IH LINAC WITH HIGHER ORDER MODES

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Abstract

As one of the drift tube type of linacs (DTL), an Interdigital-H (IH) linac has been used for ion acceleration in low beta range. It can realize a resonant cavity of convenient size at low frequencies band and higher shunt impedance at low energy range. These characteristics are advantageous especially for heavy ion acceleration; therefore, this structure has been applied for heavy ion cancer therapy. Although the electric field is resonated by the TE_{111} mode, it does not have the axial component in the cylindrical cavity without drift tubes. The accelerating field is excited by using the drift tubes of Interdigital shape. To apply this structure to middle and high energy range, we propose a IH linac with the TE_{11n} mode of the higher order mode (HOM). The operating frequency becomes higher due to HOM, and this property is suitable to accelerate ion beam of middle and high energy. The design of the cavity structure and the possibility are presented.

INTRODUCTION

As one of the drift tube type of linacs (DTL), an Interdigital-H (IH) linac has been used for ion acceleration in low beta range. It can realize a resonant cavity of a convenient size at low frequencies and higher shunt impedance at low energy range ($\beta \leq 0.1$). These characteristics are advantageous especially for heavy ion acceleration; therefore, this accelerating structure was applied for heavy ion cancer therapy recently [1-2].

The beam focusing of the IH linac is usually carried out with quadruple magnets installed within drift tubes. However, we proposed the IH linac using Alternating Phase Focusing (APF) for moderate intensity beams and succeeded the beam acceleration [3]. The APF eliminated the focusing magnets from the drift tubes; therefore, it realized to release design restrictions of the drift tubes and decrease the incident energy.

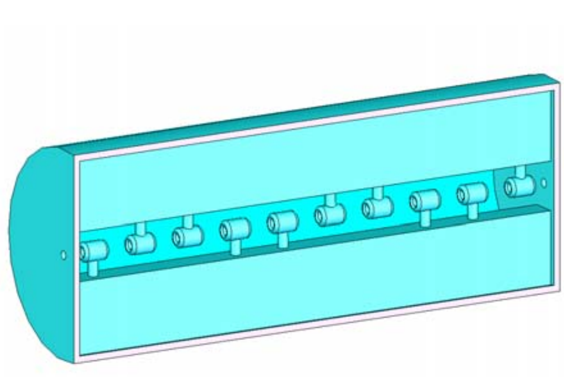

Figure 1: HOM-IH linac.

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Since the shunt impedance of the IH linac reduces according to the increasing of beam energy, the linacs operated by the TM_{010} mode such as an Alvarez type and a coupling cavity type are adopted for medium and high energy range. However, we propose the new IH linac using the TE_{11n} mode, the higher order mode IH (HOM-IH) linac. The configuration is shown in Figure 1. The resonance frequency becomes higher due to HOM, and this property is suitable to accelerate ion beam of those energies.

CONCEPT

RF modes in a resonant cavity

A microwave waveguide terminated at both ends by a short is worked as a cavity resonator and standing wave may exist in it. The electromagnetic field distribution is classed under two types: Transverse Magnetic (TM) mode and Transverse Electric (TE) mode. The resonance frequencies of a cylindrical resonant cavity are obtained from

$$TM_{mnl}\ \text{mode} \quad f = \frac{c}{2}\sqrt{\left(\frac{l}{d}\right)^2 + \left(\frac{j_{mn}}{\pi a}\right)^2} \qquad (1)$$

$$TE_{mnl}\ \text{mode} \quad f = \frac{c}{2}\sqrt{\left(\frac{l}{d}\right)^2 + \left(\frac{j_{mn}'}{\pi a}\right)^2} \qquad (2)$$

where c is light speed, d is cavity length and a is cavity radius. The subscript m (m = 0, 1, 2, ...) is the number of full-period variations in the azimuthal field components. The subscript n (n = 1, 2, 3, ...) is the number of zeros of the axial field components in the radial direction. The subscript p (0 = 0, 1, 2, ...) is the number of the half-period variations in the axial field components. The j_{mn} is the zeros of the Bessel functions. The j_{mn}' is the zeros of the derivatives of the Bessel functions. Since the IH linac and the HOM-IH linac have drift tubes in the resonant cavities, Eq. 2 is not applied directly for the resonance modes. However, it matches them qualitatively.

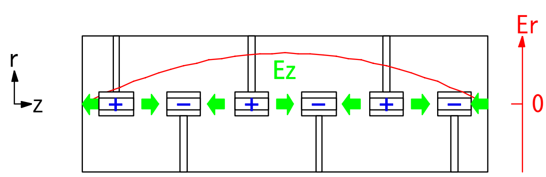
HOM-IH cavity

The IH cavity consists of drift tubes and ridge electrodes and it is operated by the TE_{111} mode. In the original TE mode, the electric field does not have the axial component in the normal cylindrical cavity. It is difficult to accelerate beams in this condition. However, the cavity is used for beam acceleration because the electric field is able to have the axial component by attaching drift tubes interdigitally. Figure 2 (a) shows the configuration and the accelerating field Ez without the ridges for simplification and the field distribution Er for the normal cylindrical cavity. Since the IH cavity is operated by the TE_{111} mode, it has the electric field distribution that the whole cavity becomes one. Although it has high shunt impedance in low energy range, it is replaced by linacs with the TM_{010} mode in middle and high energy range.

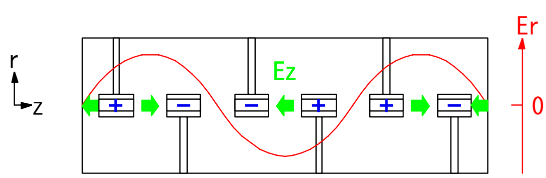
We propose the HOM-IH cavity for middle and high energy beam acceleration. It is resonated by the TE_{11n} mode. By using the higher order mode, based on Eq. (2), the resonance frequency is higher than that of the IH linac. This property is suitable for middle and high beta linacs, and a proton linac as well.

The electric field of the TE_{11n} mode repeats n half-cycles at regular intervals along the axial direction. If the TE_{11n} mode of n=3 is applied to the normal IH cavity, the accelerating field is excited only partially in the gaps, as shown in Figure 2 (b). Therefore, although the HOM-IH cavity has drift tubes and ridge electrodes similar to those of the IH cavity, the configurations of the stems of the drift tubes are different, as shown in Figure 2 (d). By fitting the dispositions of the drift tubes to the electric field distribution of the TE_{11n} mode appropriately, the accelerating fields in the HOM-IH cavity are flattened and it is suitable for beam acceleration.

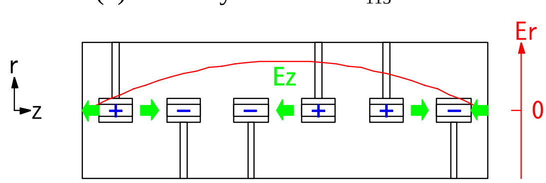
The cell length of an ion linac becomes long according to the acceleration energy and the increasing rate is large in the low energy range. In the IH cavity, the lengths of the drift tubes change greatly and the field distribution on the beam axis is not uniform. Therefore, an adjusting scheme such as the ridge electrode and the end ridge tuner is introduced to solve this problem. On the other hand, the HOM-IH cavity is for middle and high energy acceleration slowing down the growth of the cell length. In addition, if it does not have a serious influence on beam acceleration, some cells might be brought together by the same cell length for reasons of fabrication in high energy range. In this condition, the HOM-IH cavity is the most useful because it has the same cell length to use the electric field distribution of the TE_{11n} mode for beam acceleration. The beam focusing magnets can be separated from drift tubes to outside of the cavity for middle and high energy linacs; therefore, the HOM-IH cavity can have the drift tubes of a simple structure without the APF scheme.



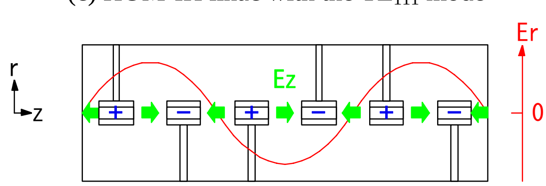
(a) IH cavity with the TE_{111} mode



(b) IH cavity with the TE_{113} mode



(c) HOM-IH linac with the TE_{111} mode



(d) HOM-IH linac with the TE_{113} mode

Figure 2: Configurations and accelerating fields of the IH cavity and the HOM-IH cavity. Er is the electric field distribution for the normal cylindrical cavity without drift tubes.

SIMULATION AND MEASUREMANT

The electric properties of the HOM-IH cavity were confirmed by electromagnetic simulation and cold model measurement. As an analytical model of the convenient size, the cavity of 300 mm in diameter and 800 mm in

Table 1 Main dimensions of the simulated HOM-IH linac.

Cavity inner radius (mm)	150
Cavity inner length (mm)	800
Cell length (mm)	80
Numbers of drift tubes	10
Drift tube radius (mm)	15
Beam bore radius (mm)	7
Width of ridge electrodes (mm)	40
Height of ridge electrodes (mm)	112.5
RF mode	TE_{115}

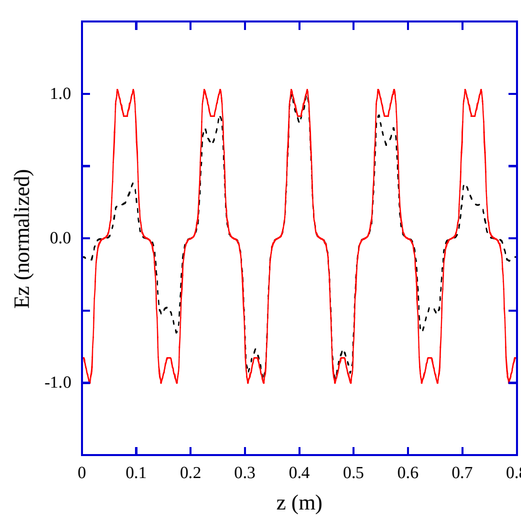


Figure 3: Accelerating field distributions of the HOM-cavity and the IH cavity. The solid line and the dotted line are the field distributions of the HOM-IH cavity and the IH cavity, respectively.

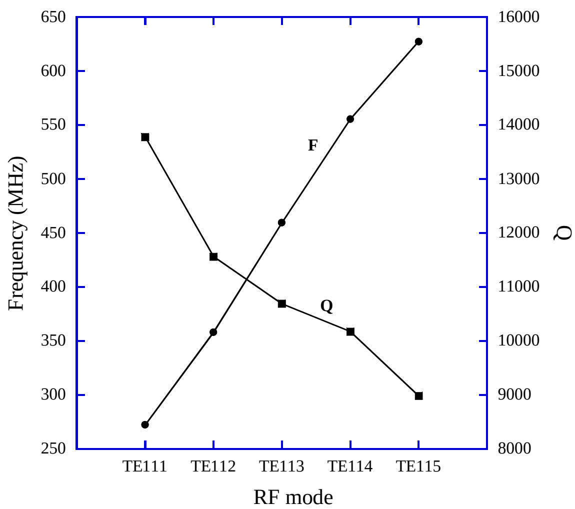


Figure 4: Resonance frequencies and Q-values for the RF modes.

length was designed, as shown in Figure 1. The main dimensions are shown in Table 1. It has 10 drift tubes set on two ridge electrodes and they have the same cell length and dimensions in the intermediate cell except at both ends.

For the comparison, the IH cavity of the same dimensions was simulated, in which the arrangements of the stem electrodes of the drift tubes were changed. The models were designed with the 3D-CAD software SolidWorks [4] and the simulations were carried out with the MicrowaveStudio [5].

The simulated electric field distributions of the HOM-IH cavity and the IH cavity are shown in Figure 3. The solid line and the dotted line are the field distributions of the HOM-IH cavity and the IH cavity, respectively. The solid line has flat distribution compared that with the dotted line. As a result, it is confirmed that the field distribution of the HOM-IH linac has the predicted form. Figure 4 shows the dependences of the resonance frequencies and the Q-values for the RF modes. The resonance frequency increases according to the mode number, and that of the TE_{115} mode is 628.5 MHz. It is entirely separated from the neighbour modes. The Q-value can be improved by about 20 % by optimizing the stem radius. The cold model of the HOM-IH linac has the same dimensions as the analytical model and it was made of brass. The measured frequency of the TE_{115} mode was 627.8 MHz.

DISCUSSION

The electric properties of the HOM-IH linac were confirmed by the simulations and the cold model; therefore, we consider its possibility on middle and high energy linacs. Figure 5 shows the HOM-IH cavity designed for a high energy linac. The beam focusing magnets are to be a separation type. Coupling cavity linacs used in high energy regions have many cells formed by stacking copper plates and their configurations are complicated. On the other hand, since the HOM-IH linac is a single cavity type, the configuration is simple and the fabrication is easy. This saves the construction cost of the linac system, and it is advantageous as the possibility for the high energy linac.

However, the cavity diameter of the HOM-IH linac is decreased according to the increase of the resonance frequency. In addition, it is difficult to compress the beam size from the viewpoint of the beam dynamics extremely. Therefore, the volume of the drift tubes relatively grows compared with the cavity in high frequencies, and it brings the reduction of the shunt impedance. This is an important point that should be considered for practical use.

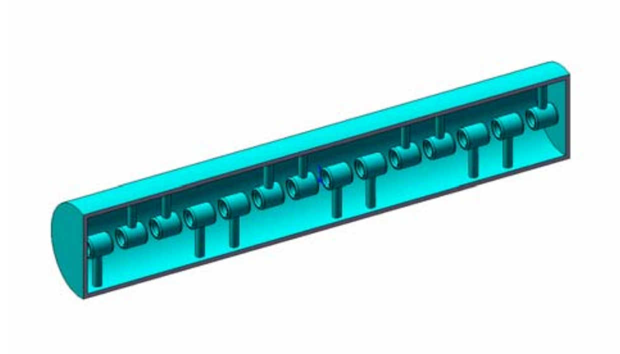


Figure 5: HOM-IH linac for high energy

SUMMARY

The HOM-IH linac is proposed as a new accelerating structure for middle and high energy. It is operated by the TE_{11n} mode and the resonance frequency is higher than that of the IH linac. This property is also suitable for a proton linac. Since periodic fields along the beam axis are excited in this mode, the flat electric field distribution is realized by arranging the drift tubes at regular intervals. The feasibility was confirmed by electromagnetic simulations and a cold model. However, there is still a problem in practical use, and we will continue to evaluate the possibility.

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