第 30 卷 第 6 期 高 能 物 理 与 核 物 理 Vol. 30, No. 6
2006 年 6 月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Jun., 2006

Design Study on an Electron Linac for Irradiation Processing with a High Capture Efficiency

LIU Hua-Chang[1;1)] WANG Xiu-Long[1] FU Shi-Nian[2]

1 (China Institute of Atomic Energy, Beijing 102413, China)
2 (Institute of High Energy Physics, CAS, Beijing 100049, China)

Abstract The accelerating tube is the core of a linac. The capture efficiency is usually about 50% by ordinary design method in the electron linac for irradiation processing. Nearly half of the injected electrons are lost in the tube, resulting in strong radiation and additional heat load on the accelerating cavity, as well as a bad effect on vacuum. In this paper, a constant gradient accelerating structure is chosen to accelerate the electron beam, and the designed phase velocity is linearly increased along the tube. By adjusting the size of the accelerating cavity and the phase velocity function, a high capture efficiency is reached. After a series of simulations, we obtain a 90% capture efficiency, while the accelerator length is not increased due to the bunching process.

Key words electron linac for irradiation processing, disk-loaded wave-guide, capture efficiency

1 Introduction

At the present time, most of the electron linacs in application field all over the world are low energy linac, operating in S-band and mainly for the applications of medical treatment, industry, agriculture and radiate chemistry. Electron linac is suitable to achieve higher energy than other types of accelerators. In the electron irradiation processing field, energy less than 1MeV is called low energy, that from 1MeV to 5MeV is called middle energy, and that higher than 5MeV is called high energy. High energy electron beams are primarily produced by electron linac, which plays an active role and has a wide application in the irradiation processing. Design and manufacture of the accelerating structure is one of the key technologies of high energy electron linac for irradiation processing. High capture efficiency can reduce the request of the injected beam current from an electron gun, and depress the losses of the electrons in the accelerating tube. The electron linac for irradiation processing has no strict request for the low beam emittance and low energy spread, and actually, a big beam spot is needed at the exit of accelerating tube. Therefore one can pay attention to how to determine the phase and electric field variation function along the accelerating cells in order to reach a higher capture efficiency, as well as a higher accelerating efficiency. In this paper, we will present our design, aiming at this target for an irradiation processing linac, which is going to be built at the China Institute of Atomic Energy(CIAE).

2 Simulation and calculation

The main design parameters for the CIAE 20kW traveling wave irradiation linac are listed in Table 1.

Disk-loaded accelerating structure is chosen. Microwave parameters and electric field are calculated by the SUPERFISH[1] code. For a structure with $2\pi/3$ operation mode, only one and a half cell is needed to be calculated by properly specifying the

Received 23 November 2005, Revised 9 January 2006
1) E-mail: liuhc@ihep.ac.cn

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℃
electron gun anode voltage	60kV
beam emittance	⩽10πmm·mrad

boundary conditions in SUPERFISH simulation due to the symmetry of the electric field distribution along the longitudinal axis. There are four basic parameters in the disk-loaded wave-guide: thickness of the disk t, cell length D, inner diameter $2b$, and bore diameter $2a$. As the thickness of the disk t is not sensitive to the phase velocity, in our design t is first to be determined as 4mm from viewpoint of a sufficient mechanical strength and avoiding electric breakdown. Then, cell length D can be expressed as[2]

$$D_i = \frac{\dfrac{\phi\lambda}{2\pi}\beta_{\mathrm{P},i-1}}{1-\dfrac{\phi\lambda}{4\pi}\dfrac{\mathrm{d}\beta_\mathrm{P}}{\mathrm{d}z}} \ , \tag{1}$$

where ϕ is the operation mode, β_p is the relative phase velocity v_p/c, λ 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 known.

The average accelerating gradient is needed in the input file of PARMELA, so we should find the attenuation parameter α in advance. It can be calculated according to Eq. (2):

$$\alpha = \frac{P_\mathrm{L}}{2DP}, \tag{2}$$

where power dissipation P_L is given by the SUPERFISH. Since the cell length D is known, we only need to find the power flow P for α's calculation. The power flow density is $S=(E\times H)_\mathrm{z}=E_\mathrm{r}H_\theta$. SUPERFISH gives out the distributions of electric and magnetic fields of a standing wave. Because the electric and magnetic fields are always orthogonal for each other at a given point, the energy exchanges between electric and magnetic fields. We need to find the field distribution of a traveling wave for our linac design. The relationship of the amplitude between standing wave and traveling wave in the different position is listed in Table 2. Integrating the power flow density S in the bore radius area ($r\leqslant a$) gives out the power flow P by Methematica code. The average axis electric field is $E_0=\sqrt{R_\mathrm{s}\times 2\alpha P_0}$, where R_s is the shunt impedance, P_0 the input power.

Table 2. The relationship of the amplitude between standing wave and traveling wave in different positions[2].

	$Z=0$	$D/2$	D	$3D/2$
$E_{\mathrm{r,sw}}$	0	finity	finity	0
$E_{\mathrm{r,Tw}}$		$E_{\mathrm{r,sw}}/\sqrt{3}$	$E_{\mathrm{r,sw}}/\sqrt{3}$	
$H_{\theta,\mathrm{sw}}$	finity	finity	finity	finity
$H_{\theta,\mathrm{Tw}}$	$H_{\theta,\mathrm{sw}}/2$	$H_{\theta,\mathrm{sw}}$	$H_{\theta,\mathrm{sw}}$	$H_{\theta,\mathrm{sw}}/2$

note: $Z=0$ cell center, $Z=D/2$ disk center, sw-standing-wave, Tw-traveling-wave

After deciding of the cell size and the average accelerating gradient, we can do the beam dynamics simulation with PARMELA. The input file of PARMELA defines the transport system, input and output options. Every row identified by PARMELA contains a key word and a series of parameters. We must pay attention to the definition of E_0T, which represents the average axis electric field. There is no transit time factor T in the traveling wave accelerating structure. E_0T is only an expression of effective accelerating gradient. The simulation of the traveling wave accelerating process starts from the first TRWCELL center in PARMELA. It uses a half cell combined with a small drift tube, shown in Fig. 1,

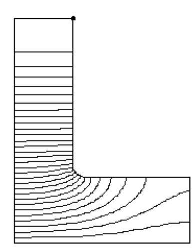

Fig. 1. A half cell combined with a drift tube.

to simulate the fringe field. According to the physics process, electrons launched from electron gun pass by a drift tube and enter the half cell. By observing the field distribution calculated with the code, we found that the position of the cell and the drift tube must be reversed in order to satisfy the smooth field transition from CELL to TRWCELL.

3 Linac design for a high capture efficiency

Capture efficiency represents the ratio of the phase acceptance which occupied by the stable electrons captured by an accelerator over 2π. Electron linac for irradiation processing needs to be designed as compact as possible. So a single accelerating cavity is chosen for both bunching and accelerating 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[1)]. 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 capture efficiency can't reach a high value, say about 30%. Fig. 2 shows a design scheme of this type.

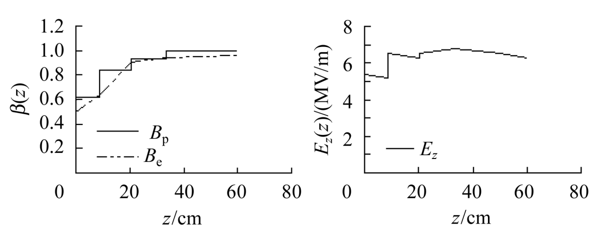

Fig. 2. The electric field and phase velocity change in a staircase form.

In order to get a higher capture efficiency, 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 $\beta_{\mathrm{P},i} = \beta_{\mathrm{P},i-1} + \left.\frac{\mathrm{d}\beta_\mathrm{P}}{\mathrm{d}z}\right|_{i-1}\cdot D_i$. By properly choosing the phase velocity of the first cell and the slope $\frac{\mathrm{d}\beta_\mathrm{P}}{\mathrm{d}z}$, 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 $\frac{\mathrm{d}\beta_\mathrm{P}}{\mathrm{d}z}$ 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 $\frac{\mathrm{d}\varphi}{\mathrm{d}z} = \frac{2\pi}{\lambda}\left(\frac{1}{\beta_\mathrm{P}} - \frac{1}{\beta_\mathrm{e}}\right)$. 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. 3(a), which has a capture efficiency of 40%. If $\frac{\mathrm{d}\beta_\mathrm{P}}{\mathrm{d}z}$ 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. 3(b) shows an example of this case, in which the capture efficiency is only about 30%.

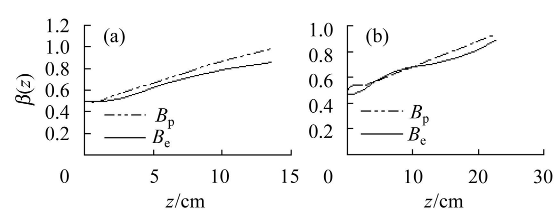

Fig. 3. Two design schemes for phase velocity variation.

If $\frac{\mathrm{d}\beta_\mathrm{P}}{\mathrm{d}z}$ 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

1) Principle of Low Energy Election Linear Accelerators, Teaching Materials. Tsinghua University. LIN Yu-Zheng.

such a scheme, as shown in Fig. 4, we designed the CIAE irradiation processing linac with a capture efficiency of above 90%. It can be observed from Fig. 4 that the velocity of electrons is slightly lower than the phase velocity in the beginning. In the early design version, we made the velocity of electron keep strictly synchronous with the phase velocity and a rather high capture efficiency was reached. However, on the other hand, this results in a rather large power dissipation in the first few cells with a short cell length D due to a low value of β=0.466 at the beam energy of 60keV. So we gave up this idea eventually. After a series of simulations, the initial phase velocity was chosen as 0.5. 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.

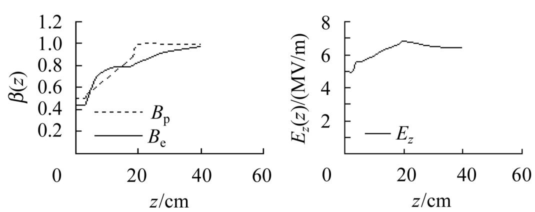

Fig. 4. Phase velocity and field variation along z axis.

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 exists, 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. 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 0.2°. 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.

Although the accelerating efficiency in the 18cm bunching segment is low in this design, and the energy of the beam just increase from 0.06MeV to 0.4MeV, the capture efficiency is obviously increased. 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 can obviously depress the request for the electron gun.

The designed accelerator consists of 59 cells. The cell length is linearly increased in the first 8 cells and then is remained constant from cell 9 to cell 59. 1000 sample electrons were used to do the beam dynamics simulations with the input beam current of 300mA. The space charge effect is taken into account in the PARMELA code. The transverse beam losses are well controlled to zero by properly adding the focusing coils. The number of electrons at the exit of the accelerator is 904, corresponding to an output beam current of 271.2mA. This indicates the capture efficiency is above 90%. The total length of the accelerator is 2m. The phase and energy spectra at the entrance and the exit of the accelerating tube are shown in Fig. 5 and 6 for the examination of the beam quality.

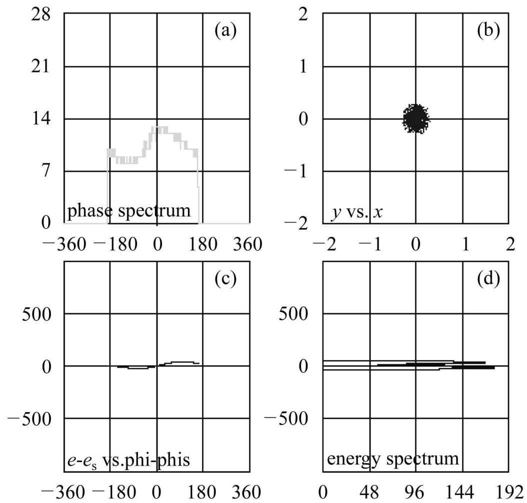

Fig. 5. Beam spectra at the entrance of the accelerating tube.
(a) phase spectrum (degree-particle numbers);
(b) x-y (cm-cm); (c) $\Delta\phi$-ΔW (degree·keV);
(d) energy spectrum (particle numbers·keV).

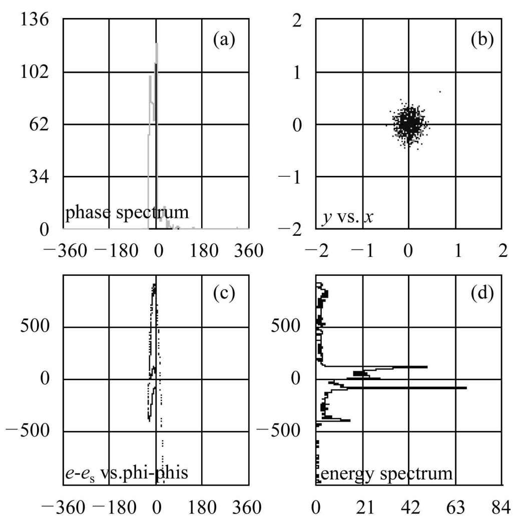

Fig. 6. Beam spectra at the exit of the accelerating tube.
(a) phase spectrum (degree-particle numbers);
(b) x-y (cm-cm); (c) $\Delta\phi$-ΔW (degree·keV);
(d) energy spectrum (particle numbers·keV).

4 Optimization of the accelerating cavity

After finishing the partial design of the accelerating cavity and the simulations of beam dynamics, we started to optimize the size of the cavity of the bunching segment. The optimization target is a higher shunt impedance and a reasonable attenuation factor. We decreased the bore radius a and adjust the inner cavity radius b for this purpose. The initial a/λ of the bunching segment was 0.118. In a series of PARMELA simulations with an adequate focusing strength, the bore radius a was kept on decreasing in order to increase the accelerating field. Finally the bore radius a became 0.115 times wavelength, namely 1.207155cm. This optimization makes the bunching segment a higher electric field.

With the optimized design described above, PARMELA gives the results of the beam parameters as listed in Table 3, which completely satisfies the design requirement of the CIAE linac for the irradiation processing application.

Table 3. 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

5 Conclusions

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 reach a high capture efficiency 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 decreasing of the total length of the accelerator. Of course, this proposal is suitable for the low energy linac. A model cavity will be manufactured according to the design for cold measurement in the near future.

Many thanks to Prof. Wang Shuhong, Dr. Ouyang Huafu and Dr. Xu Taoguang for their good suggestions and many supports on this work.

References

1 Billen J H, Young L M. Poisson Superfish: LA-UR-96-1834. 2003

2 YAO Chong-Guo. Electron Linear Accelerators. Beijing: Science Press, 1986. 387—392, 442—450 (in Chinese) (姚充国. 电子直线加速器. 北京: 科学出版社, 1986. 387—392, 442—450)

3 Young L M. Parmela: LA-UR-96-1835. 2003

高俘获效率电子辐照加速器的设计研究

刘华昌[1;1)] 王修龙[1] 傅世年[2]

1 (中国原子能科学研究院 北京 102413)
2 (中国科学院高能物理研究所 北京 100049)

摘要 加速管是一台加速器的核心部分. 一般电子辐照加速器的俘获效率在50%左右, 一半的电子都损失在加速管内. 丢失的电子打在加速管内壁, 产生韧致辐射、腔体发热量增加、真空变坏等许多负面影响. 采用一段等梯度加速结构, 相速沿加速管呈线形增加, 调整相速变化规律及加速管腔体的尺寸参数, 设计出的加速管最终的俘获效率提高到90%以上, 同时平均加速梯度没有因此降低, 加速管总长度没有增加.

关键词 电子辐照加速器 盘荷波导 俘获效率

2005－11－23 收稿, 2006－01－09 收修改稿

1) E-mail: liuhc@ihep.ac.cn