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Design of a post linac for an energy upgrade of a heavy-ion injector

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ABSTRACT

A post linac is being designed for an energy upgrade of a heavy-ion injector. This post linac is to be installed downstream of the formerly developed compact injector, consisting of an Electron-Cyclotron-Resonance Ion-Source (ECRIS), the Radio-Frequency-Quadrupole (RFQ) linac and the Alternating-Phase-Focused Interdigital H-mode Drift-Tube-Linac (APF IH-DTL). It is aimed to increase the output energy of a heavy-ion injector. Carbon ions are initially accelerated with the compact injector to 4 MeV/u, and further accelerated with the post linac up to 8 MeV/u. The three linacs have the same operating frequency of 200 MHz. For beam focusing of the post linac, the APF method is used. Iterative simulations of beam dynamics were performed to determine the optimum array of synchronous phases in each gap. The results of the simulations provided that the calculated efficiency of beam transmission through the post linac is as high as 98.4%. The total length of this APF post linac is estimated to be approximately 3 m. A design overview of the injector system including the post linac is presented.

1. Introduction

Cancer treatment using energetic carbon ions has been conducted at the National Institute of Radiological Sciences (NIRS) since June, 1994. Due to successful clinical results for more than 10 years, R&D work was performed to facilitate the design study of a compact accelerator complex for wide-spread use of heavy-ion therapy [1,2]. Based on the R&D work as well as the design study, a pilot facility, dedicated for heavy-ion therapy, was constructed at Gunma University [3]. A similar facility was further constructed at Saga prefecture, and is under construction at the Kanagawa Cancer Center in Japan.

In designing the compact complex, major specifications were determined through the experience of clinical treatments at NIRS, while optimizing the size and cost of the entire accelerator system. The maximum accelerating energy of carbon beams was designed to be 400 MeV/u so as to obtain a residual range of more than 25 cm in soft tissue; this range would cover all cases, even for deeply settled tumors. The required beam intensity would be a few times 10^9 pps to achieve an irradiation dose-rate of 5 GyE/min/l. To provide such beams, several types of heavy-ion accelerators, such as a synchrotron, cyclotron and FFAG, exist. Concerning the required beam intensity and the construction costs, a synchrotron would be the best choice for our purpose. The circumference of a heavy-ion synchrotron for the compact complex was designed to be approximately 63 m. The synchrotron is operated in conjunction with a heavy-ion injector, consisting of a permanent-magnet ECRIS and two linear accelerators, which are an RFQ linac and an APF IH-DTL having the same operating frequency of 200 MHz [4,5]. This injector can accelerate carbon ions having $q/m = 1/3$ up to 4 MeV/u.

Although the size of these compact facilities is reduced by roughly 1/3 of the HIMAC complex, there would still be needs to reduce the accelerator size as well as the total construction costs. To further design compact accelerators, superconducting technology needs to be employed for the magnets of a synchrotron ring and for beam-transport lines. By using superconducting magnets, which can provide a dipole field of about $B = 3$ T, the radius of a superconducting synchrotron should be reduced by half; the circumference of a superconducting synchrotron would become to be approximately 32 m. However, the maximum number of circulating carbon ions may decrease as the size of the synchrotron ring is reduced, due to the space–charge limit. To overcome this problem, we designed a post linac to increase the injection energy of a synchrotron, and thus to compensate for any effect of the space charge by doubling the output energy of the injector; the output energy of the post linac has to be more than 8 MeV/u, while the keeping emittances and energy spread of the output beam. In this paper, a design overview of the post linac is presented.

2. Design

A schematic drawing of the proposed injector system is presented in Fig. 1. The injector system consists of a permanent-magnet ECRIS and three linacs, which are an RFQ linac, an APF

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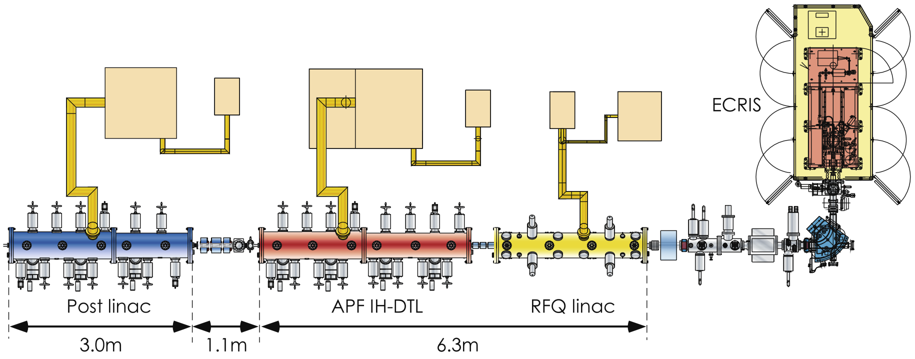

Fig. 1. Layout of the linac system, consisting of the ECRIS and three linear accelerators, which are the RFQ linac, the APF IH-DTL and the post linac.

IH-DTL and a post linac. The ECIRS and the first two linacs were formerly developed as described in Refs. [4,5], and can accelerate carbon ions of $^{12}C^{4+}$ to 4 MeV/u. At the exit of the APF IH-DTL, a matching section and a post linac are to be installed to further accelerate carbon ions up to 8 MeV/u. In the following sections, a design overview of the matching section and the post linac is presented.

2.1. Matching section

A matching section consists of a carbon-foil-stripper (CFS) and a magnetic quadrupole triplet, and is located between the APF IH-DTL and the post linac. Carbon ions of $^{12}C^{4+}$, as extracted from the APF IH-DTL, initially traverse a carbon foil having a thickness of 50 $\mu g/cm^2$ in the CFS, and two electrons of $^{12}C^{4+}$ are stripped by the foil. The stripping efficiency of two electrons from $^{12}C^{4+}$ at an energy of 4 MeV/u is estimated to be more than 90% [6]. Then, the phase–space distributions of fully-stripped carbon-ions are matched with the quadrupole triplet to obtain a good efficiency of beam transmission through the post linac. The effective lengths of the three quadrupole magnets are designed to be 100 mm, 150 mm, and 100 mm; each drift space between the magnets is 50 mm. The total length of the matching section is designed to be 1100 mm.

The calculated six-dimensional phase–space distributions of the extracted beam from the APF IH-DTL are given in the upper row of Fig. 2 [4]. With the phase–space distributions, the twiss parameters of the transverse coordinates were determined, and were used as an input condition of following matching calculations. On the other hand, the output condition of the twiss parameters is designed to be $\beta_x = \beta_y = 2$ m and $\alpha_x = \alpha_y = 0$ by considering the beam dynamics of the post linac. Under these conditions, calculations on transverse matching were made, and we obtained the horizontal and vertical beta as functions of the distance in the matching section, as shown in Fig. 3. Considering that the maximum beta is less than 7 m and that the calculated 2σ emittance is approximately 0.9π mm mrad, the maximum beam size is estimated to be within $\pm\sqrt{7 \cdot 0.9} \simeq \pm 2.5$ mm. The matching calculations yielded field gradients of the quadrupole triplet to be 25.2, 31.9 and 27.2 (m^{-2}), corresponding to 14.6, 18.4 and 15.7 (T/m) for carbon ions of $^{12}C^{6+}$ having 4 MeV/u, respectively. With the calculated phase–space distributions at the exit of the APF IH-DTL and obtained field gradients, a tracking simulation was made to calculate the phase–space distributions at the exit of the matching section. The results are shown by the middle row in Fig. 2. We can see from the figure that the transverse phase–space is as expected, and further that the phase spread, as caused in the matching section, is tolerably small.

2.2. Post linac

The post linac is to be installed downstream of the matching section, as shown in Fig. 1. After passing through the matching section, carbon ions of $^{12}C^{6+}$ having $E/A = 4$ MeV/u are injected to the post linac, and further accelerated up to 8 MeV/u. Since the post linac would accelerate fully-stripped carbon, it is anticipated to obtain a high acceleration efficiency. For an accelerating cavity of the post linac, we assumed to employ an IH structure having an operating frequency of 200 MHz, which is the same as that of the RFQ linac and the APF IH-DTL.

For beam focusing of the post linac, the APF method is again employed. The APF method utilizes the focusing and defocusing strengths, as provided by the rf acceleration field by choosing the positive and negative synchronous phases alternatively at each gap [7]. Since the focusing as well as acceleration of beam ions is accomplished just with the rf acceleration field for the APF linacs, no focusing element has to be installed in a cavity. Although the APF method has attractive features, it had rarely been practically employed for existing linacs in operation, because (1) the beam dynamics of APF linacs depends strongly on an array of alternating synchronous phases at each gap, (2) no straightforward method to optimize a synchronous phase array exists, (3) the beam motion is very sensitive to errors in the gap voltages, and (4) the electric-field distribution in an accelerating cavity could not be precisely calculated with the existing two-dimensional electromagnetic-field solvers, since the electric-field distribution would be determined by the total structure of an accelerating cavity, including drift tubes. However, we succeeded to design and construct a practical APF linac for the first time [5], and further this linac design is employed for injectors of the compact accelerator facilities at Gunma University, Saga prefecture and Kanagawa Cancer Center, where the injectors in the first two facilities are currently used during a treatment operation.

In design of the post linac, we formulated a similar design strategy as used for the APF IH-DTL. To optimize the array of an alternating synchronous phase at each gap, we used the following function to describe an phase array:

$$\phi_S(n) = \phi_0 \exp(-a \cdot n) \sin\left[\frac{n - n_0}{b \exp(c \cdot n)}\right], \tag{1}$$

where n is the cell number and ϕ_0 is the initial phase amplitude. The first exponential describes the attenuation of the phase amplitude, and the alternating phase is expressed with the sinusoidal function. A change of the period is described with the exponential in the argument of the sinusoidal function.

To optimize the five free-parameters (ϕ_0, n_0, a, b, and c) in the function, beam-tracking simulations were performed. In simulations, a set of the free parameters was randomly generated, and