A Basic Design Principle of the Magnetic Part of the High-Resolution Mass Separator of the Japanese Hadron Project

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I.15. A Basic Design Principle of the Magnetic Part of the High-Resolution Mass Separator of the Japanese Hadron Project

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The facility of accelerated RI(Radio-Isotope) beams is now eagerly planned at several laboratories of the world, and in Japan we have an Exotic-Nuclei Arena in the Japanese Hadron Project (JHP), in which a high-resolution mass separator of R_m(basal)= $2{\bullet}10^4$ is being planned.[1,2]

In this report a basic design principle is described of the high-resolution magnetic part of the JHP-ISOL, the isotope separator on-line for further acceleration of mass-separated RI beams with a heavy-ion linac. A convenient expression is given for a first-order transfer matrix of a "symmetrically-split mirror-pair configuration of symmetric focusing " together with some numerical result for double focusing.

The main part of the separator was originally designed to consist of two homogeneous dipole magnets of ρ = 2.5 m and ϕ= 90 ° ; from a manufacturing consideration each of the magnet "was split" into two mirror magnets of 45 ° deflection, separated by a free space of length d, which we call "a pair of mirror magnets, or simply mirror pair" in the following; it is symmetric with respect to the mid line. Two identical mirror pairs are connected in the fashion of adding dispersion, i.e., in an S-shape. Owing to the housing consideration ϕ has recently been changed to 120 °.

The individual magnet has the same entrance and exit cut angles ε , so that the whole system is highly symmetric, which is advantageous in avoiding certain types of higher-order aberrations. In the following we take advantage of these symmetries in calculating the required first-order matrix elements. The horizontal (x), and vertical (y) matrices of the first part corresponding from the source until the mid line of the mirror pair, are generally written as (the length is normalized by ρ)

$$h\left(\frac{\phi}{2}\right) = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad v\left(\frac{\phi}{2}\right) = \begin{bmatrix} j & k & l \\ m & n & o \\ p & q & r \end{bmatrix} = \begin{bmatrix} j & k & l \\ m & n & o \\ 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

respectively, where for convenience v is written in 3-dimension. The whole matrices of the mirror pair $\boldsymbol{H}$ (ϕ) and $\boldsymbol{V}$ (ϕ) are defined similarly. As shown in the appendix they can be expressed using the T2 operation in the following way (similarly for V):

$$H = (T_2 h^{-1})h \quad \text{with} \quad T_2 h^{-1} \equiv \begin{bmatrix} a & -b & c \\ -d & e & -f \\ g & -h & i \end{bmatrix} \equiv \Lambda^{-1} h \, \Lambda \quad \text{and} \quad \Lambda \equiv \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(2)

indicating that T2 is actually a similarity transformation.

Using the explicit matrix elements of $\boldsymbol{h}$ and $\boldsymbol{v}$ in the sharp cut-off approximation[3)], the condition of parallelism of the beams at the mid line for the sake of double focusing (d is irrelevant here and can be assumed to be 0) becomes

$$e \equiv \frac{\cos\left(\frac{\phi}{2} - \varepsilon\right)}{\cos\varepsilon} - l\,\frac{\sin\left(\frac{\phi}{2} - 2\,\varepsilon\right)}{\cos^2\varepsilon} = 0$$

and

$$n \equiv 1 - \frac{\phi}{2}\tan\varepsilon + l\left(\frac{\phi}{2}\tan^2\varepsilon - 2\tan\varepsilon\right) = 0 ,$$

(3)

which we solved for ε and l as a function of ϕ . In eq.(3) l is the length from the source to the entrance of the first magnet, which is equal to that from the exit from the second magnet to the double-focusing point of the mirror pair. Now we can utilize eq.(2) for calculating the dispersion of the whole mirror pair;

$$D_p \equiv 2D_m = C \ (\equiv H_{13}) = 2bf = 2\left\{ \sin\frac{\phi}{2} + \frac{\cos\left(\frac{\phi}{2} - \varepsilon\right)}{\cos\varepsilon} \right\}\left\{ \sin\frac{\phi}{2} + \left(1 - \cos\frac{\phi}{2}\right)\tan\varepsilon \right\}. \tag{4}$$

The result is given in Table 1 in comparison with the case of a symmetric single, i.e. unsplit, magnet. We can see that for our case of mirror pair of $\phi = 120°$, $\varepsilon = 15.8$ ° is sufficiently small, whereas for the corresponding single magnet $\varepsilon = 40.9$ ° is too large, which may induce large higher-order aberrations; this is another reason of our choice of mirror pair. The total mass dispersion $2D_m$ is 9.83 m a bit smaller than that of a single magnet of 10 m.

The present choice of the configuration of a pair of mirror magnets for $\phi = 120$ ° is a starting point for optimization under progress using the GIOS program[4)] by taking into account fringing fields and higher-order optical elements.

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Appendix: Proof of eq.(2).

The transfer matrices of the second part, i.e., from the mid line to the focal point are distinguished by an apostrophe. The both parts of the mirror pair are considered to be composed of i ($\rightarrow$ ∞) infinitesimal optical elements denoted by $\Delta_j^{(\sigma j)}$, where σ_ι indicates any of free space, dipole or quadrupole components. Then, considering the infinitesimal correspondence between the first and the second parts, we have

$$H \equiv \boldsymbol{h'h}$$

$$= \left\{ (\Delta_i^{(\sigma_i)})^{-1} (\Delta_{i-1}^{(\sigma_{i-1})})^{-1} \ldots (\Delta_2^{(\sigma_2)})^{-1} (\Delta_1^{(\sigma_1)})^{-1} \right\}^{-1} \mathrm{X}\, (\Delta_i^{(\sigma_i)})(\Delta_{i-1}^{(\sigma_{i-1})}) \ldots (\Delta_2^{(\sigma_2)})(\Delta_1^{(\sigma_1)}), \qquad (5)$$

to which we apply

$$(\Delta_j(\sigma_j))^{-1} = \mathrm{T}_2\ \Delta_j(\sigma_j) \quad ,$$

valid for any infinitesimal element, and the fact that T_2 is a similarity transformation; finally we generally obtain, $h' = \mathrm{T}_2\, h^{-1}$ and $v' = \mathrm{T}_2 v^{-1}$.

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Table 1. Parameters of a symmetric double-focusing system of a pair of mirror magnets in comparison with a single magnet [a)]

A pair of mirror magnets				A single magnet			
ϕ (°)	ε (°)	l (ρ)	$2D_m$ (ρ)	ϕ (°)	ε (°)	l (ρ)	$2D_m$ (ρ)
60	7.6244	3.5996	3.9966	60	16.1021	3.4641	4.0000
70	8.9447	3.0163	3.9936	70	19.2953	2.8563	4.0000
80	10.2854	2.5690	3.9887	80	22.7605	2.3835	4.0000
90	11.6471	2.2120	3.9812	90	26.5651	2.0000	4.0000
100	13.0291	1.9181	3.9702	100	30.7897	1.6782	4.0000
110	14.4285	1.6696	3.9545	110	35.5296	1.4004	4.0000
120	15.8399	1.4548	3.9325	120	40.8934	1.1547	4.0000
130	17.2543	1.2656	3.9027	130	46.9969	0.9326	4.0000
140	18.6578	1.0960	3.8627	140	53.9476	0.7279	4.0000
150	20.0305	0.9417	3.8104	150	61.8132	0.5359	4.0000

[a)] All the magnets are themselves symmetric with respect to their mid line.