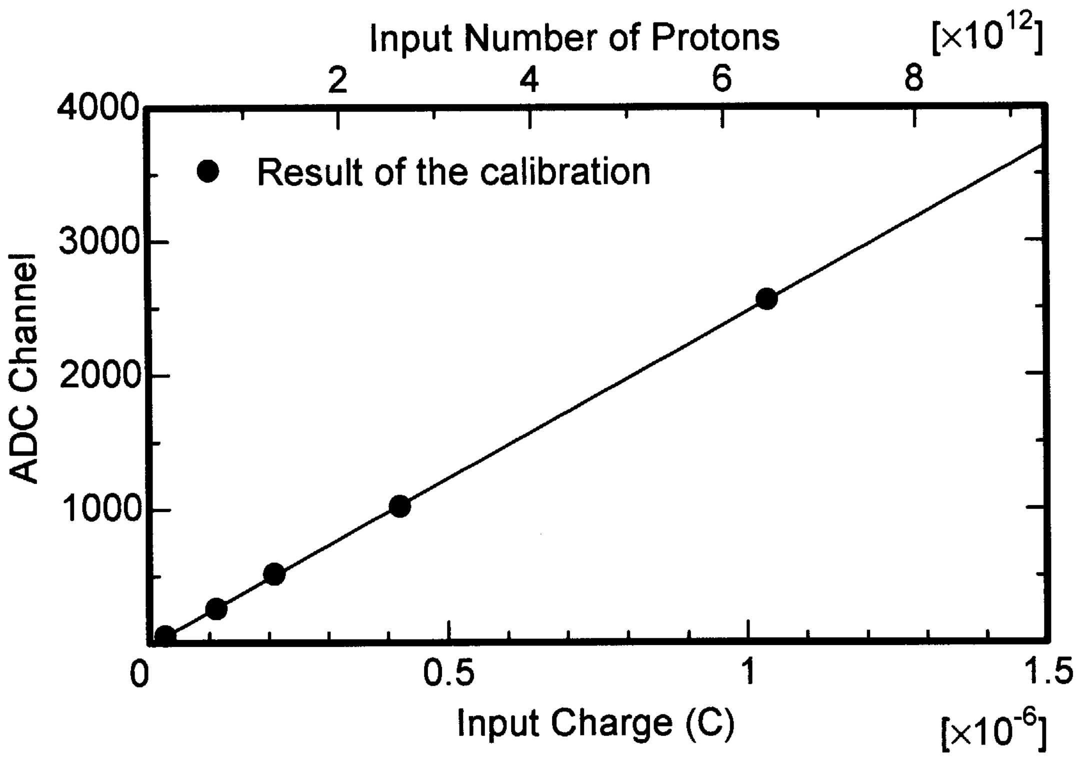

Fig. 6 Result of calibration of the ICT using the electric circuit shown in Fig. 5.

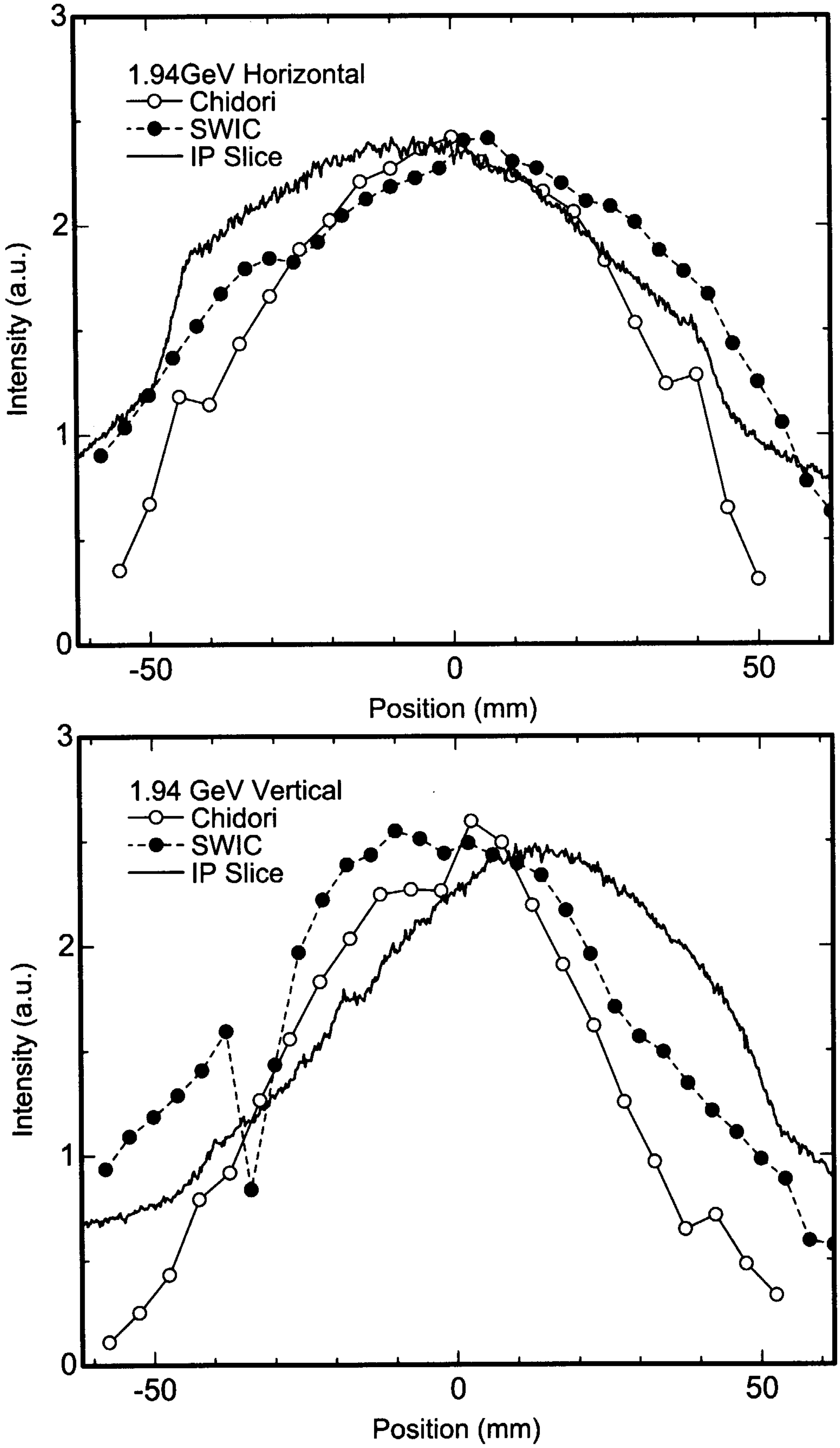

Fig. 7 Comparison of the results of beam profiles of vertical and horizontal directions for 1.94 GeV obtained by CHIDORI, IP and SWIC. Result of imaging plate is projected of the two-dimensional distribution on the vertical and horizontal axes in the peak area.

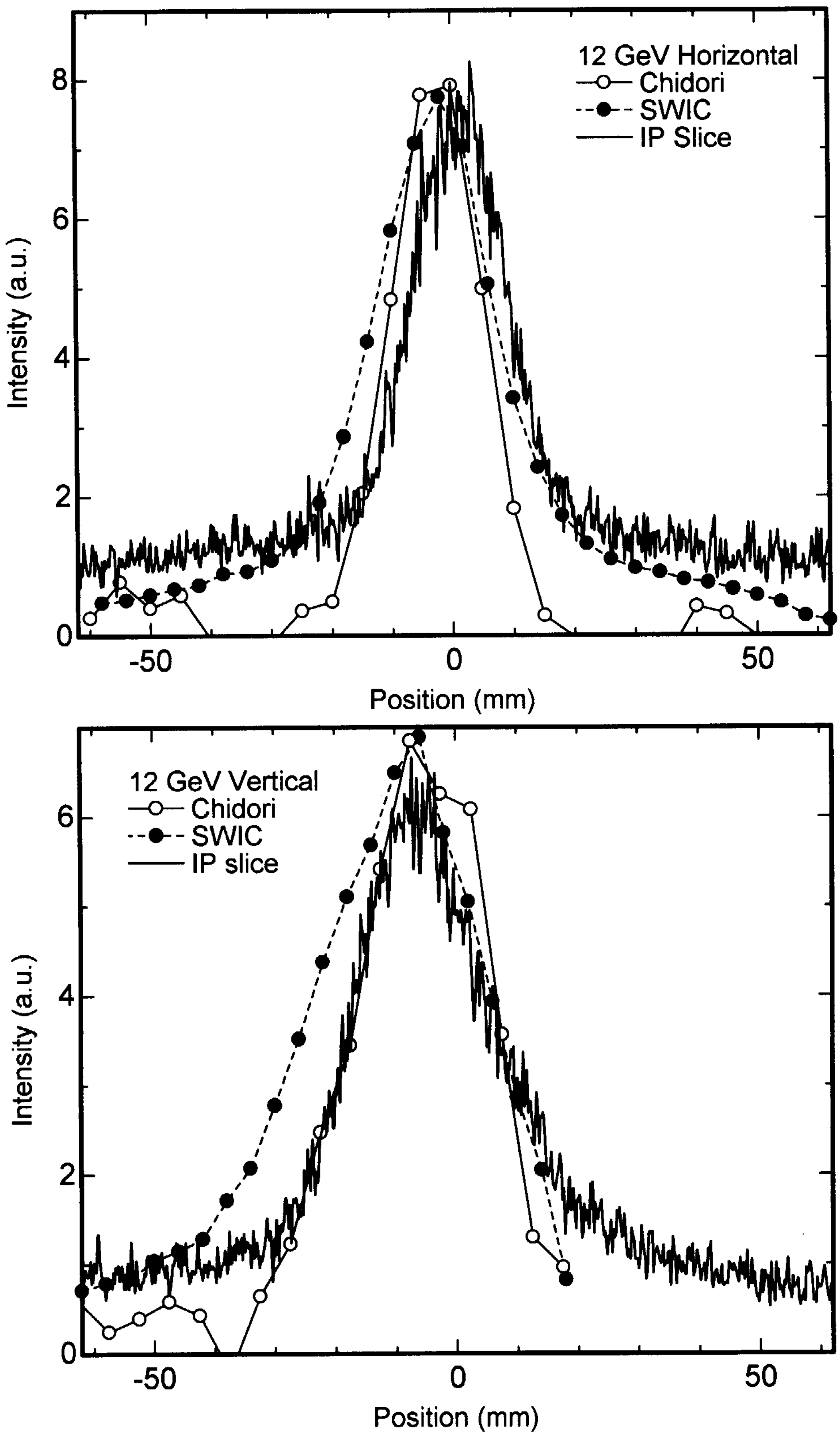

Fig. 8 Comparison of the results of beam profiles of vertical and horizontal directions for 12 GeV obtained by CHIDORI, imaging plate and SWIC.

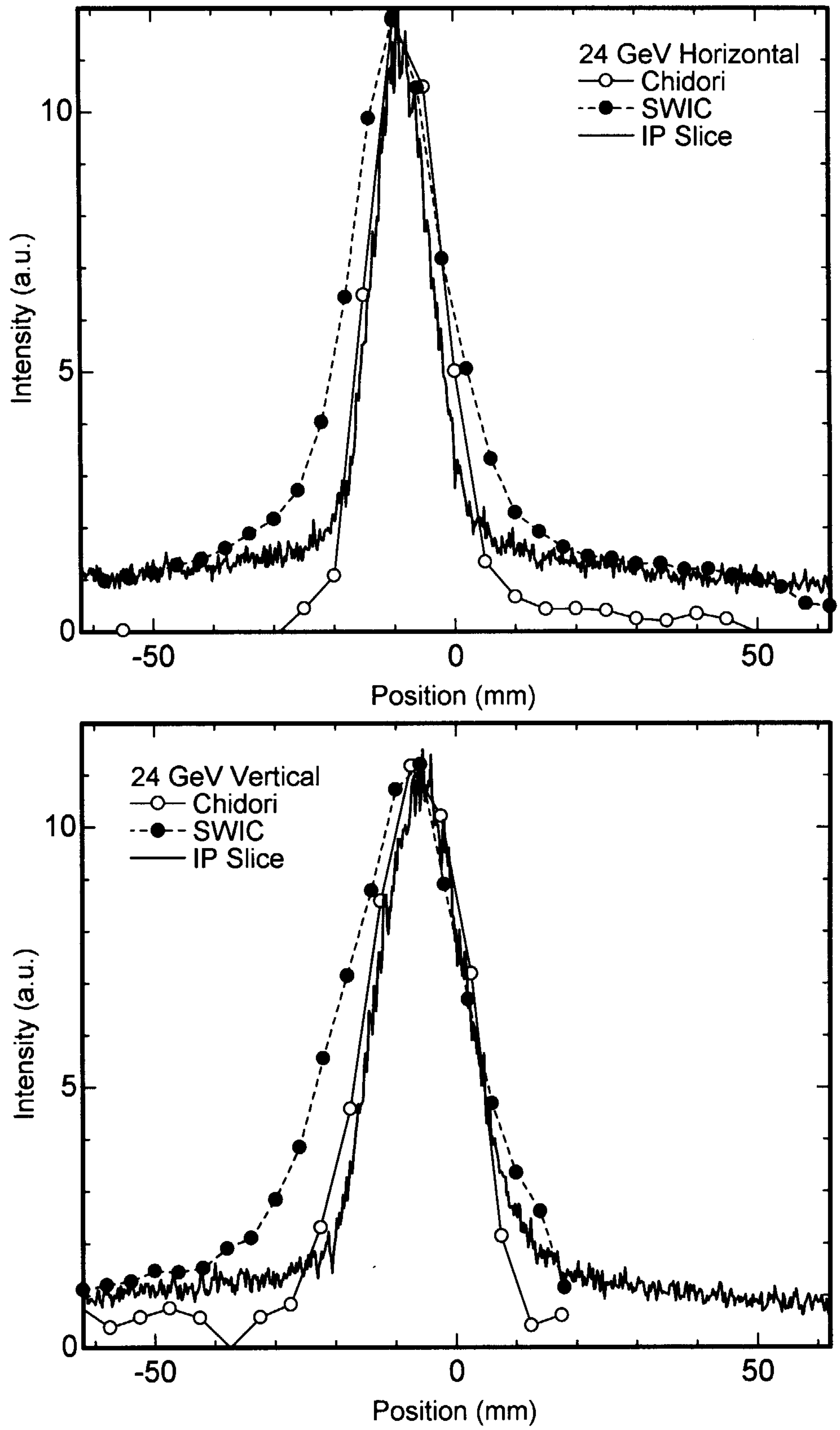

Fig. 9 Comparison of the results of beam profiles of vertical and horizontal directions for 24 GeV obtained by CHIDORI, imaging plate and SWIC.

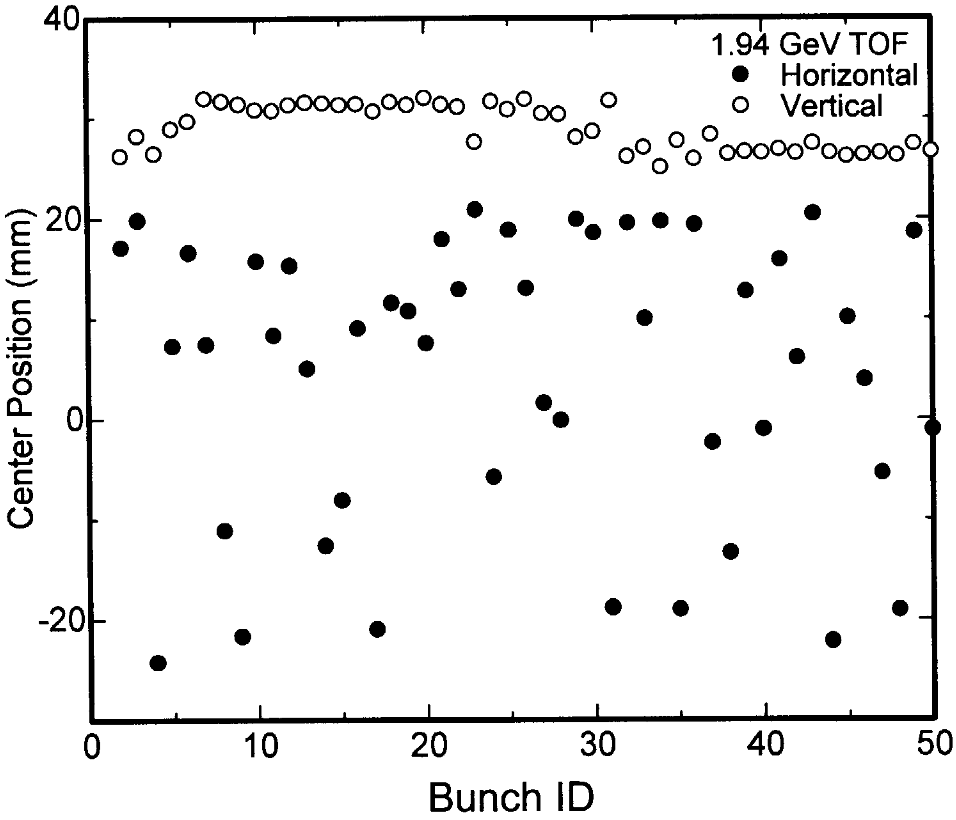

Fig. 10 Trend of peak position of the beam for 1.94 GeV obtained by CHIDORI.

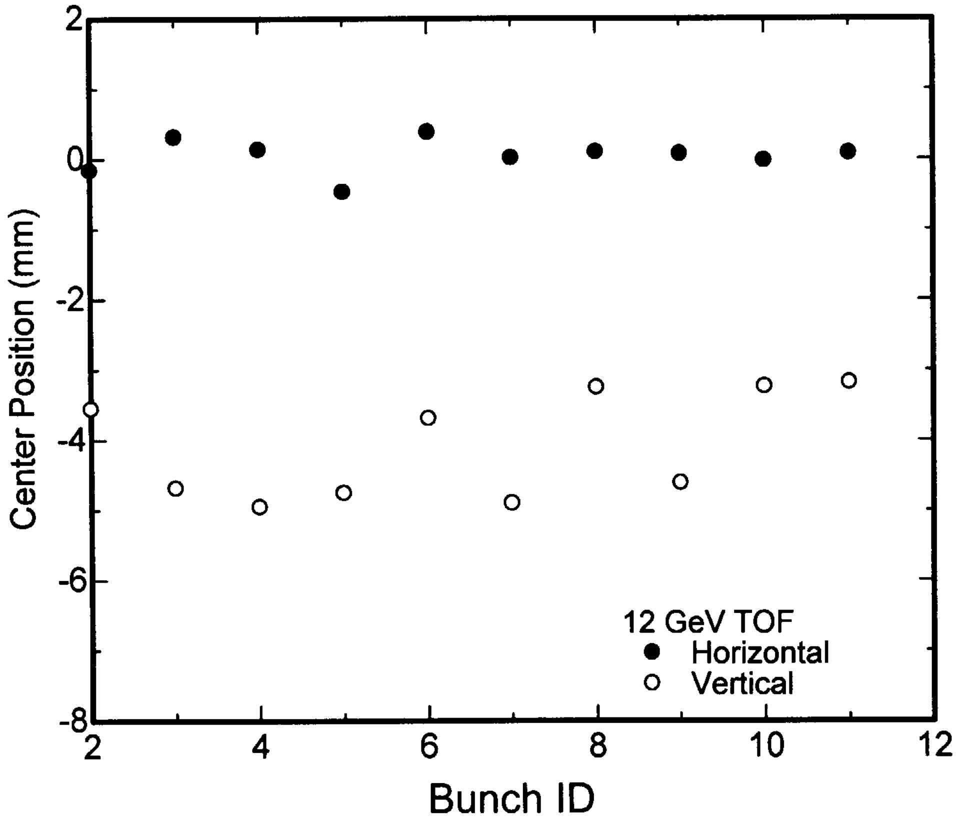

Fig. 11 Trend of peak position of the beam for 12 GeV obtained by CHIDORI

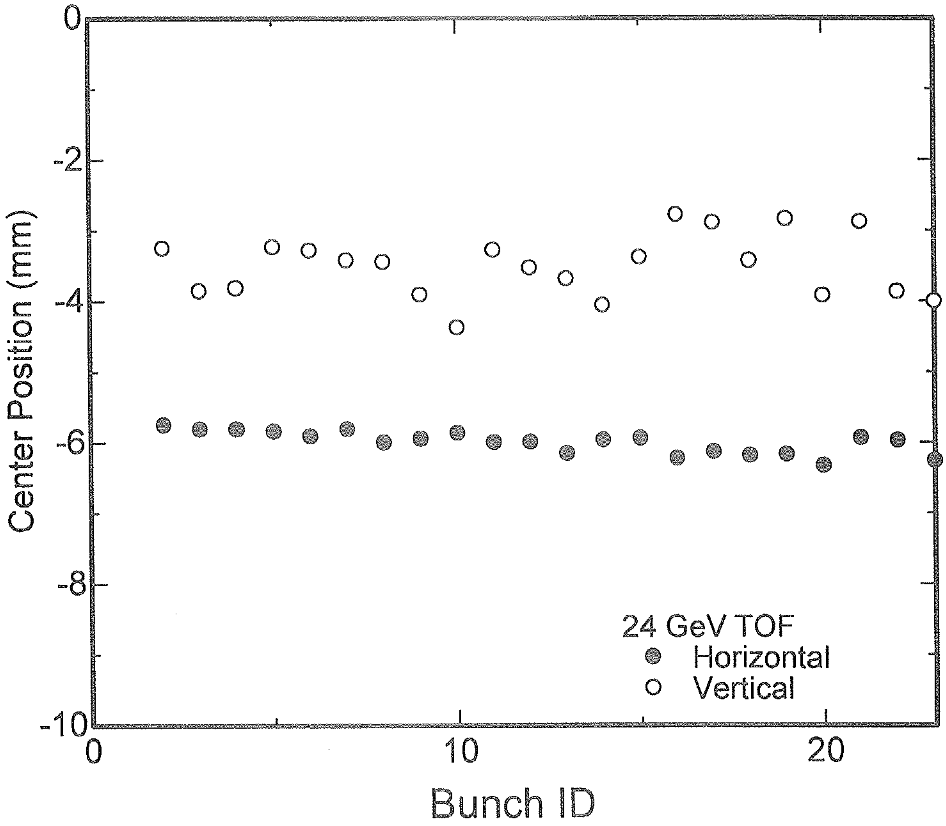

Fig. 12 Trend of peak position of the beam for 24 GeV obtained by CHIDORI

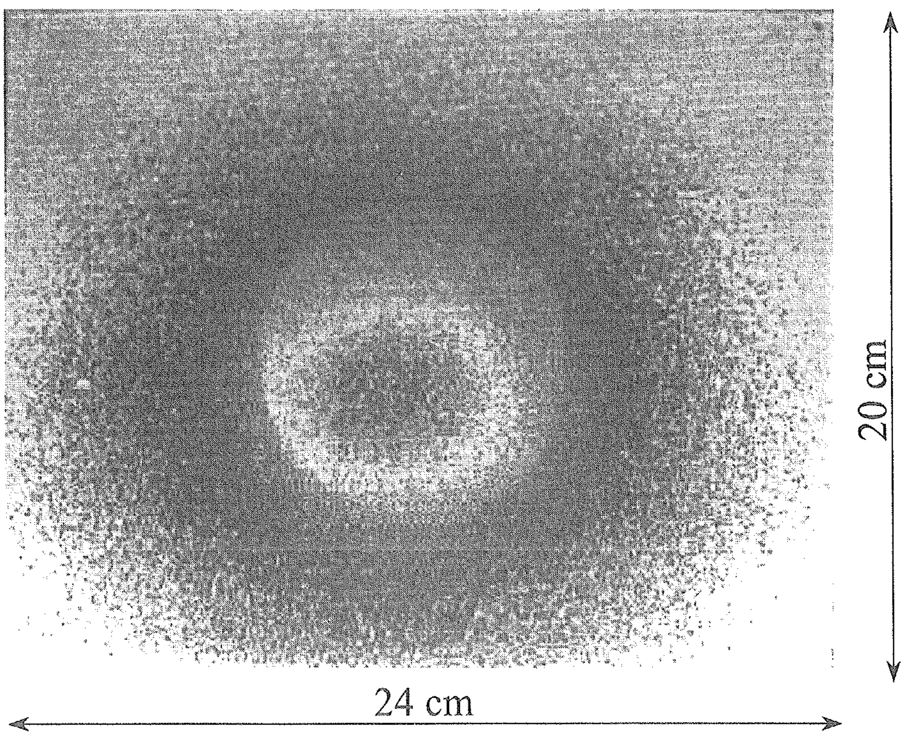

Fig. 13 Two-dimensional distribution of the incident protons for 1.94 GeV obtained by imaging plate technique

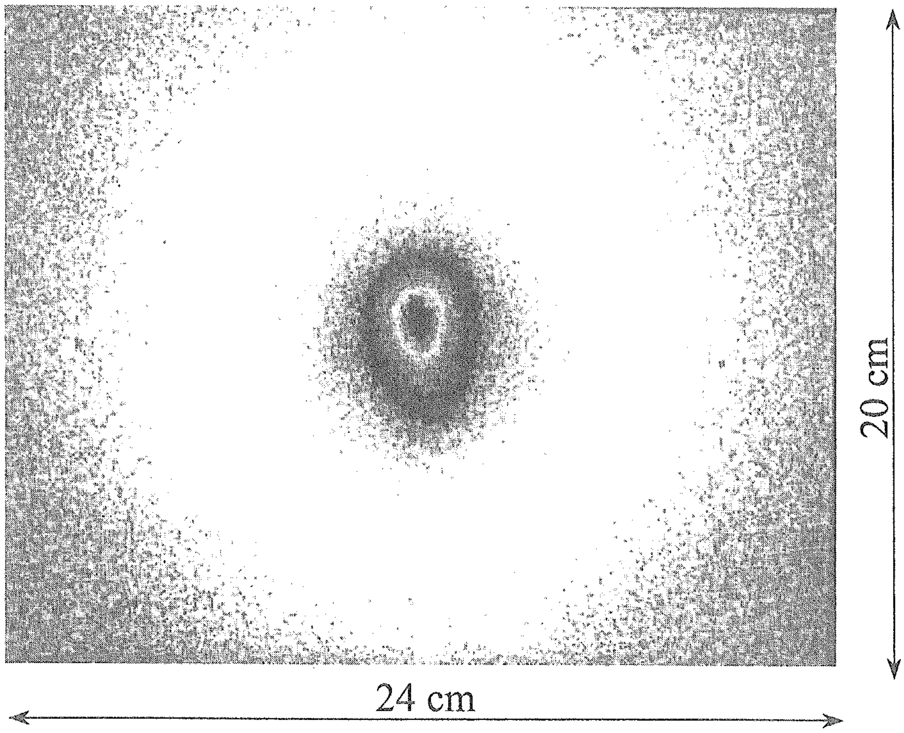

Fig. 14 Two-dimensional distribution of the incident protons for 12 GeV obtained by imaging plate technique

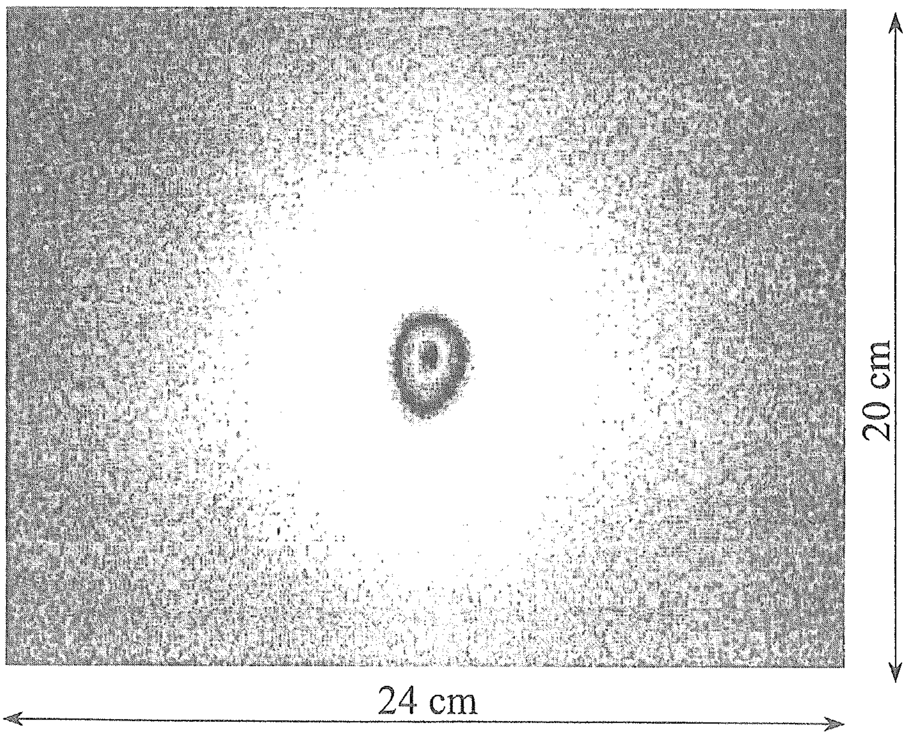

Fig. 15 Two-dimensional distribution of the incident protons for 24 GeV obtained by imaging plate technique

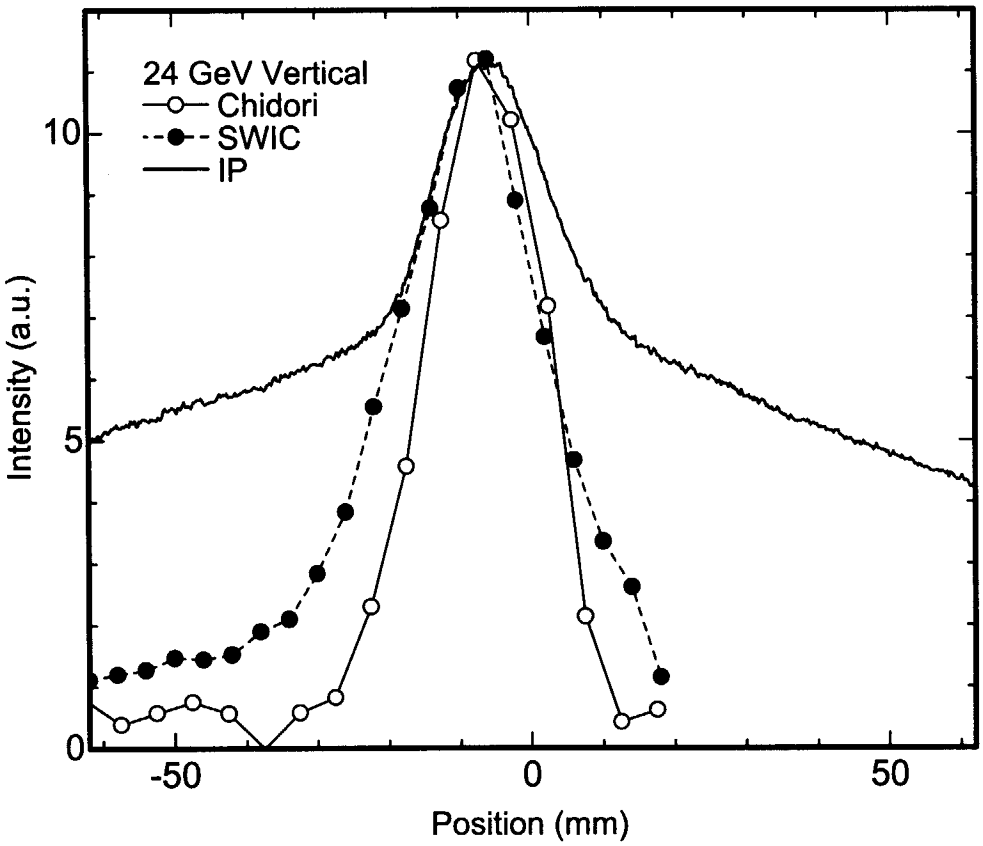

Fig. 16 Comparison of the results of beam profile for 24 GeV obtained by CHIDORI and IP which is projected in all area of two-dimensional distribution.

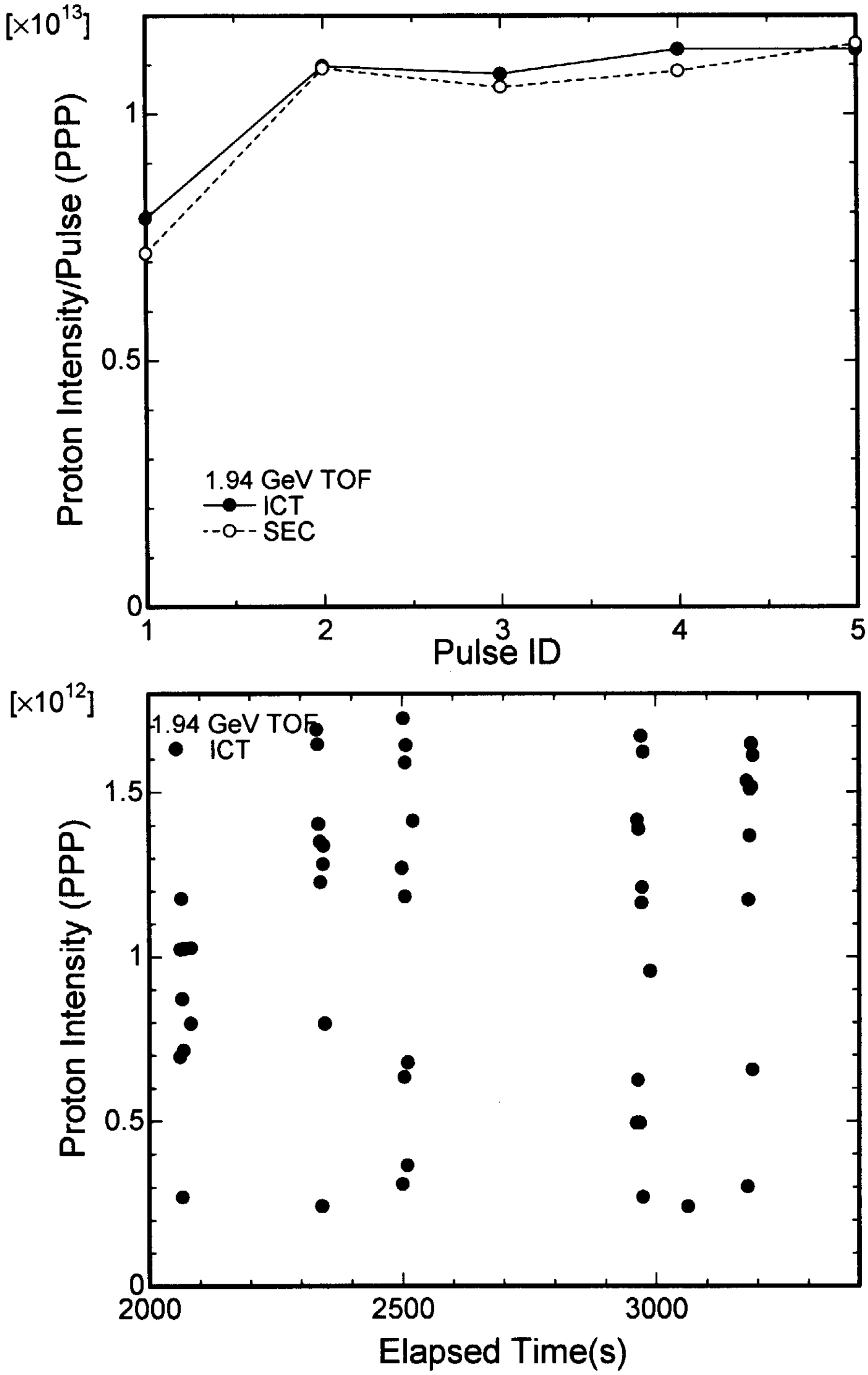

Fig. 17 Trend of beam intensity for 1.94-GeV protons obtained by ICT and SEC used in TOF measurements. For 1.94-GeV protons, a configuration of 8 micro bunches per macro pulse was employed. Cumulative intensities per macro pulse is shown in above. Each individual intensity per micro bunch is shown in below as a function of elapsed time.

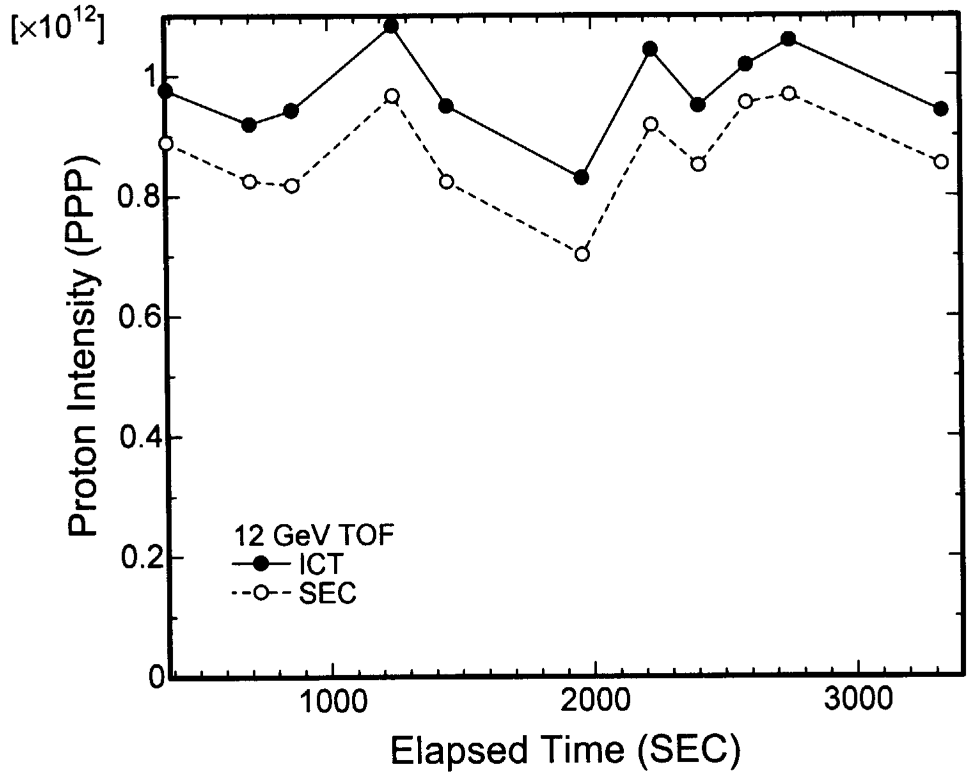

Fig. 18 Trend of beam intensity for 12-GeV protons obtained by ICT and SEC used in TOF measurements.

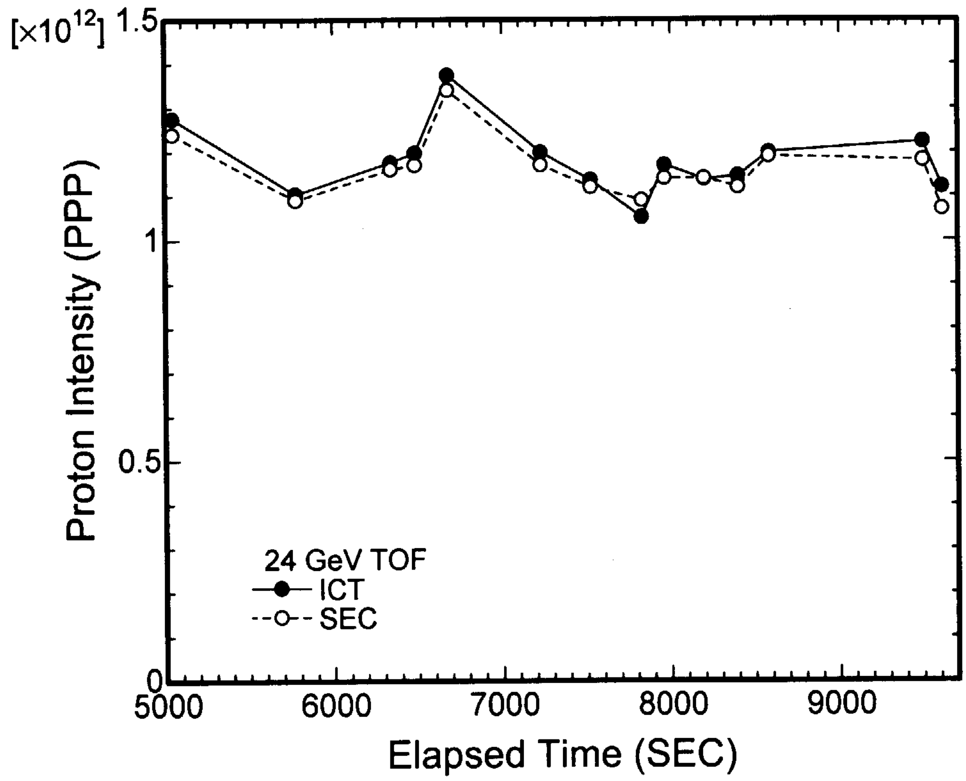

Fig. 19 Trend of beam intensity for 24-GeV protons obtained by ICT and SEC used in TOF measurements.

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国際単位系（SI）と換算表

表1　SI基本単位および補助単位

量	名　称	記　号
長　　さ	メートル	m
質　　量	キログラム	kg
時　　間	秒	s
電　　流	アンペア	A
熱力学温度	ケルビン	K
物 質 量	モル	mol
光　　度	カンデラ	cd
平 面 角	ラジアン	rad
立 体 角	ステラジアン	sr

表2　SIと併用される単位

名　称	記　号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV=1.60218×10^{-19}J
1 u=1.66054×10^{-27}kg

表5　SI接頭語

倍数	接頭語	記　号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

表3　固有の名称をもつSI組立単位

量	名　称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	m·kg/s^2
圧力，応力	パスカル	Pa	N/m^2
エネルギー,仕事,熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量等量	シーベルト	Sv	J/kg

表4　SIと共に暫定的に維持される単位

名　称	記　号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å=0.1nm=10^{-10}m
1 b=100fm²=10^{-28}m²
1 bar=0.1MPa=10^5Pa
1 Gal=1cm/s²=10^{-2}m/s²
1 Ci=3.7×10^{10}Bq
1 R=2.58×10^{-4}C/kg
1 rad=1cGy=10^{-2}Gy
1 rem=1cSv=10^{-2}Sv

（注）
1．表1－5は「国際単位系」第5版，国際度量衡局1985年刊行による。ただし，1 eVおよび1 uの値はCODATAの1986年推奨値によった。
2．表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3．barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4．EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換　算　表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　1 Pa·s(N·s/m²)=10 P(ポアズ)(g/(cm·s))
動粘度　1m²/s=10^4St(ストークス)(cm²/s)

圧力	MPa(=10bar)	kgf/cm²	atm	mmHg(Torr)	lbf/in²(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7 erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal= 4.18605J（計量法）
= 4.184J（熱化学）
= 4.1855J（15℃）
= 4.1868J（国際蒸気表）

仕事率　1 PS(仏馬力)
= 75 kgf·m/s
= 735.499W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

（86年12月26日現在）

Measurement of Profile and Intensity of Proton Beam by an Integrating Current Transformer and a Segmented Parallel–Plate Ion Chamber for the AGS–Spallation Target Experiment (ASTE)