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Abstract

An ion-optical design of the JHP-ISOL is presented. This separator consists of a beam guidance system, a main magnetic separator stage and an electrostatic energy focusing stage. This separator is to be coupled with a heavy-ion linac for post-acceleration of mass separated ions up to 6.5 MeV/u. The design goal of the separator is to realize a mass resolving power of $R_M = 20{,}000$ (basal) at a transmission approaching 100 % with the initial phase space of ± 0.2 mm ×± 20 mrad.

1. Introduction

A radioisotope-beam (RI beam) facility, which is called Exotic Nuclei Arena (E-arena)[1], is being planned as one of the research arenas in Japanese

Hadron Project (JHP)[2]. The E-arena uses part of the beam from a 1-GeV proton linac, which will also be used as an injector to a storage ring to produce intense mesons and neutrons[2]. The facility of E-arena consists of two parts; one is a high-resolution ISOL (Isotope Separator On-Line) and the other a heavy-ion (HI) linac. The radioactive nuclei produced by bombarding a thick target with a high-intensity 1GeV proton beam are ionized in an ion source similar to that of ISOLDE at CERN. Then such ions are accelerated to $\approx$ 100 keV, mass-analyzed by the ISOL, and introduced into the HI linac for post-acceleration.

Recently, the study of exotic nuclei using nuclear reactions induced by RI beams is planned[4] not only for nuclear physics applications but also for astrophysical investigations. Until now, various informations of nuclei, which are stable or close to a beta stability line, have been obtained using nuclear reactions only with stable projectile beams. But once one wants to use beams of nuclei far from beta stability, the experiment becomes very difficult since one cannot easily obtain pure and high intensity nuclear beams far from stability. The facility of E-arena is one way to offer such RI beams. We consider this facility of E-arena from the viewpoint of the ISOL,which is a powerful tool for studying exotic nuclei. Usually an isotope separator supplies a mass-separated RI beam for nuclear spectroscopy, but the beam usually has contamination of a few isobars because of a small mass-resolving power (e.g., up to a few thousand). For these reason the ISOL should have a mass-resolving power sufficient for separating the neighboring isobars and in some case even isomers. In the following sections we describe a corresponding ion-optical design for the JHP-ISOL.

2. Ion optics

The ion optics is being calculated using the computer code "GIOS" (General Ion Optics Systems), developed in Giessen[5], which can calculate an ion-optical system up to the third order. The program GIOS determines numerically the optical properties of systems consisting of magnetic and electrostatic sector fields as well as magnetic and electrostatic quadrupoles, hexapoles and octupoles with their respective fringing fields using the transfer matrix method[5,6].

2.1. Guiding principle of the design

Table 1 shows the basic design goal of the JHP-ISOL. The mass range of the separator is 1 to 300 amu at 100 kV acceleration, but the linac for post acceleration restricts the charge-to-mass ratio to $\geq 1/60$ with an energy-to-mass ratio 1 keV/amu [1].

Figure 1 shows the required mass resolving power for the separation of neighboring isobars of mass numbers 60 and 120. For A = 60 a mass resolving power $R_{\mathrm{M}} = 20{,}000$ seems to be sufficient, but for A = 120 a $R_{\mathrm{M}} = 30{,}000$ is necessary.

The mass resolving power of an isotope separator is given by

$$R_{\mathrm{M}} = D_{\mathrm{M}}/(2x_0|M_x| + \delta_{\mathrm{abe}}) \quad , \tag{1}$$

where D_{M} is the mass dispersion, x_0 is a half the initial object width (horizontal), M_x is the x-magnification and δ_{abe} the width increase due to aberrations. By assuming $x_0 = 0.2$ mm a mass dispersion D_{M} larger than 8 m is required for $R_{\mathrm{M}} = 20{,}000$ choosing $|M_x| = 1$. Since "a symmetric pair" of sector magnets (having a deflection radius of ρ) has a mass dispersion of $D_M = 2\rho$[7], we chose $\rho = 2.5$ m for two symmetric pairs of sector magnets.

Figure 2 shows the layout of the separator system. The 1 GeV proton beam line and target (ion source) area are located deep underground to shield intense radioactivities. At first a rough mass selection will be made on the underground level, while the main mass analysis will be achieved on the surface level. Two ion sources are foreseen for the two proton beam lines for ease of maintenance. The beams from the ion sources are transported by a beam guidance system to the surface level to be analyzed by two stages of ISOL.

2.2. Beam guidance system

Figure 3 shows the layout of the beam guidance system. It consists of quadrupole triplets, doublets and four 45°-sector magnets with a deflection radius of 1 m each. The ions are accelerated up to 100 keV, bent firstly to the vertical direction through QQQ $D_{11}D_{12}$ and then to the horizontal direction by QQ QQ $D_{21}D_{22}$ and focused at S_4. Then the ion beam is focused again to a point 3.7 m before the entrance of the first main separator magnet ($S_{4'}$, see figure 4) using additional quadrupoles and a bending magnet. In this part a solenoid or a quadrupoles multiplet should be included to rotate the beam around its axis to avoid a phase space mixing of x and y directions. The calculation of the transport line from S_4 to $S_{4'}$ is still to be done since the design of this part greatly depends on the building and floor plans and these are not yet fixed until now.

The intermediate images at S_1 and S_3 between each pair of magnets show dispersion, so that one can make a rough mass selection by a slit. The dispersion at S_1, e.g., after the first magnet is 5 mm per mass unit at mass 100 perpendicularly to the central beam. However, the total beam guidance system as well as the individual 90° bendings are achromatic.

A specific feature of this system is that all quadrupole lenses are magnetic. The reason is to avoid the maintenance problems inherent to electrostatic elements as well as to avoid the destruction of the space-charge compensation effects. In addition the focusing points of the horizontal (x) and vertical (y) directions are purposely located at different points to reduce any leftover space-charge effect.

2.3. Main magnetic stage

Figure 4 shows the main magnetic stage together with an electrostatic energy focusing stage. The first four quadrupole elements are fictionally added to simulate the beam guidance system since the connecting part between the beam guidance system and the main magnetic system has not been designed yet as stated above. In Table 1 some of the parameters of these stages are summarized.

The main part of this magnetic stage consists of two symmetric pairs of sector magnets[7]. The deflection angle of each of the four sector magnets is chosen to be $\phi_B = 60°$ because of the limited size of the building. To achieve the overall mass dispersion $D_M = 10$ m at the final focus of the magnetic stage, the radius of deflection of all sector magnets is chosen $\rho_B = 2.5$ m $(|M_x|) = 1)$. This corresponds to a mass resolving power of $R_M = 25{,}000$ (1st order).

To achieve a double focusing each of these homogeneous sector magnets has the same entrance and exit angle of $\epsilon = 16.1°$[7]. These sector magnets also have surface coils[8] in order to minimize the aberrations up to the third order.

To make the air gap of the magnets as narrow as possible we chose the magnification in y-direction as $|M_y| = 8$ in stead of $|M_y| = 1$ by adjusting the beam guidance system properly. In the present calculation this condition is simulated by using the four quadrupoles. As a result the beam width in y-direction is very narrow, about ± 2 cm, in comparison with that of the x-direction, about ± 10 cm. Thus the pole gap of the magnets is only ± 5 cm.

In order to combine the main magnetic stage with an electrostatic stage we use additional magnetic quadrupole elements after the two pairs of dipole magnets for matching purpose. These "quadrupoles" also have hexapole and octapole components to minimize the aberrations up to the third order.

2.4. Energy-focusing stage

The energy-focusing stage consists of four identical electrostatic cylindrical sectors that have an energy dispersion which exactly compensates that of the main magnetic stage. Each electrostatic sectors has a deflection angle of 90° and a deflection radius of 1.8 m (see fig. 4). The "quadrupoles" of the energy-focusing system is all electric, e.g., the "quadrupole" triplet in this system has also hexapole and octupole components to minimize the aberrations up to the third order.

When the energy spread of the ion source is large, the energy-focusing stage is very useful as discussed in the next section. When the energy-focusing stage is not necessary, we plan to replace it with a straight beam line as a by-pass. For this purpose the first(ES1) and fourth(ES4) sector fields are separated into parts of $\phi_E = 10°$ and $\phi_E = 80°$, respectively, so that one can directly connect the magnetic stage and the HI linac using the by-pass line. Another idea of such a by-pass line is to move the whole system of the electrostatic stage and the by-pass line mechanically (see fig. 4).

2.5. Beam profiles

The GIOS program[9] can simulate beam profiles by Monte Carlo calculation, i.e., by letting a number of ions start from the initial conditions randomly filling the phase spaces in x- and y- directions.

Figure 5 shows the beam profiles for 20000 particles starting from the ion source and arriving at the final focus point (S_7) of the magnetic stage and at the very end of the system (S_8). There are three figures corresponding to an energy spread of $\delta_K = 0$, 1 and 10 eV, respectively. The initial phase space is a parallelogram of ± 0.2 mm × ± 20 mrad for the x- and y- directions, which simulates expected conditions of plasma or surface ion sources. Each figure shows one of the profiles of three groups of particles having mass differences of 0 and ± 1/20,000. In the case of $\delta_K = 0$ eV (fig. 5(a)), a mass difference of 1/20,000 is resolved almost completely with transmission of $\approx$ 100 %. However, the energy spread has a serious effect on the mass resolution at the focus point of the magnetic stage (S_7) already for the spread of 1 eV (fig. 5(b)). When the energy-focusing stage is used, the energy spread of 1 eV has a negligible effect on the mass resolution at the final focus point (S_8). If the energy spread becomes larger than 5 eV, the remaining aberrations contribute and one cannot achieve a 1/20,000 mass resolution (basal) for a transmission of $\approx$ 100 % . However, if the transmission is reduced from 100 % to 60 % or the initial object width is reduced from $x_0 = \pm$ 0.2 mm to x_0

= ± 0.13 mm, a 1/20,000 mass difference can be perfectly separated even in the case of $\delta_K = 10$ eV (fig. 5(c)).

3. Conclusion

The main part of the ion optics of the JHP-ISOL for radioisotope beams has been designed. In table 2 the present status of high resolution ISOL facilities are summarized[10] in comparison with the present design. The central part of this system consists of two pairs of analyzing magnets of $\rho_B = 2.5$ m, $\phi_B = 60°$ and four electrostatic sectors for energy focusing. When the energy spread of an ion source is small, the present result of calculation satisfies our demand of a high resolving power of 20,000 at near 100 % transmission, but if the energy spread become large, e.g. 10 eV, the mass resolving power is 20,000 at 60 % transmission and only 13,000 at 100 % transmission.

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Figure Captions

Fig. 1. Required mass resolving power for separating neighboring isobars for A ~ 60 and 120.

Fig. 2. Layout of the JHP-ISOL including the beam guidance system.

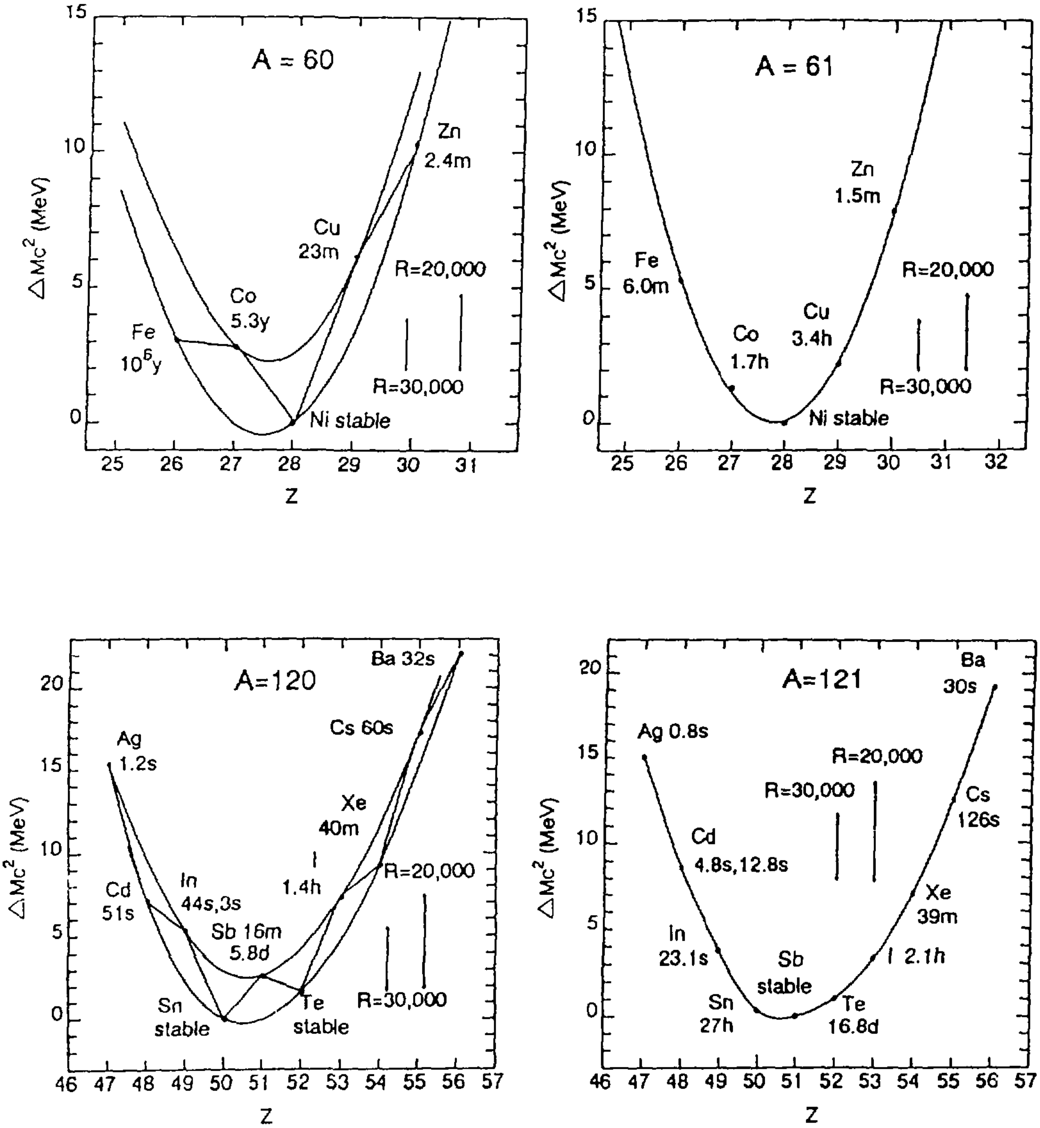
Fig. 3. Layout of the beam guidance system. The scale in the transversal direction is exaggerated.

Fig. 4. Layout of the main magnetic stage with the energy-focusing stage and the by-pass line. The scale in the transversal direction is exaggerated. S_7 and S_8 are the focus points of MS and ES stages, respectively. (MS : magnetic sector, ES : electrostatic sector)

Fig. 5. Beam profiles in horizontal (x) direction at the focus point of the magnetic stage (S_7) and the electrostatic stage (S_8). The three different cases of energy spread are shown, $\delta_K = 0$, 1 and 10 eV. The initial condition is a parallelogram of ± 0.2 mm × ± 20 mrad for each direction.

Table 1. Parameters of JHP-ISOL

Mass range		$M \leq 300$ amu
Acceleration voltage		100 kV
Mass dispersion	D_{M}	10 m
Assumption of beam emittance		16 mm mrad
($x_0 = y_0 = \pm$ 0.2 mm)		
($a_0 = b_0 = \pm$ 20 mrad)		
Mass resolving power (1st order)	R_{M}	25,000
Magnetic sector		
deflection radius	ρ_{B}	2.5 m
deflection angle	Φ_{B}	60 °
half air gap	G_0	5 cm
Electric sector		
deflection radius	ρ_{E}	1.8 m
deflection angle	Φ_{E}	90 °
half electrode gap	G_0	7 cm


A = 60
ΔMc² (MeV)
Z
Fe 10⁶y
Co 5.3y
Cu 23m
Zn 2.4m
Ni stable
R=20,000
R=30,000
A = 61
Fe 6.0m
Co 1.7h
Cu 3.4h
Zn 1.5m
Ni stable
R=20,000
R=30,000
A=120
Ag 1.2s
Cd 51s
In 44s,3s
Sn stable
Sb 16m 5.8d
Te stable
I 1.4h
Xe 40m
Cs 60s
Ba 32s
R=20,000
R=30,000
A=121
Ag 0.8s
Cd 4.8s,12.8s
In 23.1s
Sn 27h
Sb stable
Te 16.8d
I 2.1h
Xe 39m
Cs 126s
Ba 30s
R=20,000
R=30,000
0
5
10
15
20
25
26
27
28
29
30
31
32
46
47
48
49
50
51
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55
56
57

Fig. 1

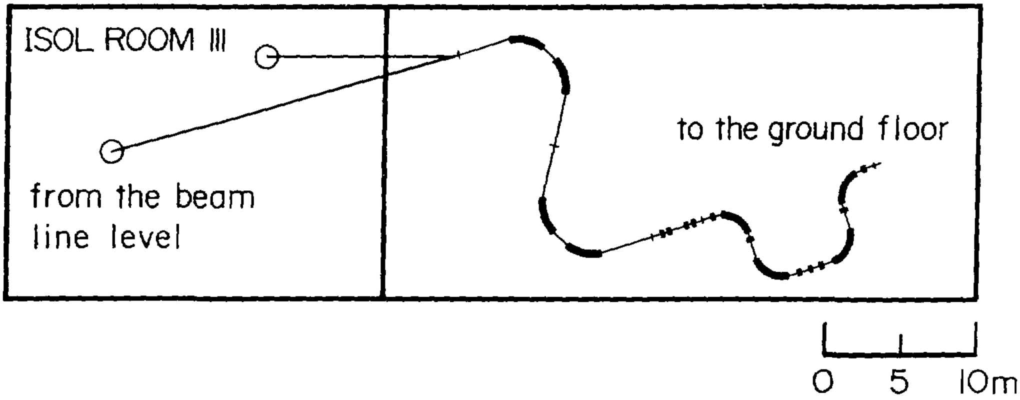

ISOL ROOM III
from the beam
line level
to the ground floor
0
5
10m

Fig. 2

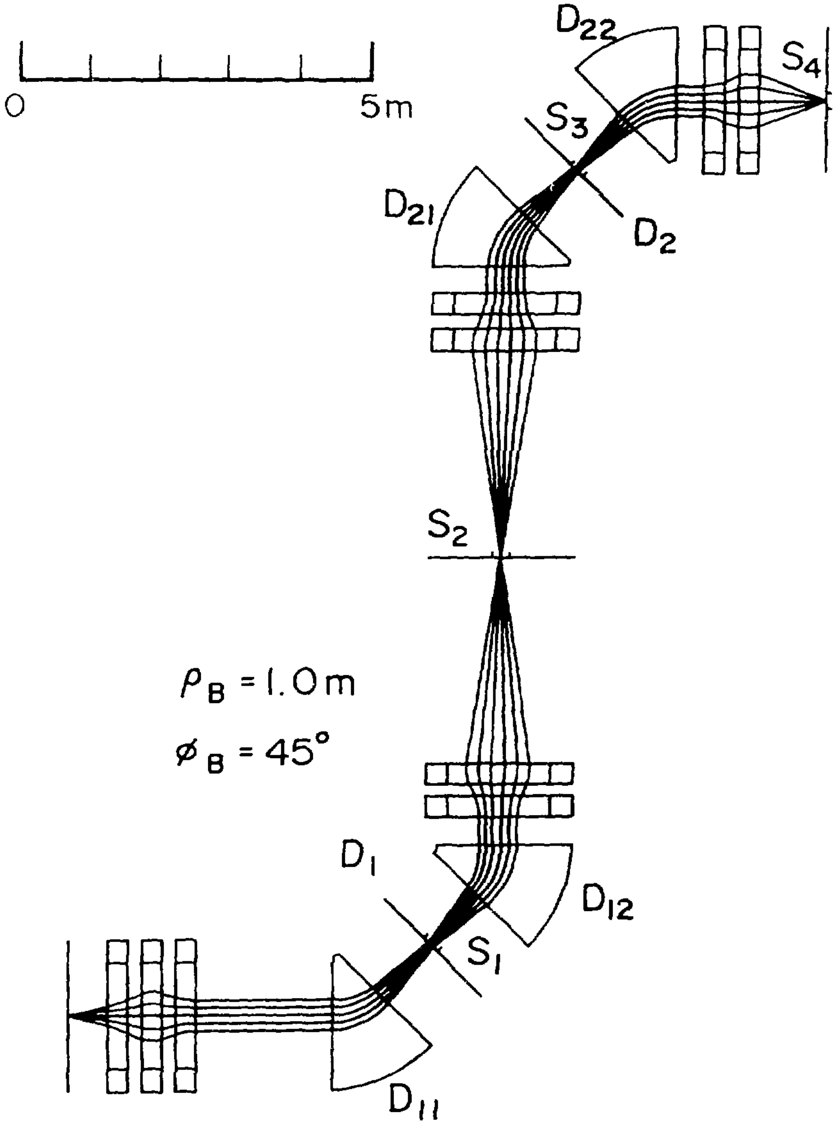


Fig. 3

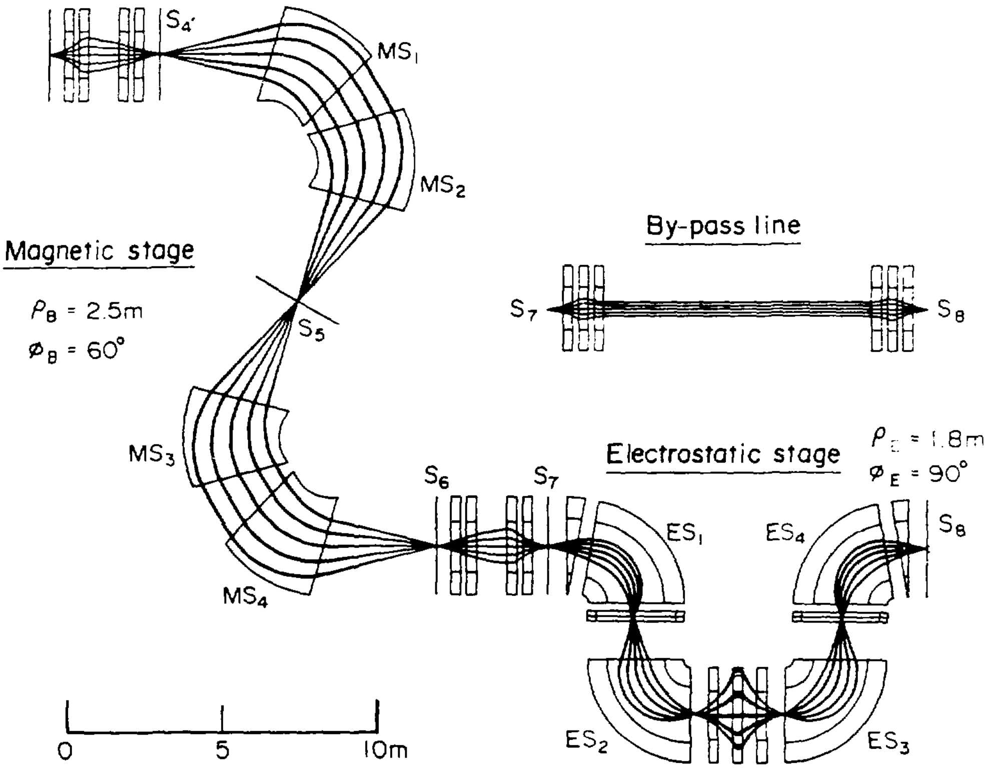
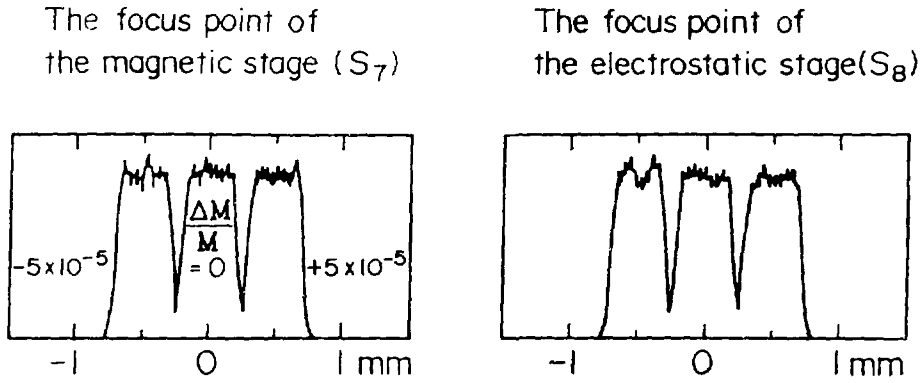
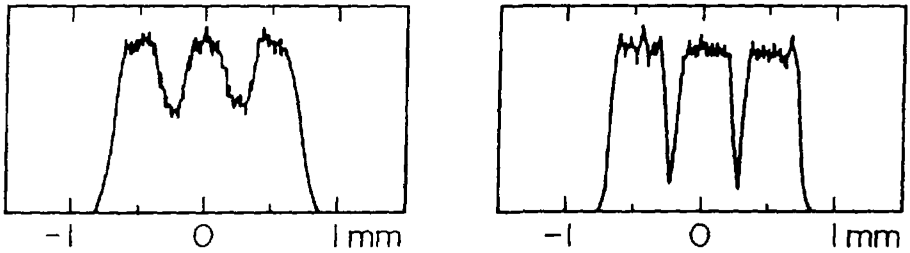

$S_{4'}$
MS_1
MS_2
Magnetic stage
$\rho_B = 2.5m$
$\phi_B = 60°$
S_5
MS_3
MS_4
By-pass line
S_7
S_8
Electrostatic stage
$\rho_E = 1.8m$
$\phi_E = 90°$
S_6
S_7
ES_1
ES_4
S_8
ES_2
ES_3
0
5
10m

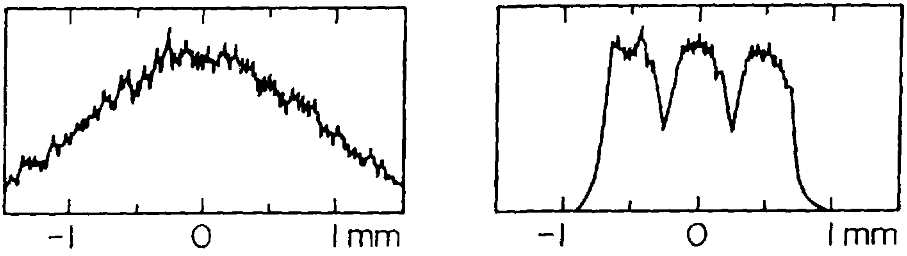
Fig. 4



(a) $\delta_K = 0eV$



(b) $\delta_K = 1 eV$



(c) $\delta_K = 10 eV$

Fig. 5