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Charge identification of highly ionizing particles in desensitized nuclear emulsion using high speed read-out system

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Abstract

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We performed an experimental study of charge identification of heavy ions from helium to carbon having energy of about 290 MeV/u using an emulsion chamber. Emulsion was desensitized by means of forced fading (refreshing) to expand a dynamic range of response to highly charged particles. For the track reconstruction and charge identification, the fully automated high speed emulsion read-out system, which was originally developed for identifying minimum ionizing particles, was used without any modification. Clear track by track charge identification up to Z=6 was demonstrated. The refreshing technique has proved to be a powerful technique to expand response of emulsion film to highly ionizing particles.

Key words: nuclear emulsion, emulsion chamber, film refreshing, charge identification, heavy ion

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1 Introduction

Recent development of the nuclear emulsion technology is remarkable. Despite its excellent performance as a particle detector with sub-micron resolution and ability to record a very short track in 4π solid angle, nuclear emulsion became an obsolete technology in late 60's in the nuclear and elementary particle experiments. The time consuming measurement of tracks with a manually handled microscope mainly overwhelmed the advantages of nuclear emulsion, and yielded its position as a major detector to emerging new technologies at that time such as bubble chamber and electronic counter. However the recent success of developing an automated image processing system (Ultra Tracking Selector - UTS [1]) for nuclear emulsion and its event reconstruction software package (NETSCAN [2]) changed the situation drastically. This system opened up a road to apply nuclear emulsion to a large-scale elementary particle experiment which requires a high statistics data. The successful application of the system to the DONUT experiment [3] resulted in the discovery of tau neutrino. This success has brought the old technology back to the frontier of the field of elementary particle experiments.

Motivated by this remarkable progress in the nuclear emulsion technology, we recently started a project to apply it to study the interactions of relativistic heavy ions in matter. Heavy ions of several hundred MeV/u are important sources for cancer therapy [4]. The ^{12}C ion beam of this energy range has been used in practical treatments for more than 10 years at the Heavy Ion Medical Accelerator in Chiba (HIMAC), Japan. Despite this practical usage of heavy ions to radiotherapy, it is still considered fundamental to fully understand their interactions with matter. Especially the understanding of fragments from the

interaction has a critical importance in improving the ion therapy technology and, because of its high spatial resolution and capability to record short tracks, nuclear emulsion can be one of the most suitable devices for this study.

However there is a challenge to be overcome when we try to apply this new technology to study fragmentations from ion interactions. Charge identification of ions in nuclear emulsion is essential for the study, though its automated procedure has not been established yet. It is well known that the grain density of a track in emulsion is approximately proportional to the energy loss of charged particle. Based on this fact, in old days, charge identification was done by means of manual measurements [5] which counts developed grains. There were also several attempts to automate the process using photometric methods [6] and image analysis taken with CCD [7]. Recently several authors of the current report demonstrated that pions and protons near the minimum ionizing region can be separated using information related to the grain density [8] in Opera films - a nuclear emulsion film developed for the OPERA experiment [9]. The NETSCAN system automatically provides this grain density related information when it reconstructs tracks. Although this technique has been developed for particles with Z=1, it also can be applied for charge identification of ions if we can use nuclear emulsion which would not saturate its response to highly ionizing particles like ions. Therefore the key technology we need to develop is a realization of non-saturating Opera films for highly ionizing particles and an automated procedure of charge identification using them.

To realize a emulsion film of above mentioned quality, we studied a possibility to utilize the so-called refreshing technique. Refreshing is a technology to erase tracks in emulsion film by means of forced fading. Fading occurs in any

type of photographic film with the passage of time. It is caused by destruction of latent image center in a silver bromide crystal by oxidation. It is known that, by adding 5-methylbenzotriazole to emulsion, forced fading (i.e., to accelerate fading) can be realized under high temperature and high humidity environment [10]. Opera film has this feature of forced fading. This implies that, adjusting the amount of forced fading of track images in the film by controlling temperature and humidity, the saturation of grain density by passage of ions can be resolved.

In this paper we report the results of our study for applying the refreshing technique to Opera films in order to extend its dynamic rage of the response for energy loss by ionization. We also show experimental results of charge identification of ions from Z=2 to 6 with energy of $\sim$290 MeV/u ($\beta\gamma$ $\sim$0.8) using refreshed Opera films.

2 Setup and Beam exposure

The experiment was performed using the secondary beam line of HIMAC [11] at NIRS (National Institute of Radiological Sciences). The schematic view of secondary beam line is shown in Fig.1. The primary ^{12}C beam of 290 MeV/u from HIMAC was extracted to the secondary beam line and transported to the beryllium production target with thickness of 2 mm. Various types of nuclear fragments having almost equal velocity with the primary beam were produced by fragment reactions. The selection of a specific type of nuclide for the secondary beam line was done by tuning the current of the double bending magnets, which have a degrader in between, and the position of the momentum slit.

In the current experiment we exposed an emulsion chamber, which consists of stacked Opera films, to the secondary beams of ^{3}He, ^{7}Li, ^{9}Be and ^{11}B with $\sim$290 MeV/u. We also exposed the primary ^{12}C of 290 MeV/u by removing the production target in the secondary beam line. The beam parameter for each nuclide were tuned to maximize its purity. For this tuning the ΔE counter and the time-of-flight system, which were standardly equipped in the beam line, were utilized. The achieved purity and the nominal center value of energy for each beam are summarized in Table 1. As seen in the table there is at the maximum 4% difference in the beam velocities. This is due to our approach of beam tuning. Because it was not mandatory to adjust to equal all beam energies in the current study of charge identification, we set a higher priority on attaining the maximum beam purity. Despite this beam tuning approach, the attained results were $\sim$60% for ^{9}Be and $\sim$80% for ^{7}Li. The reason of low purity for these nuclides is that, because of relatively small difference in their charge to mass ratios, they tend to contaminate each other.

A schematic drawing of the emulsion chamber is shown in Fig.2. It is composed of stacked 32 sheets of Opera film. To guarantee a uniform response to beam particles these sheets were selected from a single batch of film production. A film sheet has 44 μm thick emulsion layers coated on both sides of a 205 μm thick TAC (cellulose triacetate) base. The surface measures 102 mm $\times$ 127 mm. Each sheet was packed with aluminum-coated film and thermosealed under vacuum. On the front surface (i.e., the upper-stream side of the beam line) of emulsion chamber, an extra film called changeable sheet was set. At the emulsion chamber exposure to each nuclide beam of ^{3}He, ^{7}Li, ^{9}Be, ^{11}B and ^{12}C, this sheet was replaced with a new one. During the data analysis stage, we used these changeable sheets for a reference to identify each beam track in

emulsion chamber.

One of the most critical parameters for exposing emulsion chamber to beam was the beam density. Exposure to a beam of too high density causes overlapping of particles, which makes the track reconstruction at the analysis stage difficult. To avoid this problem we kept the beam density in the order of 10^3 tracks/cm^2 in the current experiment. It took about 6 hours to complete the exposure of emulsion chamber to all beam types, though the most time was consumed for tuning the parameters of the secondary beam line.

3 Desensitization: Refreshing and Development

After the exposure of emulsion chamber to the HIMAC secondary beams, we transported emulsion chamber to Scanning Laboratory of Nagoya University to study the performance of the refreshing technique for charge identification. As described in the introduction, refreshing makes the sensitivity of emulsion lower and provides a possibility to avoid the saturation of response to highly charged particles. According to the report [10], the refreshing of Opera film for three days under the environment of 30 ^{o}C and relative humidity of 98% resulted in more than 70% of decrease in the grain density of tracks created by minimum ionizing particles. It was also reported that an increase of fog in the film was not observed by this refreshing. Here fog is due to accidental grains randomly distributed in the film and it causes a problem during the track recognition if its density is too high.

As shown in Fig. 2, we chose the first 16 film sheets in emulsion chamber and classified them into four groups (i.e., each group has four film sheets).

Following the report quoted above, we refreshed the first group with 30 ^{o}C. We also refreshed other two groups with 38 ^{o}C and 45 ^{o}C. The fourth group was not refreshed and used as a reference. During the refreshing process the films were kept in a light-shielded environmental chamber for three days. The chamber was controlled to humidity of 98$\pm$1% and to the specified temperature with an accuracy of $\pm$0.1 ^{o}C. After completing the refreshing, all film sheets were processed in the exactly same condition with respect to the development time and temperature.

4 Track Reconstruction and Pulse Height Measurement

We used UTS to read out a track image in the refreshed films. UTS creates 16 layers of tomographic CCD images from a 44 μm thick emulsion layer of the film. Based on these tomographic images, the image processor in UTS automatically recognizes track segments in an emulsion layer as three dimensional vectors. The UTS system has the field view of 150 μm $\times$ 120 μm and processes three views per second. The detection efficiency of a track segment was 98%. The area of 5 mm $\times$ 5 mm was scanned on both of the two emulsion layers from the uppermost sheet to the 16th sheet along the direction of each incident beam. During a scan the angles and positions of each track segment were recorded. After the scanning, two corresponding track segments in the emulsion layers of both sides were connected across the TAC base - a new track segment thus created is called a base track. By connecting based tracks which lay within a certain road, NETSCAN constructed a beam track. The tracks are unambiguously identified in the consecutive emulsion sheets with 99.5% probability. During this process NETSCAN also tried to align the geometrical

position of films and generated alignment parameters. These parameters were utilized to the fine-tuning of track reconstruction at the later stage. The accuracy of alignment of emulsion sheets with respect to each other and to the changeable sheet thus obtained were 2 μm after internal calibration of chamber using beam tracks. The loss of ^{12}C beam tracks due to the fragmentation in the thickness of 16 film sheets is estimated to be 2%.

During the recognition of a track segment, UTS also recorded information related to the grain density of the segment. This information consists of the number of tomographic CCD image layers having pixels associated with the track segment. The size of one pixel in CCD image was 0.29 μm $\times$ 0.23 μm. This grain density related information is called pulse height (PH) - this name comes from the fact that on and off of a pixel is measured by digitized output of CCD. If a particle creates a track image on all sixteen tomographic layers, then the PH value is 16 (i.e., saturated). For particles with Z=1 the PH is not usually saturated but for highly ionizing particles like ions it is 16 for most cases. This implies that PH is not a good measure for identifying the charge of ions.

In the current study we used information called volume pulse height (VPH) to identify ions' charge. It is well known that the thickness of track increases with the charge of particle [5]. By defining VPH as the sum of the number of pixels associated with each recognized track in all sixteen layers of tomographic CCD images (Fig.3), VPH reflects the width of tracks. It measures the grain density of a track segment in the three dimensional space along the track. The VPH value of a base track is the addition of VPHs on both emulsion layers. Applying the refreshing technique (i.e., desensitized the film) it is expected that we can eliminate associated pixel hits created by δ-rays from ions. This

expands the dynamic range of *VPH* and, by tuning the refreshing condition, we can maximize the charge separation.

5 Results and Discussion

The emulsion sheets refreshed in different temperature conditions have different sensitivity to ions. By selecting an appropriate refresh temperature it is possible to maximize the separation of one type of ion to others. Combining films which are refreshed in various temperatures, it is possible to realize emulsion chamber which has a wide dynamic range of the charge separation of ions. Taking this in mind, we studied the response of the refreshed films to the exposed ion beams. We averaged the *VPH* values of 4 sheets ($VPH_{av.4}$, total length in emulsion is 0.35 mm for each track) refreshed in the same temperature condition as

$$VPH_{av.4} \equiv \frac{\sum_{i=1}^{N} VPH_i}{N},$$

where VPH_i is the volume pulse height on i-th sheet. N denotes the number of sheets on which track were detected (maximum 4). Fig.4 shows the distribution of $VPH_{av.4}$ for each ion beam at four refreshing conditions (i.e., non-refresh, 30 ^{o}C, 38 ^{o}C and 45 ^{o}C). As seen in the figure, *VPH* increases with the charge of ions. This shows that *VPH* measures the ionization of ions without a saturation. The figure also shows that the average *VPH* values decrease with increasing the refreshing temperature for all ions. This demonstrates that the films were more desensitized by refreshing with a higher temperature.

To study quantitatively the overall performance of charge separation, we averaged VPH values of 16 sheets ($VPH_{av.16}$, total length in emulsion is 1.4 mm for each track). Here 16 sheets consists of four films from each four refreshing conditions. Fig.5 shows the distribution of $VPH_{av.16}$ for each beam. As seen in the figure the ^{9}Be data has one main peak of beryllium and two sub-peaks corresponding to lithium and boron. Also the ^{7}Li data has a sub-peak corresponding to beryllium. The height ratios of these sub-peaks to the main peaks are consistent with the purity of the beam shown in Table 1. Therefore we can consider that these sub-peaks are from the contaminations in main beam. The clear separation of peaks observed in Fig.5 demonstrates an excellent capability of the refresh technique for charge identification.

To quantify the charge identification capability, we calculated the significance of separations between the peak of $VPH_{av.4}$ by one nuclide and others. Here the significance was defined as $(p(1)-p(2))/\sqrt{\sigma^2_{p(1)}+\sigma^2_{p(2)}}$, where $p(1(2))$ and $\sigma_{p(1(2))}$ denotes center value and standard deviation for nuclide 1(2) respectively. The results are summarized in Table 2 and Table 3. In these calculations the cut of $190 \leq VPH_{av.16} \leq 225$ for ^{9}Be and the cut of $VPH_{av.16} \leq 190$ for ^{7}Li were applied to eliminate the beam contamination. As seen from the table, the higher the refresh temperature, the larger the significance of separation. However the separation was not improved significantly in higher temperature over 38 ^{o}C, because the increase of the fog density during the refreshing process deteriorated the quality of track measurement. In Table 4 we show the fog density observed in different refreshing temperature. The results in the table suggest that the refreshing temperature of 45 ^{o}C (and higher) should be avoided in a practical application.

To study the performance of the refreshing technique further we carried out the charge identification of beam particle based on the maximum likelihood method. It is possible to consider that the $VPH_{av.4}$ distributions shown in Fig.4 give response functions of refreshed films to various ions. We denote observed $VPH_{av.4}$ for the beam type (charge z) by the films in the refresh conditions t as VPH_t. Here t runs from 1 to 4, and covers the conditions of non-refreshed, refreshed at 30 ^oC, 38 ^oC and 45 ^oC. Assuming these $VPH_{av.4}$ distributions Gaussian, the observed response functions R of charge z by the film with the refresh condition t can be expressed as

$$R_{z,t}(VPH_t) \equiv \frac{1}{\sigma_{z,t}\sqrt{2\pi}} e^{-\frac{(VPH_t-\mu_{z,t})^2}{2\sigma_{z,t}^2}} \quad ,$$

where $R_{z,t}(VPH_t)$ is normalized to unity in the whole range of VPH_t. The value of $\mu_{z,t}$ and $\sigma(z,t)$ for each response function are given in Table 2.

If we regard the above response function as a function of charge z, then it can be interpreted as the probability function of the particle of charge z giving VPH_t in the film refreshed by the condition of t. Replacing $\mu_{z,t}$ to $\mu_t(z)$ and $\sigma_{z,t}$ to $\sigma_t(z)$, we can define the probability function as

$$P_t(z, VPH_t) \equiv \frac{1}{\sigma_t(z)\sqrt{2\pi}} e^{-\frac{(VPH_t-\mu_t(z))^2}{2\sigma_t^2(z)}} \quad .$$

Using this probability function we can define the likelihood function as

$$L(z) \equiv \prod_{t=1}^{4} P_t(z, VPH_t) \ .$$

We now can estimate the charge of a given track by varying the z and to find the value which gives the maximum of the above likelihood function. The distribution of estimated z for each beam is shown in Fig.6-(a) in linear

scale and Fig.6-(b) in logarithmic scale. We can estimate the error of charge identification based on this maximum likelihood using the results from the carbon beam. As shown in Table 1, we know that the purity of the carbon beam is 100%. According to the result seen in Fig.6-(a) and Fig.6-(b), the probability that carbon is wrongly identified as boron is 5.7%.

The above study demonstrates that the likelihood analysis of volume pulse height measured in emulsion sheets having refreshed in various condition is a powerful tool for charge identification. In the study, we used in total 16 sheets, which corresponds to the track length of only 1.4 mm. In a practical application, we can utilize much larger number of films, which promises much higher performance of charge identification. It is also worth to emphasize the unique characteristics of the refreshing technique. Refreshing can be applied after the exposure of emulsion film to beam. This implies that, after the beam exposure, it is possible to tune the response of emulsion chamber to ionizing particles according to the goal of data analysis. This provides a large flexibility when we consider a charge identification measurement using emulsion chamber.

6 Conclusions

It has been demonstrated that forced fading of nuclear emulsion film called refreshing is a powerful technique to expand the dynamic range of film's response to highly ionizing particles. The dynamic range of the film can be optimized by controlling the refreshing temperature. Using the Opera film, which has the refreshing capability, we could identify the charge of ^{3}He, ^{7}Li, ^{9}Be, ^{11}B, whose energies were around 290 MeV/u. Combining pulse height information from the films refreshed at the temperatures of 30 ^{o}C, 38 ^{o}C and 45 ^{o}C, the

significance of separation between various nuclides were >4.6 sigma for ^{3}He to ^{7}Li, 4.8 sigma for ^{7}Li to ^{9}Be, 3.0 sigma for ^{9}Be to ^{11}B, and 2.3 sigma for ^{11}B to ^{12}C. A higher temperature gave better separation of highly charged particles, though it was not possible to go beyond 45 ^{o}C because the increasing of film's fog density deteriorated the quality of track measurement. The charge identification based on maximum likelihood method using information of volume pulse height was a powerful tool. In the study we used information of the pulse height from a small portion (1.4 mm) of the entire track of a particle. In a practical application, it is possible to utilize much larger part of the track, which promises much better performance of charge identification. An emulsion chamber having combination of films refreshed under various conditions can be envisaged as a powerful device for charge identification of highly ionizing particles.

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Table 1

Beam property

nuclide	E(MeV/u)	$\beta\gamma$	purity(%)
^{3}He	276	0.82	>90
^{7}Li	277	0.82	∼80
^{9}Be	272	0.82	∼60
^{11}B	269	0.81	>90
^{12}C	290	0.84	100

Table 2

Center value of volume pulse height with sigma () after Gaussian fit

nuclide	average of 16 all sheets	not refreshed	30 ^{o}C	38 ^{o}C	45 ^{o}C
^{3}He	-	256.7 (7.4)	126.9 (11.1)	81.5 (12.9)	-
^{7}Li	174.4 (5.2)	284.7 (6.7)	189.7 (7.8)	155.6 (9.7)	69.3 (12.0)
^{9}Be	209.8 (5.3)	299.5 (8.1)	223.0 (7.8)	202.9 (8.3)	114.7 (11.5)
^{11}B	230.9 (4.8)	312.2 (9.1)	240.2 (7.6)	223.3 (7.8)	148.6 (11.0)
^{12}C	246.4 (4.7)	318.5 (8.8)	256.5 (9.0)	242.1 (8.6)	170.0 (9.9)

Table 3

Significance of discrimination

nuclide	average of 16 all sheets (sigma)	not refreshed (sigma)	30 ^{o}C (sigma)	38 ^{o}C (sigma)	45 ^{o}C (sigma)
^{3}He to ^{7}Li	-	2.8	4.6	4.6	-
^{7}Li to ^{9}Be	4.8	1.4	3.0	3.7	2.7
^{9}Be to ^{11}B	3.0	1.0	1.6	1.8	2.1
^{11}B to ^{12}C	2.3	0.5	1.4	1.6	1.4

Table 4

Fog density

	not refreshed	30 ^{o}C	38 ^{o}C	45 ^{o}C
Fog density (/1000 μm^3)	3.1±0.4	4.8±0.4	5.7±0.5	12.4±0.7

Figure captions

Fig.1

Schematic view of the secondary beam line at NIRS-HIMAC.

Fig.2

Schematic view of emulsion chamber structure.

The uppermost four subsequent sheets in emulsion chamber were not refreshed.

From 5th to 8th, 9th to 12th and 13th to 16th sheets from up-stream were refreshed in 30 ^{o}C, 38 ^{o}C and 45 ^{o}C respectively.

Fig.3

Schematic view of tomographic CCD images.

Sixteen layers of tomographic images along the tracks are taken with UTS.

Size of one pixel in CCD image is corresponding to 0.29 μm $\times$ 0.23 μm.

Fig.4

Distribution of volume pulse height using four subsequent sheets having each refresh temperature. (a) not refreshed, (b) 30 ^{o}C, (c) 38 ^{o}C and (d) 45 ^{o}C.

From top to bottom results of ^{3}He,^{7}Li,^{9}Be,^{11}B and ^{12}C beams are shown.

In (d) ^{3}He has no signal because helium tracks cannot be detected in the emulsion sheets refreshed.

Fig.5

Distribution of volume pulse height using all sixteen sheets.

From top to bottom results of ^{3}He,^{7}Li,^{9}Be,^{11}B and ^{12}C beams are shown.

^{3}He has no signal because helium tracks cannot be detected in the emulsion sheets refreshed in 45 ^{o}C.

Fig.6

Distribution of estimated charge.

From top to bottom results of ^{3}He,^{7}Li,^{9}Be,^{11}B and ^{12}C beams are shown. Signals corresponding to Z=4 in ^{7}Li beam, Z=3 and 5 in ^{9}Be beam and Z=3 and 4 in ^{11}B beam are due to contamination of wrong charge particles in secondary beam. (a)linear scale, (b)logarithmic scale.

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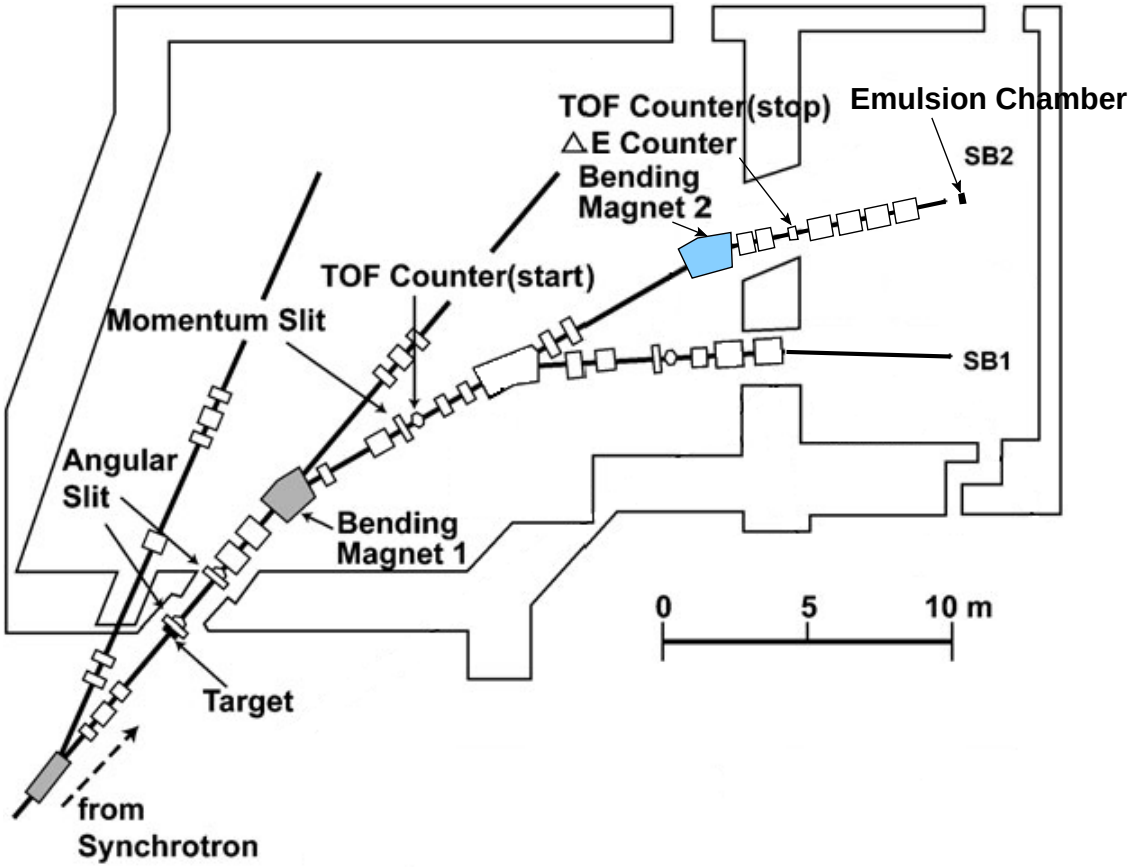
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Emulsion Chamber
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TOF Counter(start)
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Synchrotron

Fig. 1.

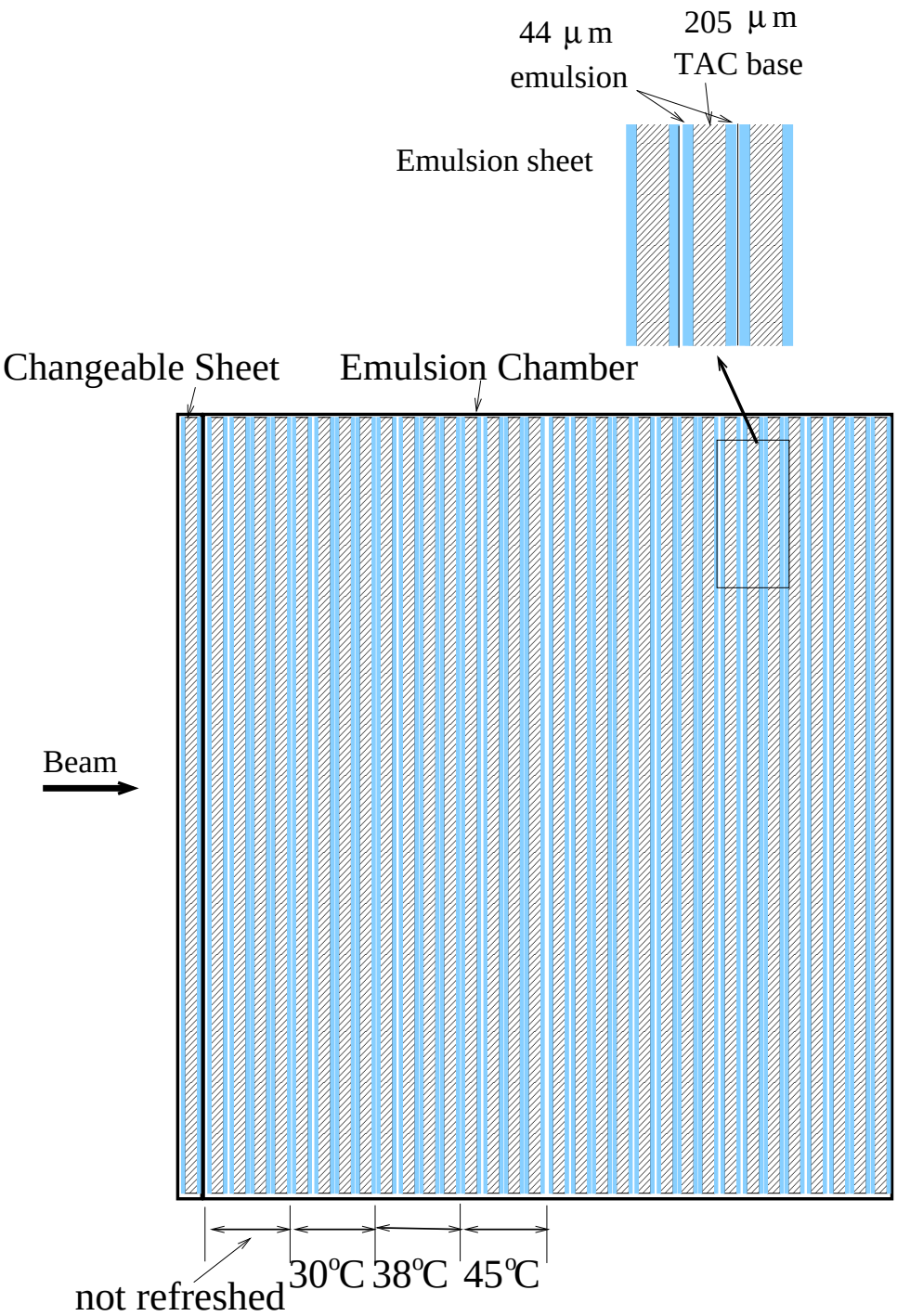

44 μm
emulsion
205 μm
TAC base
Emulsion sheet
Changeable Sheet
Emulsion Chamber
Beam
not refreshed
30℃
38℃
45℃

Fig. 2.

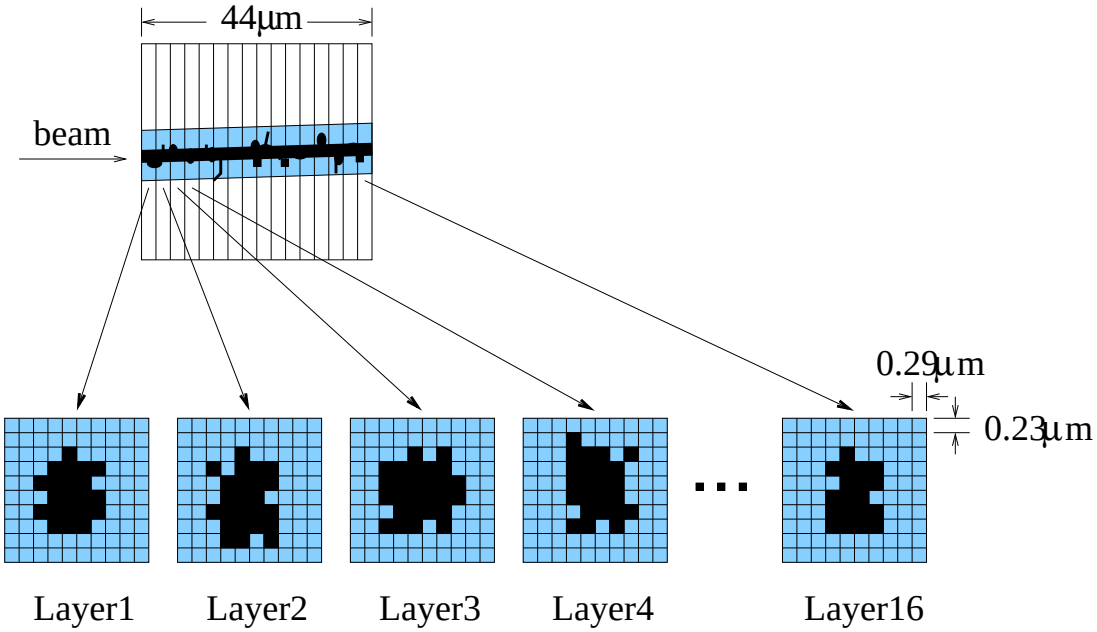


Fig. 3.

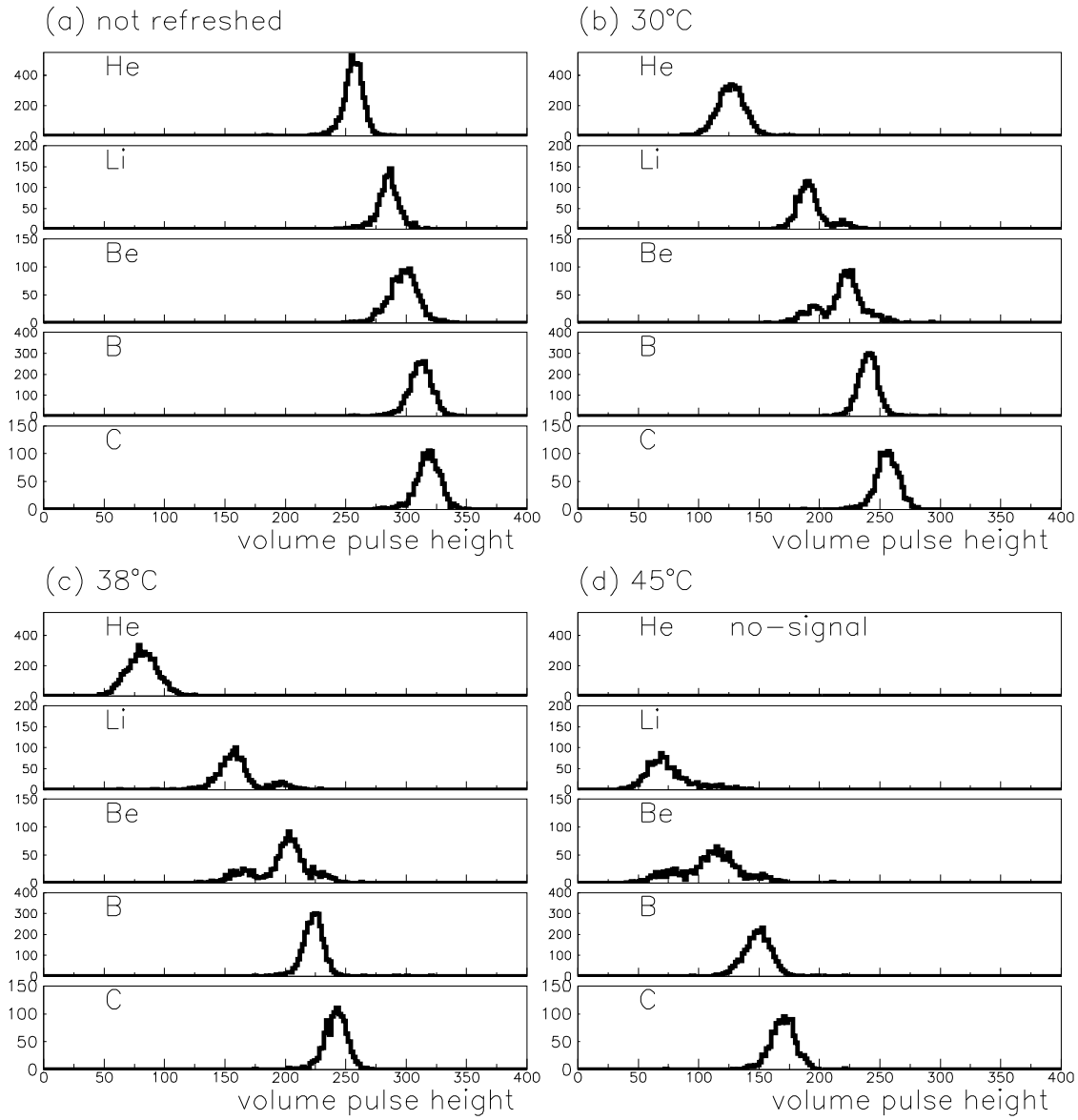

(a) not refreshed
(b) 30°C
(c) 38°C
(d) 45°C
He
Li
Be
B
C
no−signal
volume pulse height

Fig. 4.

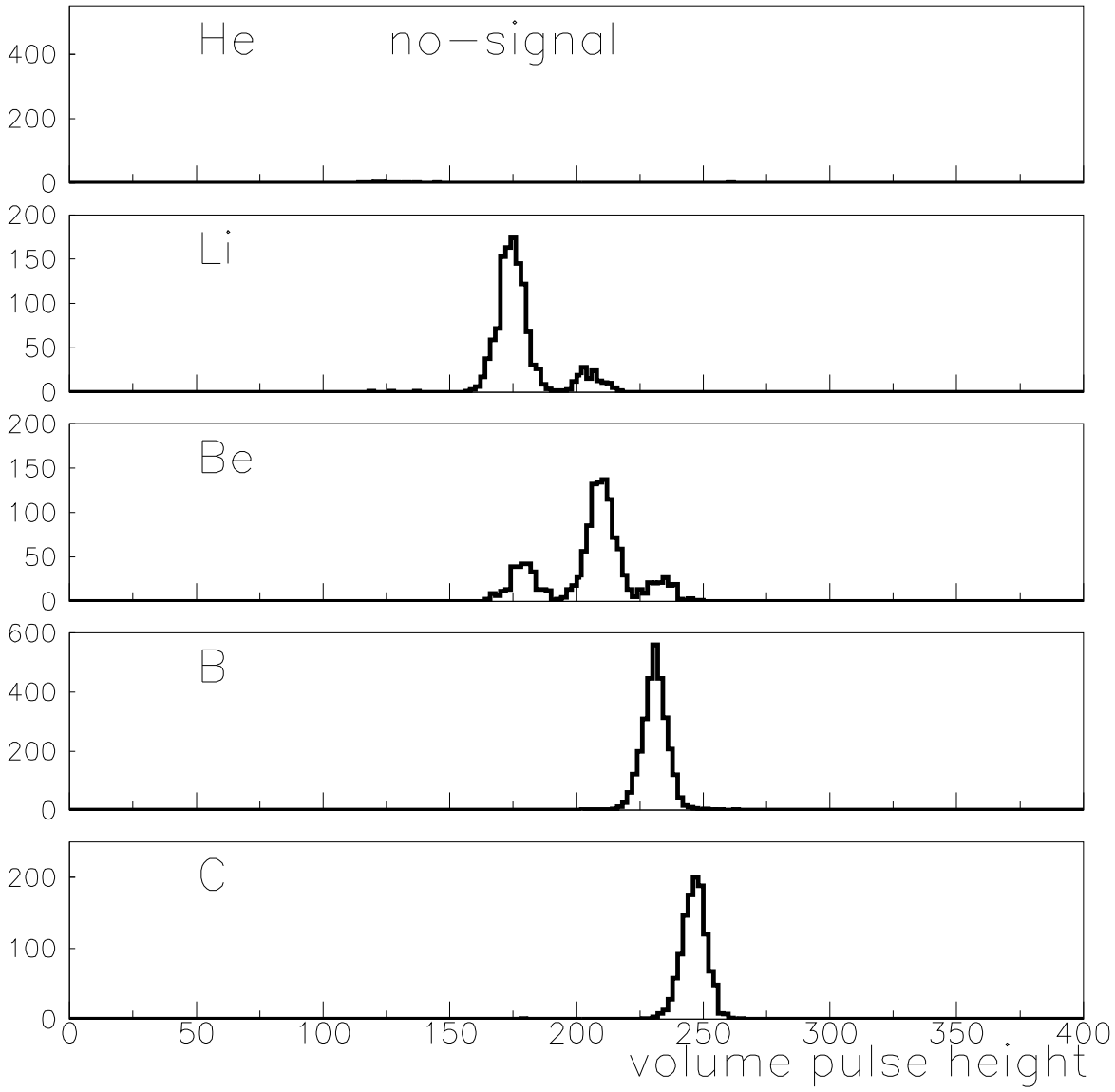
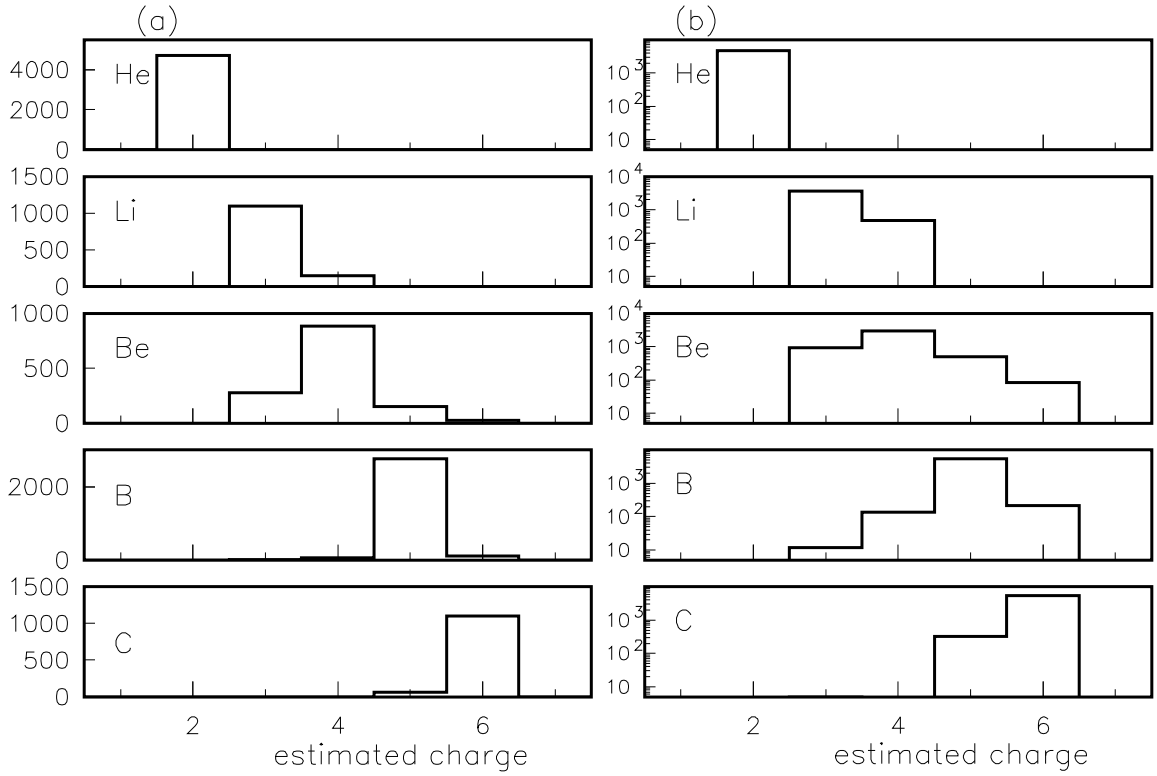


Fig. 5.


(a)
(b)
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1000
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1000
500
2000
10^4
10^3
10^2
10
2
4
6
estimated charge

Fig. 6.