Beam Matching Section in the INS Heavy Ion Linac Complex

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Abstract

The beam transport system between a 25.5-MHz split-coaxial RFQ and a 51-MHz interdigital-H linac has been designed. This transport system is composed of a charge stripper, a 25.5-MHz rebunching cavity and two quadrupole doublets. A 170-keV/u beam passes through the stripper and its charge state is increased up to a charge-to-mass ratio greater than 1/10. The rebuncher causes an aberration of the longitudinal beam profile due to its non-linear accelerating field. In order to contain the distorted beam profile by the aberration in the acceptance of the IH, the rebunching cavity must be operated at 25.5 MHz. We have carried out a beam trace by taking account of the aberration and the effects of the increase of the charge state, the energy-loss, the straggling and the scattering in the stripper, and compared its results with the design assuming a linear system.

I. INTRODUCTION

Exotic nuclei arena (E-arena) project, the acceleration of the unstable nuclei beams from an isotope separator on-line (ISOL), is proposed in the Japanese Hadron Project (JHP). A prototype E-arena project at Institute for Nuclear Study is proceeding since 1992. We are constructing two linacs: a 25.5-MHz split coaxial RFQ (SCRFQ) and a 51-MHz interdigital-H (IH) linac. The former accelerates unstable nuclei up to 170 keV/u, and the latter up to 1 MeV/u at maximum. The minimum charge-to-mass ratio (q/A) is 1/30 at the SCRFQ and 1/10 at the IH linac; hence, a charge stripper is necessary. For the charge stripping and the beam matching between the linacs, we have designed a beam transport system, as shown in Fig. 1. The design procedure is reported in this paper.

II. ACCEPTANCE OF THE IH LINAC

The acceptances of the IH linac is shown in Fig. 2. We designed the transport system so that the beam profiles match to the solid ellipses in the figure. The parameters of these

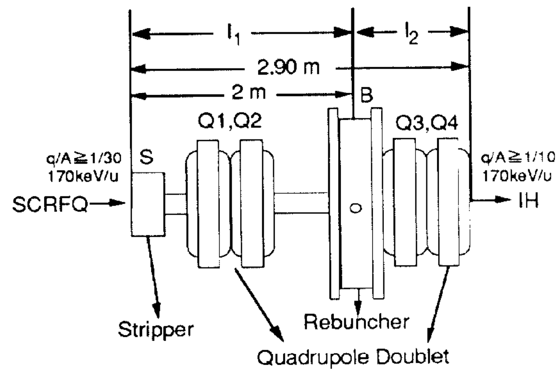

Figure 1. The schematic view of the transport system

ellipses are listed in Table 1, where the emittance parameters of the beam at the exit of the SCRFQ are also listed. The acceptances of the IH linac is larger these ellipses, as indicated by the dots and open circles in the figure. The normalized area of the solid ellipses in the x-x' and y-y' space are about 2.4 π mm•mrad. The normalized emittances from the SCRFQ are 0.6 π mm•mrad. The solid ellipse area in the $\Delta\phi$-ΔT space is

Table 1

(a) Ellipse parameters in x-x' and y-y' space

	x-x'		y-y'		x-x',y-y'
	β (m)	α	β (m)	α	ε_{norm} (π mm•mrad)
RFQ_{out}	0.3858	-1.379	0.4238	1.431	0.6
IH_{in}	0.8	2.8	0.8	2.8	2.4

(b) Ellipse parameters in $\Delta\phi$-ΔT space

	$\Delta\phi$-ΔT (51MHz)		
	δφ (deg)	δT (keV/u)	ε (π keV/u•deg)
RFQ_{out}	30.0	2.5	75
IH_{in}	19.3	10.3	200

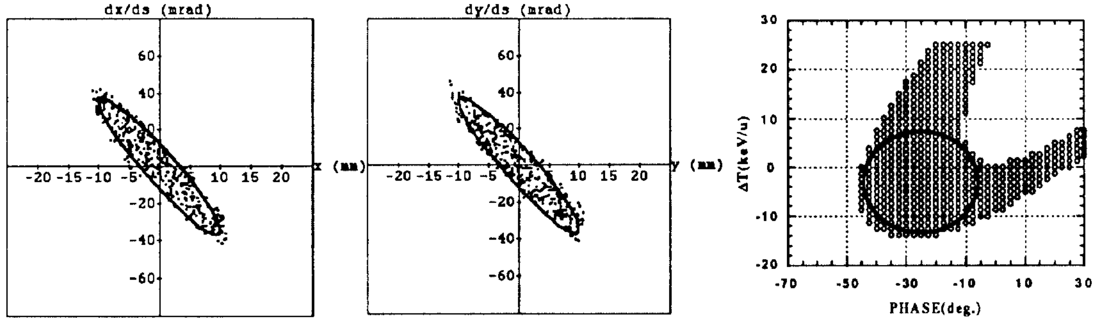

Figure 2. Emittance profiles at the input of the IH linac. The dots (x-x' and y-y' spaces) and open circles ($\Delta\phi$-ΔT space) indicate the acceptances of the IH linac. The solid lines are the ellipses to which the beam profiles are to be matched by the design. See the ellipse parameters in Table 1.

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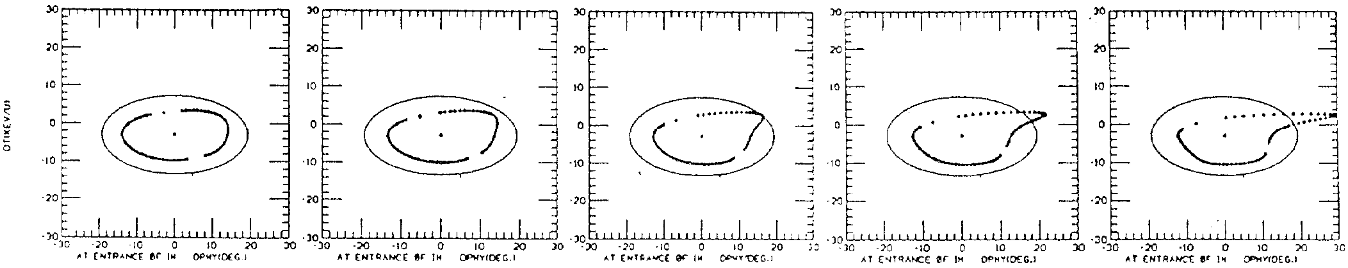


(a) (1.0 m, 0.6 m) (b) (1.5 m, 0.75 m) (c) (2.0 m, 0.9 m) (d) (2.5 m, 1.05 m) (e) (3.0 m, 1.2 m)

Figure 3. The beam profiles at the entrance the IH linac (a 10-μg/cm^2 stripper and a 25.5-MHz rebuncher). (l_1, l_2)

about 200 π keV/u·deg and the emittance from the SCRFQ is about 75 π keV/u·deg.

III. CHARGE STRIPPER

We designed this transport system by using $^{12}C^+$ ions as a beam from the SCRFQ, because they have larger energy-loss and -straggling per nucleon in the stripper than other ions with a q/A less than 1/10 [3]. The energy loss is about 6 keV/u and the straggling is about ±1 keV/u in rms when the 170-keV/u beam through a carbon foil with a thickness of 10 μg/cm^2. The charge states after the stripper are 1.7% (1+), 23% (2+), 57% (3+), 18% (4+) and 0.7% (5+) [4]. In order to make the energy loss and the straggling small, a thin stripper foil is preferable. However, for the handling safely and the achievement of the complete charge equilibrium state, a thick foil would be better. The thickness of 10 μg/cm^2 is enough to achieve the equilibrium charge state. The thickness of 5 μg/cm^2 may be enough. The two thickness are considered as the candidates.

IV. LONGITUDINAL MATCHING

When a single buncher is used for the beam matching in the longitudinal phase space, the optimized condition is determined by the following parameters: the emittance at the SCRFQ output (δφ,δT), the position and the thickness of the stripper foil, the position and the frequency of the rebuncher, and the acceptance of the IH linac (δφ,δT). The voltage and the phase of the buncher are uniquely determined as functions of these parameters when the longitudinal matching is satisfied between the SCRFQ and the IH linac. In these parameters, the position of the stripper foil is determined at 10 cm after the SCRFQ, because the transverse emittance-growth in the stripper foil is proportional to the beam size and the position where the beam size is relatively small is just behind the SCRFQ. Consequently the free parameters are the thickness of the stripper foil, the position and the frequency of the rebuncher.

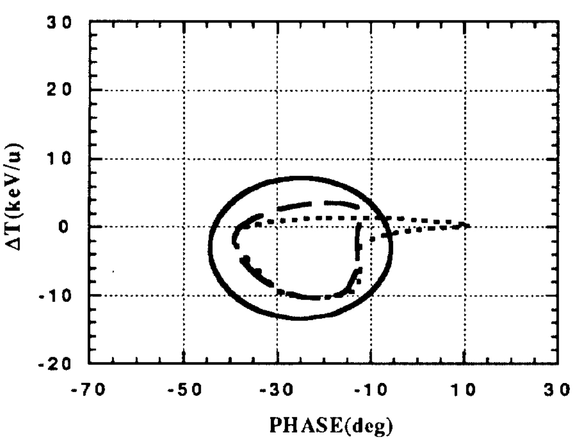
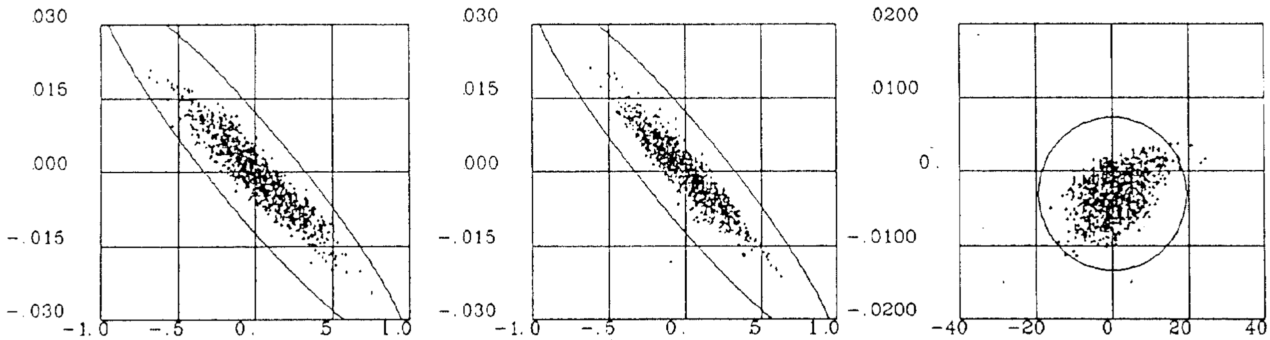


Figure 4. The dashed and dotted lines indicate the beam profiles obtained by the 25.5-MHz rebuncher and the 51 MHz one, respectively. These profiles are with l_2 of 0.9 m and the 10-μg/cm^2 stripper. The solid line is the acceptance of the IH linac.

As discussed in Sect. 3, the thickness of the stripper foil might be 5 or 10 μg/cm^2. The operating frequency of the rebuncher should be 25.5 or 51 MHz, the frequencies of the linacs. Since a linear accelerating filed would cause no distortion of the beam profile, the lower frequency is better. However, the higher frequency can easily keep the size of the cavity small. Finally we have four possibilities about the thickness of the stripper foil and the frequency of the rebuncher. In each case, the position of the rebuncher (the distance l_1 between the SCRFQ and the rebuncher) gives the longitudinal beam profile at the entrance of the IH linac and the distance l_2 between the rebuncher and the IH linac. As a result, we chose the combination of a 10-μg/cm^2 stripper and a 25.5-MHz rebuncher. Figure 3 shows the beam profiles obtained with this combination. When l_2 is longer than 0.9 m, the distortion of the beam profile is greater. The longest l_2 in which the beam profile can be contained completely in the acceptance of the IH linac is about 0.9 m. In this case l_1 is 2.0 m and the beam profile is in Fig. 3-(c). Figure 4 indicates the beam profiles obtained by means of the 25.5-MHz rebuncher and the 51-MHz one. The profile with the frequency of 25.5 MHz is better due to the smaller aberration. Though the beam profile with the 5-μg/cm^2 stripper is better than 10 μg/cm^2, the rebuncher with the frequency of 25.5 MHz is still necessary. The result from the longitudinal design study is that the rebuncher with the frequency of 25.5 MHz is required and l_2 is less than about 0.9 m. As setting beam monitors and quadrupole magnets and etc., l_2 would better have a enough space and must be considered with the further studies of the transverse matching.



x (cm) - *x'* (rad) *y* (cm) - *y'* (rad) $\Delta\phi$ (deg) - ΔT (MeV/u)

Figure 5. The emittance profiles at the exit of this transport system. The dots are obtained by using TRACEP. V_{eff} and G_Qs are optimized for ions of $^{12}C^{3+}$ after the stripper. The solid ellipses are the goaled profiles at the IH linac entrance.

V. TRANSVERSE MATCHING

As mentioned in Sect. 2, the normalized beam acceptances of the IH linac are 2.4 π mm·mrad. The solid lines in Fig. 2 have the ellipse parameters of the β of 0.8 m and the α of 2.8. In order to match the beam profiles to these ellipses, the position and field gradient (G_Q) of the quadrupole magnets are determined by using the program MAGIC. The position, the voltage and the phase of the rebuncher are determined by the matching condition in the longitudinal phase space. As the result, the rebuncher has defocusing force expressed by the following matrix:

$$\begin{bmatrix} 1 & 0 \\ -\delta & 1 \end{bmatrix}, \quad \delta = \frac{\pi(q/A)V_{eff}}{m_u c^2 \beta^3 \gamma^3 \lambda} \sin\phi_s,$$

where V_{eff} = (gap voltage) × (transit time factor), m_u is the atomic mass unit, c is velocity of light, β is the relativistic velocity of the ions, γ is the Lorentz factor, λ is the free space wavelength, ϕ_s is the synchronous phase. Using the ellipse parameters at exit of the SCRFQ and the entrance of the IH linac, and the above matrix for the rebuncher, the position and G_Qs are determined. The result of these studies is that one quadrupole triplet is not enough to optimize the transverse matching. Two quadrupole doublets are necessary. Especially one set of doublet must be placed just before the IH linac, because the strongly focused beam must be inject to the IH linac in the both x and y plane. Consequently the spacing between the rebuncher and the IH linac must be greater than about 0.9 m for setting the doublets. Then l_2 is determined to be about 0.9 m.

VI. RESULTS AND SUMMARY

Using parameters determined in the above studies, we take a trace of $^{12}C^{+}$ ions with the program TRACEP. The parameters are optimized for ions with a charge state of 3+ after the stripper. Figure 5 indicates the emittance profiles at the exit of this transport system. The solid lines in Fig. 5 are the same ellipses as ones in Fig. 2. The profiles show a good matching to these ellipses. At the stripper, we take into account of the effects of the energy straggling and the scattering. As a result, the emittance-growth rate of the beam is about 1.6 in the horizontal plane and about 1.2 in the vertical one. In the longitudinal phase space the emittance-growth rate is about 1.4.

The non-linear accelerating field of the rebuncher causes an aberration in the longitudinal beam focusing. The rebuncher working at 25.5 MHz is required to reduce the distortion of the beam profile. Setting the rebuncher near the IH linac is also required ($l_2 \leq 0.9$ m). For the transverse matching of the beam, one quadrupole doublet must be placed just before the IH linac. A space longer than 0.9m is necessary to set a doublet between the rebuncher and the IH linac ($l_2 \geq 0.9$ m). Therefore, the distance between the rebuncher and the IH linac is determined to be 0.9 m and the total length of this transport system is 2.9 m. As the rebuncher with a frequency of 25.5 MHz, a spiral loaded cavity [5,6] is being developed to keep the size of the resonator small.

VII. ACKNOWLEDGMENT

The simulation works were executed by using the computer FACOM M-780 of INS computer room. We thank the staff at the computer room for their support.

VIII. REFERENCES

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