DESIGN ON ACCELERATING TUBE OF HIGH POWER ELECTRON LINAC FOR IRRADIATION PROCESSING

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Abstract

There is an unstable phenomenon for high-power electron linacs for irradiation processing. One main cause of the instability of these types of linacs is the beam loss in the accelerating tube. In this paper, a constant gradient accelerating structure is chosen to accelerate the electron beam, and the designed phase velocity is gradually increased along the tube. By adjusting the size of the accelerating cavities and the phase velocity function, a high capture-efficiency is reached. After a series of simulations, we gained a 90% capture-efficiency, which minimizes the probability of the unstable phenomenon in a high power electron linac.

INTRODUCTION

Some of the high power linacs suffer from unstable difficulty at 20 kW operation and the practical beam power is sometimes limited to lower than 20 kW. Beam loss in the accelerating guide gives an additional lumped heat load to some part of the accelerator guide where the beam is lost. About 5~8 kW power was taken away by the lost beam which results in the intense and uneven heat load. It may deform the cavities of the accelerating guide to destruct a correct acceleration phase relationship and cause the beam instability. To address this issue, a low beam-loss electron linac of 10MeV, 20kW for irradiation processing has been designed at a frequency of 2856MHz. In this paper, we will present the design in details.

DESIGN OF RF STRUCTURE

The main design parameters for the CIAE 20kW traveling wave irradiation linac are listed in Table1.

Table 1: Design Parameters of CIAE Irradiation Linac

Energy	10MeV
Beam power	Higher than 20kW
Input Power	4MW
Operation frequency	2856MHz
Operation temperature	30±2°C
Electron gun anode voltage	60kV
Beam emittance	≤10πmm.mrad

Disk-loaded Wave-guide Design

Disk-loaded accelerating structure is chosen. Microwave parameters and electric field are calculated by the SUPERFISH[1] code. As the thickness of the disk t is not sensitive to the phase velocity, in our design t is first to be determined as 4 mm from viewpoint of a sufficient mechanical strength and avoiding electric breakdown. Then, cell length D can be expressed as[2]

$$D_i = \frac{\frac{\phi\lambda}{2\pi}\beta_{P,i-1}}{1-\frac{\phi\lambda}{4\pi}\frac{d\beta_P}{dz}}, \qquad (1)$$

where ϕ is the operation mode, β_p is the relative phase velocity v_p/c, $\lambda$is the operation wave length, and i is cell number.

The cell length D can be determined not only with the SUPERFISH code, but also by beam dynamics simulation with the PARMELA code[3] . The bore diameter 2a is decided by the requirement of the electric field in the accelerating tube. The tube inner diameter 2b is not an independent variable, but fixed when the other three parameters are given.

After deciding he cell size and the average accelerating gradient, we can do the beam dynamics simulation with PARMELA.

BEAM DYNAMICS

Low Beam-loss Linac Design

Electron linac for irradiation processing needs to be designed as compact as possible. So a single accelerating tube is chosen for both bunching and acceleration of the beam, without a separate pre-buncher or buncher. In some designs, electric field and phase velocity gradually change in the bunching segment. A relatively high capture efficiency can be achieved by adequate resonance of electrons in the bunching segment, say about 50% for most situation [4]. And in some other designs, people often adopt a structure with two or three uniform sections to reduce the machining workload, or to simplify the microwave measurement. In this kind of design, the phase velocity keeps same in each section, and changes from section to section in a staircase form. Due to the abrupt shift of the phase velocity between two sections, electrons may be easily lost at these positions, and the beam loss is rather high, say about 70%.

In order to get a lower beam loss, we choose a bunching segment in which the designed phase velocity is linearly changed along the tube. The phase velocity of the i-th cell is approximately changed according to the formula $\beta_{P,i} = \beta_{P,i-1} + \frac{d\beta_P}{dz}\big|_{i-1} \cdot D_i$. By properly choosing the phase velocity of the first cell and the slope $\frac{d\beta_P}{dz}$, one can determine the size of the accelerating cavity D_i. We hope the velocity of the electrons can keep synchronous with phase velocity when the beam enters the accelerating tube and the beam is compressed into a narrow phase acceptance after bunching process. The phase of the reference electron gradually changes from 90°to 0°, and then the electron gets continuous accelerating by riding on the wave crest in the main accelerating segment. For this purpose, the choice of the slop is very critical. For a given input power, if the slop $\frac{d\beta_P}{dz}$ is too high for electrons to catch up with the phase velocity, the electrons will get a phase slip in one direction according to the equation $\frac{d\varphi}{dz} = \frac{2\pi}{\lambda}\left(\frac{1}{\beta_P} - \frac{1}{\beta_e}\right)$. When slipping to the wave crest, the electrons have a velocity far smaller than the phase velocity, and consequently the electrons will keep on slipping which results in the losses of a better part of the electrons. This case was modeled as an example, shown in Fig.1 (a), which has a beam loss of 60%. If $\frac{d\beta_P}{dz}$ is too low, the velocity of the electrons will exceed the phase velocity soon, and then most of the electrons will get into the decelerating phase region and be eventually lost. Fig.1 (b) shows an example of this case, in which the beam loss is about 70%.

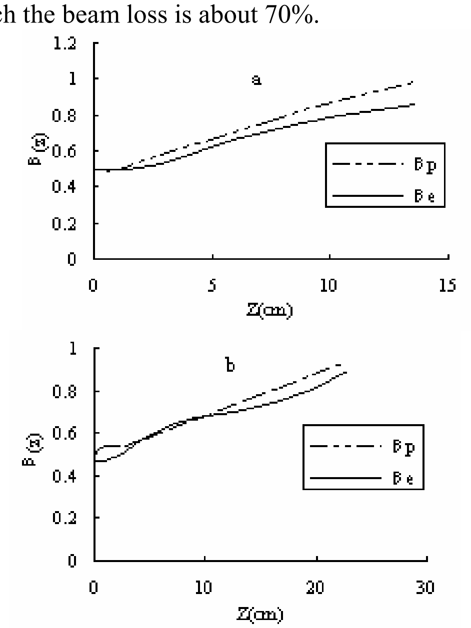

Figure 1: Two design schemes for phase velocity variation.

If $\frac{d\beta_P}{dz}$ is properly chosen, the phase of the reference electron slips from 90°to 0°with an oscillating process, namely slips toward the wave crest at first, and then, followed by a backward slip for a while, and finally moves to the wave crest rapidly. The longitudinal lost is minimized in such a case. Following such a scheme, as shown in Fig. 2, we designed the CIAE irradiation processing linac with a capture efficiency of above 90%. It can be observed from Fig.2 that the velocity of electrons is slightly lower than the phase velocity at the beginning. The velocity of electrons exceeds the phase velocity in the first two cells while the reference electron experiences a small oscillation, and then the velocity of electrons falls behind the phase velocity after the following five cells. Finally, most of the electrons slip to the wave crest and get the most effective acceleration.

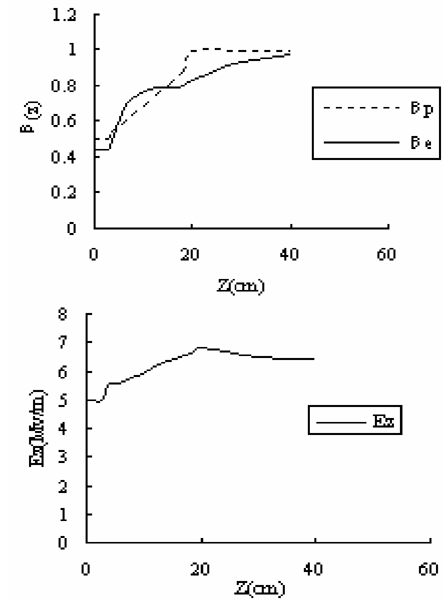

Figure 2: Phase velocity and field variation along z-axis.

Optimisation of the Main Accelerating Segment

When a high capture efficiency is reached, it usually comes with a length increase of the bunching segment and a decrease of the accelerating efficiency at the same time. For the low energy linac with a limited input power, we pursue, in fact, not only a high capture efficiency, but also a short length of the accelerating tube. It seems the bunching segment should not be too long for satisfying this requirement. This brings us a new problem. In the ordinary design, one can get a beam about 2MeV at the exit of the bunching segment with its velocity approximately the same as the velocity of light, and most of the electrons get together in a narrow phase acceptance round the wave crest. However, in our high-capture efficiency design, if we still let the synchronous phase close to the wave crest at the end of the bunching segment where the electron velocity is so low that a serious phase slip happens, then almost all of the electrons will lost in the main accelerating tube. A new design method is proposed. The phase of the reference electron is placed around 75°, and then approaches the wave crest rapidly in the first few cells of the main accelerating segment. Emerging from these cells, the electrons reach 2MeV energy while the phase of reference electron is about 3°or 4°. Here the phase slip becomes very slow, and most of the electrons can keep synchronous with the wave around the wave crest and get a continuous acceleration. However we still face another problem in the main accelerating segment. The phase slippage per cell with different energy is listed in table 2. For most of the time that electrons move in the accelerating segment, the beam energy is lower than 10MeV and thus the phase slippage per cell is larger than 0.15°. If we choose the phase velocity of the main accelerating segment equal to that of light, electrons will slip in one direction and the accumulated phase slippage after many cells is considerable. Taking account of this factor, we slightly adjusted the phase velocity of the accelerating segment, and finally we reached a design result with an increased accelerating efficiency and a decreased total length of the accelerating tube. The phase velocity in the main accelerating segment is 0.9986 instead of 1, corresponding to the cell length reduction from 3.499cm to 3.494cm. In this case, electrons oscillate only once around the synchronous phase with a tiny amplitude. The average beam energy at the end of the accelerator is 0.2MeV higher than the design with the phase velocity equal to 1 and the total length of the accelerating tube is also shorter than that.

Table2: The Phase Slippage per cell with Different Energy

Energy (MeV)	Phase slippage (degree)
2	2.20
3	1.10
4	0.70
5	0.50
6	0.35
7	0.30
8	0.25
9	0.20
10	0.15

After the optimization, we gain a 90% capture efficiency, as a result, the beam loading also increases if the beam current from the gun keeps the same. So we decreased the input beam current from 600mA to 300mA in order to control the beam loading effect. Another benefit is that we can obviously depress the request for the electron gun. The results of the beam parameters are listed in Table 3.

Table3.:The Beam Parameters in the Final Design

Input energy	60keV
Input pulse beam current	300mA
Output energy	10.2MeV
Output pulse beam current	271mA
Average beam power	24.7kW (repetition frequency 650pps, pulse width 14μs)
Spots diameter r(exit)	<10mm

SUMMARY

We designed and simulated an accelerating tube of a 10MeV S-band traveling wave linac by SUPERFISH and PARMELA. In this paper, the design process of the disk-loaded wave-guide accelerating structure is discussed and the method on how to reduce the beam loss is proposed. After a series of simulations and optimization of the RF parameters of accelerating cavity and beam dynamics, the result reaches a capture efficiency of above 90%, far more than 50% in the ordinary design. Although the energy spread and the beam emittance become larger, they are not important for the electron linac for irradiation processing. The beam spots diameter at the exit of the accelerating tube is about 9mm and the energy spread is 8.9%. The beam can completely satisfy the requirements for irradiation processing. To compensate the decrease of the accelerating efficiency, a new idea was proposed to reduce the cell length of the main accelerating segment from 3.499cm to 3.494cm, resulting in an increase of accelerating efficiency as well as a decrease of the total length of the accelerator. A model cavity will be manufactured according to the design for cold measurement in the near future.

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