ALTERNATING-PHASE-FOCUSED LINAC FOR AN INJECTOR OF MEDICAL SYNCHROTRONS

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Abstract

A preliminary design of a compact heavy-ion injector for medical synchrotrons was presented. The compact injector consists of the Radio-Frequency-Quadrupole (RFQ) linac and Interdigital H-mode (IH) Drift-Tube-Linac (DTL). For the IH-DTL, Alternating-Phase-Focusing (APF) method will be applied. The electric field distribution of the IH cavity was calculated with a three-dimensional electromagnetic field solver and used for the simulations on the beam dynamics. By performing iterative calculations of the electric field and beam dynamics, the satisfactory emittance and acceptance were obtained. The compact injector will be constructed, and their beam test will be performed by the end of FY2005.

INTRODUCTION

Cancer therapy using high-energy carbon beams from Heavy Ion Medical Accelerator in Chiba (HIMAC) has been carried out at National Institute of Radiological Sciences (NIRS) since June 1994. Due to the successful clinical trials over ten years, number of projects to construct facilities of the heavy-ion cancer therapy was proposed over the world. The required specification of such medical accelerator is to accelerate carbon ions up to *E/A*=400 MeV to obtain a range of 25 cm in water. However these accelerators are large in its size, and therefore a compact accelerator is needed to establish standards for the heavy-ion cancer therapy. This requirement led us to develop the compact and cost-effective medical accelerator.

The medical accelerator such as HIMAC consists of an injector, synchrotron and beam transport line. Among these devises, the injector usually takes a large part of the facility. For the case of HIMAC, the injector comprises a RFQ linac of 100 MHz and Alvarez type DTL with the same frequency; the length and diameter of the cavities are 7m and 60cm for the RFQ, and 24m and 2m for the Alvarez DTL, respectively. The total length of the injector is more than 40m. Since the size of the injector would affect that of the facilities as well as the total construction cost, the development of a compact injector would play an important role in designing the medical accelerator.

For the compact injector, we propose the RFQ linac and DTL with the same operating frequency of 200 MHz. A cavity of the RFQ linac will have a conventional four-vane structure. For the DTL, the Interdigital H-mode (IH) structure with APF will be employed.

The APF method was proposed in early 50's. It uses the negative or positive synchronous phases alternatively at each gap. The negative (positive) synchronous phase provides axial (radial) focusing and radial (axial) defocusing. By analogy with the principle of strong focusing, both the axial and radial stability would be obtained just with the rf acceleration-field. Hence, no additional focusing element is necessary for the APF linac. This feature would make the construction and operation costs lower than those of conventional linacs, and therefore is attractive for an injector of medical accelerators.

Because of its attractive feature, number of studies has been made for the beam dynamics of the APF linacs[1-4]. Since the focusing of the beam relies only on the rf acceleration-field, the beam dynamics of the APF linac depends strongly on a choice of the alternating synchronous phases. Thus, a major task of those studies was devoted to optimize an array of the synchronous phase. Although number of studies has been made, there is no straightforward method to find the array of the alternating synchronous-phase. In this paper, a simple method to find an array of the synchronous phases and preliminary design of the medical injectors were presented.

LAYOUT OF COMPACT INJECTOR

As mentioned previously, the compact injector consists of the RFQ linac and IH-DTL. The schematic drawing of the injector is shown in Fig. 1. Carbon ions of $^{12}C^{4+}$ are generated with a compact ECR ion source and extracted with the applied voltage of 24kV, corresponding to the energy of 8 keV/u. The carbon ions having 8 keV/u are then bunched and accelerated up to 600 keV/u with the RFQ linac of 200 MHz. Due to the rather high operating-frequency and low injection energy, the length and diameter of the cavity will be approximately 2m and 35 cm, respectively.

The beam extracted from the RFQ linac traverses through a matching section, which composed of a quadrupole triplet. In the section, the emittance of the RFQ linac would be matched to the acceptance of the IH-DTL. The total length of the matching section is about 35cm.

After the matching section, the beam will be injected to the IH-DTL, which has the same operating frequency as that of the RFQ linac. To avoid possible voltage breakdowns, the maximum surface field along surfaces of

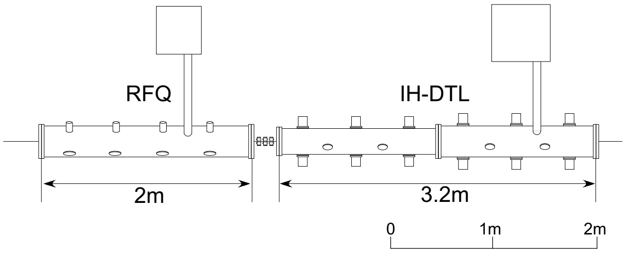

Fig. 1: A layout of the compact injector.

Table 1: A summary of the major parameters.

Parameter	RFQ	IH-DTL	Units
Injection energy	0.008	0.6	MeV/u
Extraction energy	0.6	4.0	MeV/u
Operating frequency	200	200	MHz
Cavity length	~2.0	~3.2	m
Cavity diameter	~35	~35	cm
q/m	1/3	1/3	-
Maximum surface field	23.6	23.6	MV/m
Kilpatric factor	1.6	1.6	-

the drift tubes is kept to be ~23.6 MV/m corresponding to 1.6 of the Kilpatric limit. The total length and diameter of the cavity will be 3.2m and 35cm, respectively. The basic parameters of the compact injector are summarized in Table 1.

PRACTICAL DESIGN

Beam dynamics

The calculated phase space distributions for the extracted beam from the RFQ linac were shown in Fig. 2. The normalized emittances for the X-X', Y-Y' and $\Delta\phi$–ΔW spaces are 0.408 π·mm·mrad, 0.431 π·mm·mrad and 1.27 π·ns·keV/u, respectively. These phase space distributions are used to calculate those in the IH-DTL.

In contrast to conventional linacs, entire characteristic of the beam dynamics for the IH-DTL depends strongly on an array of the synchronous phases, because of the APF method. Thus, a choice of the phase array plays a key role in designing the beam dynamics of the IH-DTL.

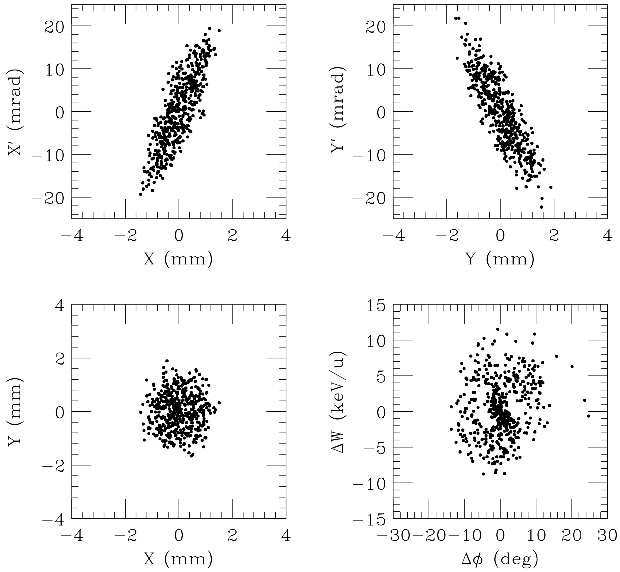

Fig. 2: The phase space and X-Y distributions for the extracted beam from the RFQ linac.

For the APF method, the focusing force depends on a period of the alternating phase. Since the focusing force needs to be increased as the beam accelerates, the period should be changed. However, a sudden change of the period during the acceleration would cause a mismatch which will induce the considerable emittance growth[2]. Thus the period needs to be changed adiabatically to keep the beam emittance low over entire drift tubes. To accomplish this, we employed the following function to describe the phase array:

$$\phi_s(n) = \phi_0 \exp(-a \cdot n) \sin\left(\frac{n - n_0}{b \cdot \exp(c \cdot n)}\right), \qquad (1)$$

where n is the cell number. The first exponential describes an attenuation of the phase amplitude, and the alternating phase is expressed with the sine function A change of the period is described with the exponential in the argument of the sine function. The function has the five free-parameters of ϕ_0, n_0, a, b, and c.

With a set of the parameter, a cell table can be generated. By using the calculated phase space distributions of the RFQ linac shown in Fig. 2, a simulation on beam dynamics for the IH-DTL was made, and the phase space distributions of the extracted beam were calculated. Then the parameters were varied, and numbers of these simulations were performed. A good set of the parameters

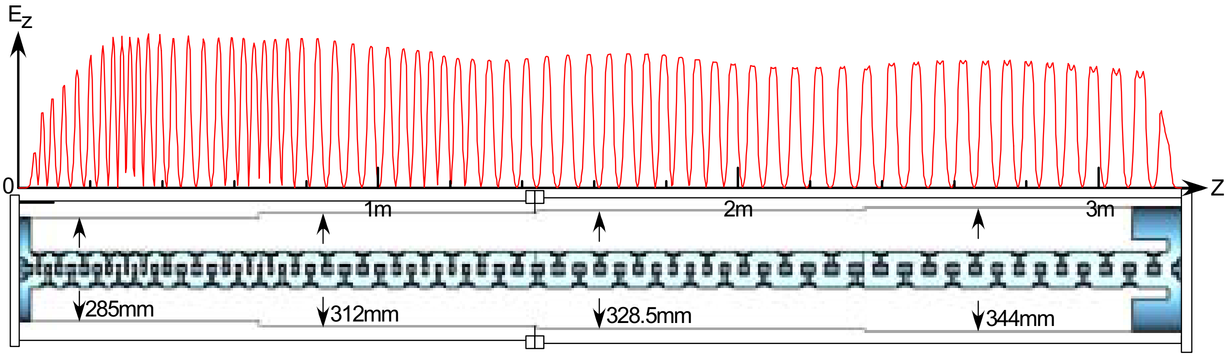

Fig. 3: A cross-sectional view of the IH-cavity and calculated electric field distribution along the beam axis.

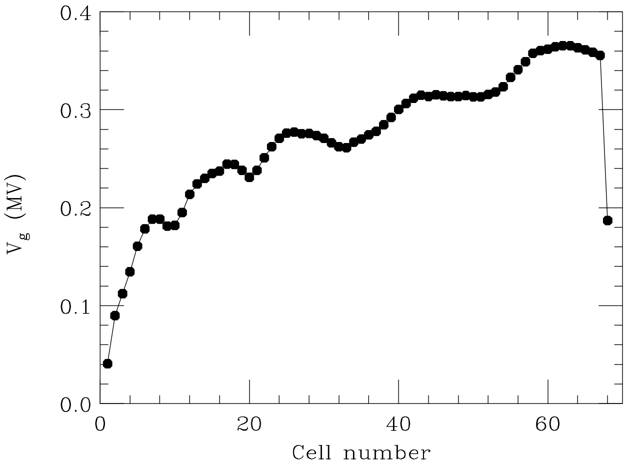

Fig. 4: The gap voltage distribution calculated with the MWS code.

was determined to obtain the large acceptances and small emittances.

Cavity design

Since the electromagnetic field distributions depend strongly on the total structure of the cavity for the IH structure, the field distributions were calculated with a three-dimensional field solver, MicroWave Studio (MWS). In the field calculations, a model of the cavity was generated using the cell table which was determined by the beam dynamics simulations.

The cavity was divided into two tanks, and each tank has the two different inner radiuses as shown in Fig. 3. These inner radiuses were adjusted to obtain the uniform field distributions through the entire cavity. In addition, the ridges around the last cell were cut to induce magnetic flux and adjust gap voltages for the last few gaps.

Iterative procedure

Once the parameters of eq. (1) were determined by the beam dynamics simulations, a tentative cell table was generated. With that cell table, the electric field distribution for the structure can be calculated using the MWS code. With the calculated field distribution, the parameter search of eq. (1) was made, and the cell table was modified. This iterative procedure has been performed to determine the final cell table. Consequently, the calculations were converged with the 2nd iterative procedure; the obtained electric field and gap voltage distributions are shown in Fig. 3 and Fig. 4, respectively, and the parameters in eq. (1) are a=0.00688, b=1.38, c=0.00483, ϕ_0=90°, and n_0=-13.0. The emittance growth of the transverse component is about 50% which is comparable to the recent report[4]. The calculated phase space distributions using the field distribution are shown in Fig. 5. The required RF power was estimated to be about 430 kW, which is significantly lower than that of conventional linac such as the Alvarez structure. Major parameters of the IH-DTL are summarized in Table 2.

Table 2: A summary of parameters for the IH-DTL.

Parameter	Value	Unit
Number of gaps	68	-
Tank length	3.20	m
Inner radius of drift tubes	7	mm
Outer radius of drift tubes	14-15	mm
Maximum gap voltage	365	kV
Transmission	98	%
Normalized X-X' emittance	0.600	π·mm·mrad
emittance growth	50.4	%
Normalized Y-Y' emittance	0.620	π·mm·mrad
emittance growth	45.9	%
Δϕ–ΔW emittance	1.31	π·ns·keV/u
emittance growth	6.89	%
Effective shunt impedance	107	MΩ/m
Total RF power (70% Q)	430	kW

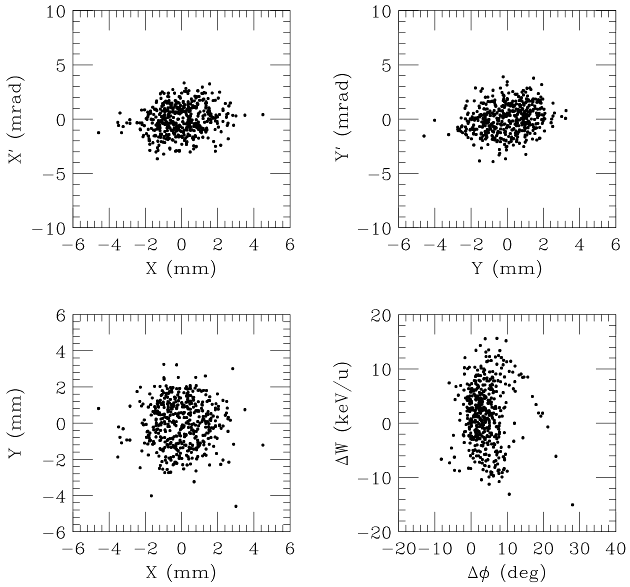

Fig. 5: The phase space and X-Y distribution for the extracted beam from the IH-DTL.

SUMMARY

The preliminary design of the compact injector for a medical accelerator was presented. The compact injector consists of the RFQ linac and IH-DTL. By performing iterative calculations between the beam dynamics and electric field using the MWS code, satisfactory acceptance and emittance were obtained. Constructions of the RFQ linac and model cavity of the IH-DTL are in progress. After the field measurements, the IH-DTL will be constructed, and beam test will finally be performed by the end of FY2005.

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