Ion-Optical Design of a Pilot Separator for the JHP-ISOL

I. 19. Ion-Optical Design of a Pilot Separator for the JHP-ISOL

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In the so-called E-Arena[1] (Exotic Nuclei Arena) of JHP (Japanese Hadron Project) radioactive nuclides produced by irradiation of a refractory target with an intense beam of 1 GeV protons will be ionized, accelerated to several tens of keV and mass-separated in an ISOLDE-type ISOL[2,3] (Isotope Separator On-Line). The mass-separated beam is then accelerated up to 6.5 MeV/u in a heavy-ion linac for subsequent use in various researches related with exotic nuclei.[1]

This ISOL, the JHP-ISOL, is expected to realize a mass-resolving power of 20000 at a good transmission for ordinary ion sources for mass number $A \leq 60$, thus enabling to separate the neighboring isobars, or even isomers of the same nuclide for nuclei far from stability; the detailed ion-optical design is described elsewhere.[2,3] It has been proposed, however, to construct a part of the JHP-ISOL as a pilot instrument for obtaining sufficient experiences of ion-source development and radiation protection as well as for testing the acceleration of mass-separated beams in a heavy-ion linac[1] up to 100 keV/u. This pilot separator should be used also in researches of short-lived nuclei using the beams of the SF (Sector-Focusing) Cyclotron of K = 75 MeV of INS (Institute for Nuclear Study). Also the main parts of this separator will finally be moved and utilized in the JHP-ISOL.

The main parts of the JHP-ISOL will be four dipole magnets of 45-degree deflection having $\rho = 2.5$ m and an optional set of electrostatic analysers to realize energy focussing. These ion-optical elements require a large space apart from the preceding beam-guidance system.[2,3] On the other hand the pilot separator should be located in one of the existing experimental rooms of the SF Cyclotron. Therefore, only one half the magnetic part of the JHP-ISOL will be taken for the pilot separator, i.e., two 45-degree dipole magnets of $\rho = 2.5$ m in an arrangement to add dispersion.

Initially the "C-arrangement" of the two analyzer magnets was proposed with a bending magnet of 68.5-degree and $\rho = 0.6$ m before the analyzers and another bending magnet of 41.5-degree and $\rho = 0.6$ m after the mass-discriminating slit. This arrangement,

however, was discarded, because for realizing a high resolving power very stringent requirements must be fulfilled for the 68.5-degree magnet having a small ρ corresponding to a strong magnetic field. Therefore, we proceeded to adopt the other arrangement, i.e., the "S-arrangement" which does not need such a preceding bending magnet. It is noted that the final bending magnet is easy to construct since it is after the mass discrimination; see Fig. 1.

The design aim of the pilot separator is a performance just one half of the JHP-ISOL, i.e., a mass-resolving power of R = 10000 at a transmission of T ≑ 100 % for ordinary ion sources having an effective slit width of 0.2 mm and an angular divergence of 20 mm mrad in both directions.

We introduced many quadrupole elements, i.e., one quadrupole triplet and four quadrupole doublets. One of the reasons for this is the limit of space of the existing experimental room to house the main parts of the separator. The role of the quadrupole triplet in the initial stage is to obtain a freedom to match the acceptance of the separator to the ion-source condition, i.e., the phase-space condition of the ions extracted from the ion source. Two multipole (i.e., hexapole plus octupole) magnets were introduced to cancel the most important image aberrations of the second and third orders besides the surface coils in the analyser magnets corresponding to N_2 (second order) and N_3 (third order) coefficients. All the ion-optical elements in the present design are magnetic considering ease of maintenance.

The present ion-optical calculations were made by using the GIOS program[4,5], which considers the ion orbit up to the third order in the x- (horizontal) and y- (vertical) directions; the aberrations in the y-direction, however, are expected to be correct only up to the second order since the treatment of the fringing-field effects is not sufficient for the y-direction. In the first place the first-order design was made. As shown in Fig. 2 we have three focal points F_1 (S_1), F_2 (S_2) and F_3 for the x-direction, the mass-discriminating focus being F_2; at the intermediate focus F_1 a rough mass separation can be made and the last focus F_3 is for injection into the heavy-ions linac. Besides we made a requirement that the beam be parallel at the centers of the analysing magnets (Fig. 2). For the y-direction, on the other hand, we imposed focussing at the centers of the analyser magnets besides the final focus (F_3) and parallelism at S_2.

The first-order ion-optical properties at F_2 are given in eq. (1) as well as the remaining higher-order terms after correcting or reducing by adjusting the multipole magnets and surface coils the most important aberrations corresponding to (x,aa), (x,yb), (x,bb), (x,xaa), (x,aaa), (x,ayb) and (x,abb);

$$x(S_2) = 0.3254\ x_0 = 1.444\ g - 12.01\ a_0 g + 5961\ a_0 y_0 y_0$$
$$+ 15.2\ a_0 y_0 b_0 - 1.663\ a_0 b_0 b_0 + \ldots\ldots, \qquad (1)$$

where x_0 and y_0 are the ion position in the x- and y-directions, respectively, and a_0 and b_0 are the angle of the ion velocity in the x- and y-directions, respectively, at the exit of the ion source, and g is the fractional mass deviation $g = (m - m_0)/m_0$. The length and the angle are measured in meter and radian, respectively. From eq. (1), since magnification is (x,x) $= M_x = 0.3254$ and dispersion $(x,g) = D_M = 1.449$ m, we get the first-order mass-resolving power R_M for an ion-source exit slit width of $w_0 = 2x_0 = 0.2$ mm.

$$R_M = D_M/(M_x \cdot w_0) = 1.449 \text{ m}/0.0651 \text{ mm} = 2.23 \cdot 10^4. \tag{2}$$

From the higher-order aberrations in eq. (1) we can roughly estimate the allowable limit of $a_0 = b_0$ for $y_0 = 0.2$ mm; from the term $-1.663 \, a_0 b_0 b_0$, which is taken to contribute one half of 0.0651 mm, we have

$$(a_0)_{max} = (b_0)_{max} \doteqdot [6.51 \cdot 10^{-4}/(2 \cdot 2 \cdot 1.663)]^{1/3} = 21 \text{ mrad}. \tag{3}$$

This value is somewhat too large and a practical limit is around 10 mrad as shown in the following.

The GIOS program[5] can simulate the beam profile by the Monte Carlo method, i.e., by letting started a number of ions from the initial conditions randomly filling the phase spaces in x- and y-directions. Fig. 3 shows the beam profiles for 2000 particles starting from the ion source and arriving at S_2. The initial phase spaces are a parallelogram of ± 0.1 mm $\times \pm 10$ mrad and ± 0.2 mm $\times \pm 10$ mrad for x- and y-directions, respectively, which simulates ordinary conditions of an ion source of plasma or FEBIAD types; all the particles reached S_2. The three peaks in the x-direction correspond to mass deviations of $g = 0$ and $\pm 1 \cdot 10^{-4}$. They are seen to be resolved completely, the basal width of the central peak being 0.129 mm corresponding to

$$(R_M)_{base} = 1.449 \text{ m}/0.129 \text{ mm} = 1.12 \cdot 10^4. \tag{4}$$

Therefore, a mass-resolving power of 10000 is expected for transmission of $T \doteqdot 100$ % together with a good enhancement factor.[3]

References

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2) Fujioka M. et al., Proc. Internat. Symp. Heavy Ion Phys. and Nucl. Astrophys. Probl., eds. Kubono S., Ishihara M. and Nomura T. (World Sci. Publ. Co., Singapore, 1989) p.311.

3) Wollnik H. et al., ibid. p.603.

4) Wollnik H. et al., Nucl. Instr. Methods A258 (1987) 408.

5) Wollnik H. et al., "Manual for GIOS" (II. Physikalisches Institut Univ. Giessen).
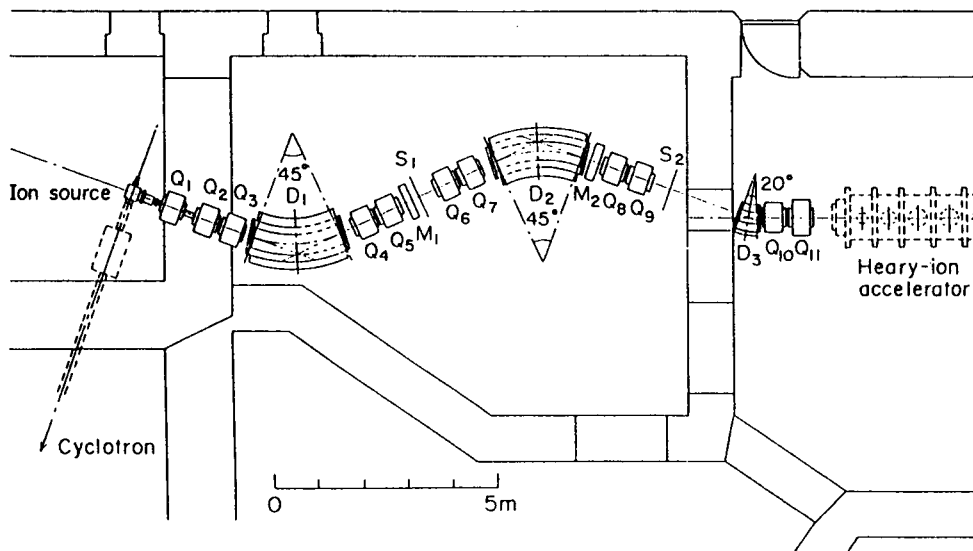
Fig. 1. Arrangement of the pilot separator in the existing experimental rooms associated with the Sector-Focussing Cyclotron of INS.
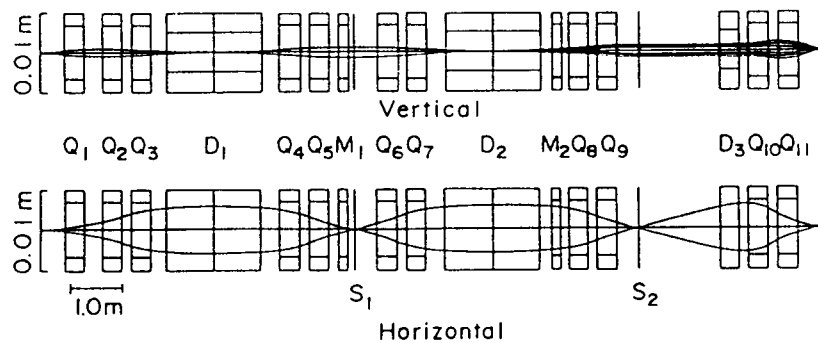

Fig. 2. Beam profiles in horizontal (x) and vertical (y) directions of the ion optics of the pilot separator.
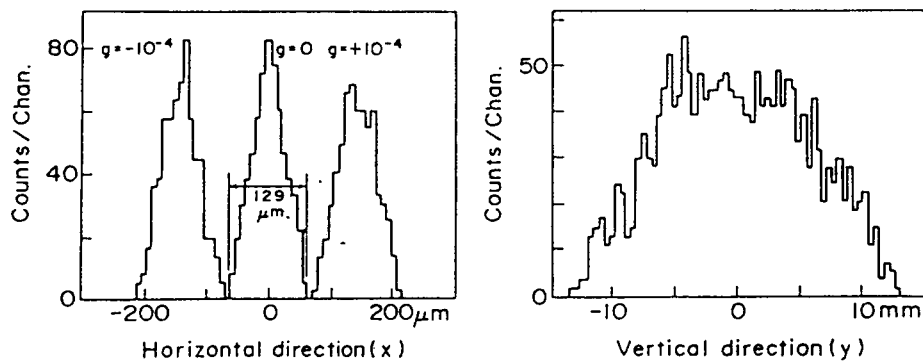

Fig. 3. Beam profiles in horizontal (x) and vertical (y) directions at the mass-separating slit S_2 calculated by starting 2000 particles from the ion source; see the text for the initial condition.