EFFECTS OF FIELD DISTORTIONS IN IH-APF LINAC

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Abstract

The project on developing compact medical accelerators for the tumor therapy using carbon ions has been started at the National Institute of Radiological Sciences (NIRS). Alternating-phase-focused (APF) linac using an interdigital H-mode (IH) cavity has been proposed for the injector linac. The IH-cavity is doubly ridged circular resonator loaded by the drift-tubes mounted on ridges with supporting stems. The effects of intrinsic and random field distortions in a practical design of the 4-MeV/u 200 MHz IH-APF linac are considered. The intrinsic field distortions in IH-cavity are caused by the asymmetry of the gap field due to presence of the drift-tube supporting stems and pair of ridges. The random field distortions are caused by drift-tube misalignments and non-regular deviations of the voltage distribution from programmed law. The RF fields in IH-cavity have been calculated using Microwave Studio (MWS) code. The effects of field distortions on beam dynamics have been simulated numerically.

INTRODUCTION

The progress of the radiation therapy in clinical cancer treatments with carbon ions at the Heavy Ion Medical Accelerator (HIMAC) facility [1] of NIRS encourages developments of a small-sized therapy system aiming to spread the carbon therapy for local hospitals in the whole country [2]. The project on developing compact and reliable medical accelerators using carbon ions has been started at NIRS from April 2004 [3]. The accelerator complex for this compact facility consists of two ECR ion sources, an 4 MeV/u injector linac cascade, a synchrotron ring with the maximum energy of 400 MeV/u and beam delivery system for three treatment rooms.

The linac cascade (Fig.1) consists of the 600 keV/u 4-vane RFQ-cavity and the 4 MeV/u drift-tube IH-cavity with APF. Both structures operate at the RF frequency of 200 MHz. Since beam intensities of ECR carbon ion sources are near their limits, it is important to preserve high beam transmission of the linac. Design and preliminary calculation results for this injection linac has been already presented in our reports [4-6].

The beam dynamics calculations have been performed for a practical design of the 4-MeV/u 3.2 m long IH-APF linac [7]. The simulations for the IH-APF structure with ideal fields having a pure axial symmetry and programmed voltage distributions have shown satisfactory results. However, a real IH-APF structure has several kinds of the field distortions, which can strongly affect on the beam quality. The practical design of the IH-APF linac has been explored with possible intrinsic and random field distortions. The effects of field distortions on beam dynamics have been simulated numerically. The basic results are presented in this report briefly. The details are published in the HIMAC report [8].

BEAM DYNAMICS WITH IDEAL FIELDS

The IH-structure is a kind of a π-mode multigap accelerating structure, where a time-alternating RF voltage is applied to a sequence of drift-tubes whose lengths tend to increase with increasing a particle velocity. It is usual to consider the multigap drift-tube linac as a sequence of unit cells. It is assumed, that the cell boundaries are located at the electrical centers of successive drift-tubes, where by symmetry the electric field has only a longitudinal component. Thus, the cell consists of a gap and two halves of adjoining drift-tubes.

The beam dynamics has been simulated with DYN1-code written by Kapin. The code computes the trajectories of the particles through the linac cell-by-cell, while the motion equations within every cell are solved by the numerical integration using the 4-th order Runge-Kutta method. The electrical fields within every cell have been derive in the electrostatic approach with the electrical field as a gradient of the potential, while potential in the accelerating is presented as Fourier-Bessel series.

The beam dynamics calculations have been performed for a practical design of the 4-MeV/u IH-APF linac [7], which accelerates the carbon ions 12C++ from the injection energy of 600 keV/u. The cell table is given in Ref. [8]. In this linac design, a gradient type of voltage distribution along the tank is used, while the gap voltage is approximately proportional to the relative velocity of the synchronous particle. The maximum electric field on the drift-tube surfaces is kept constant along the whole tank with the bravery factor for the Kilpatrick limit 1.6.

The beam dynamic calculations have been performed for the randomly distributed particles. The number of the particles in simulations is equal to \( N_{\text{particle}} = 1000 \). The phase-space ellipses of the injected beam correspond to...
the phase-spaces of the beams after the matching section located between RFQ and IH-APF. The longitudinal emittance of the injected particles corresponds to the divergent beam bounded within the RF phases [-62°, -17°] and within the relative velocities [3.57 %, 3.63 %]. In the transverse phase spaces, particles are uniformly distributed within the upright ellipses determined by formulae \( \varepsilon_x = \gamma_x \cdot x^2 + \beta_x \cdot x^2 \) with \( \gamma_x = 2.0 \text{ rad/m} \) and \( \beta_x = 0.5 \text{ m/rad} \).

The dependencies of the beam transmission \( T_{\text{beam}} \) for different values of \( \varepsilon_x \) have been calculated (see Fig. 5). The beam transmission is rapidly drop down when the value of \( \varepsilon_x \) increases. For this linac, the lower permissible transmission threshold is about 50 %. Since RFQ may lose up to 10 % of the injected particles, the beam transmission of the IH-APF tank must be higher than 60 %. Therefore, the threshold value of \( \varepsilon_x \) is about \( \varepsilon_x = 18.0 \text{ mm × mrad} \). Note, that this value corresponds to the phase-space area occupied by all particles after the matching section between RFQ and IH-APF [5].

The calculation results for a smaller value of \( \varepsilon_x = 8.0 \text{ mm × mrad} \) provide a more appropriate value of the beam transmission \( T_{\text{beam}} = 92 \% \). The longitudinal and transverse beam emittances at the exit of the IH-APF linac are shown in Figures 2 and 3, respectively. The transverse emittance of the output beam occupies area \( 22.2 \pi \text{ mm × mrad} \). The phase portrait of the beam in the longitudinal phase-space has a dense core with width of about 25 degrees and a long tail is smearing over about 50 degrees. The energy spread is about \( \Delta W/W \approx 0.7 \% \). It is still higher, than the requirements for the energy spread of output beam, which is \( \Delta W/W \leq 0.4 \% \).

The influence of the ridge cross-section on the performances of the IH-cavities has been examined with trapezoidal cross-section of the ridges at different angles \( \alpha_R \). Calculations have shown that the variations of the shunt impedance are almost negligible.

The effects of stem shapes have been studied with cylindrical, conical and triangular configurations. The shunt impedance and Q-factor are almost the same.

The intrinsic field distortions in the IH-cavity appear as dipole fields acting in the vertical direction. The dipole fields in the gaps are in-phase. Since drift-tube lengths are calculated for \( \pi \)-mode of the gap fields, the dipole fields act in opposite directions in neighbouring gaps and their sum effects are almost compensated. The beam dynamics simulations in the presence of the dipole fields have not shown any degradation of the beam transmission.

Thus, a simple configuration of cavity with cylindrical stems and rectangular ridges have been adopt.

FIELD DISTORTIONS IN IH-STRUCTURE

Let’s distinguish intrinsic and random field distortions. The former are inherent to the structure and exist even in a structure with an ideal drift-tube channel, and the latter are caused by the errors arising at the stage of the mechanical alignment and RF tuning of the structure.

The intrinsic field distortions in IH-cavity have been analyzed using computer simulations of RF fields with MWS code [9]. The IH-cavity (Fig. 4) is doubly ridged circular resonator loaded by the drift-tubes mounted on ridges with supporting stems. The intrinsic field distortions in IH-cavity are mainly caused by the asymmetry of the gap field due to presence of the drift-tube supporting stems and pair of ridges.

Figure 4: The schematic drawing of an IH-cavity

Many geometrical configurations of the ridges and stems are known and used [10,11]. It is believed, that the shapes of the ridges and stems affect on the RF performances of the structure and magnitudes of field distortions. Special configurations are aimed to eliminate dipole components of the accelerating field or to increase the shunt-impedance.

We have performed a quite comprehensive study of different configurations of the ridges and stems using MWS-code in order to estimate their influence quantitatively. The detailed data are published in Ref. [8].

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EFFECTS OF RANDOM ERRORS

The random field distortions are caused by drift-tube misalignments and non-regular deviations of the voltage distribution from a programmed law. It is a serious problem for APF linacs having relatively weak focusing forces and sensitive to any field perturbations [12, 13]. Although there are analytical methods for estimations of the random effects, a numerical simulation of beam dynamics provides more reliable results [13].

The effects of the random field distortions on beam dynamics have been simulated numerically with DYN1 code at an approach preserving the axially-symmetrical pattern of the gap field [13]. The number of random experiments is equal to \( n = 100 \). The dependence of the beam transmission \( T_{beam} \) on the emittance parameter \( \varepsilon_x \) has been explored at two different levels of random errors for voltage distribution and drift-tube positions (Fig. 5).

\[ \text{Figure 5: } T_{beam} \text{ versus the parameter } \varepsilon_x \text{ for “small” (a) and “large” tolerances (a).} \]

The mean value of \( T_{beam} \) provides the transmission drop of 3-5% with the standard deviation 5-6% at “small” tolerances and the transmission drop is 5-10% with the standard deviation 6-10% at “large” tolerances.

CONCLUSION

One may conclude, that the level of permissible errors for the drift-tube longitudinal and transversal displacements is about ±200 \( \mu \)m and ±100 \( \mu \)m, respectively. The fluctuations of the gap voltages should be minimized to the levels of about ±3%. At this level of tolerances the beam transmission is decreased within about 10% (standard-deviation value) comparing to the beam transmission for the ideal structure.

These tolerance levels are achievable with a modern technology, e.g. HIMAC drift-tube Alvarez linac [1] has the same tolerance band for drift-tube positions. However, it requires time-consuming procedures for a careful mechanical assembling and RF tuning.

It may result in a difficult and expensive manufacturing technology, which is not appropriate for several batch-produced linacs. A possible way to relax the level of permissible errors is to shorten the IH-APF structure by increasing the transition energy between RFQ and IH-APF linacs. A modified linac layout is outlined and discussed in the Ref. [8]. It may require designing the RFQ structure with an increased energy gain [14].

REFERENCES


‡ PDF-file at site: http://weblib.cern.ch/share/hepdoc/.