Physical calculation for an X-band hybrid dielectric-iris-loaded accelerator*

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Abstract A small, high performance X-band hybrid dielectric-iris-loaded travelling-wave linac with the length of 1.47 m and the maximum accelerating gradient of 45 MV/m has been designed. The beam energy of 33 MeV, the energy spread of 0.5%, the beam emittance of about 5.7 πmm·mrad and the capture efficiency of 40% are reached by adjusting the sizes of the accelerating cavities and the phase velocity. The attenuation per unit length of structure, the shunt impedance R_s, the quality factor Q, the group velocity and the phase velocity are also presented.

Key words hybrid dielectric-iris-loaded, phase velocity, beam energy, energy spread, beam dynamics

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1 Introduction

There are obvious advantages for using X-band range than the S-band one. First, the shunt impedance per unit length of X-band is higher than that of S-band. Second, the maximum permissible electric field strength is also higher.

One disadvantage of conventional iris-loaded accelerating structures is the high ratio of the peak surface electric field to the peak axial electric field. Typically this ratio of Es/Ea is more than 2. A hybrid dielectric and iris loaded periodic structure can reduce Es/Ea to near unity, while maintaining high acceleration efficiency as measured by r/Q compares favourably with conventional metallic structures[1] and the r/Q values of dipole modes for the new accelerating structure are much lower than those for the iris-load accelerating structure[2]. The device is shown in Fig. 1.

This paper presents the physical design of an X-band hybrid dielectric and iris-loaded travelling wave electron linear accelerator with the beam energy being 33 MeV and the beam current being 100 mA. The RF parameters and the transverse and longitudinal beam dynamics for this accelerator are calculated.

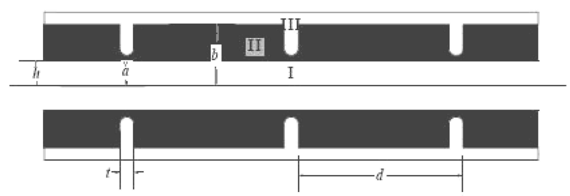

Fig. 1. Sketch of regular accelerator cavities. In the figure, Region I is vacuum; Region II is ceramic with dielectric constant ε_r; Region III is copper. a is the iris radius, b is the outer radius, and h is the beam hole radius. t is the thickness of the iris, and d is the length of one cell.

2 Theory

To reduce the accelerator length, a compact structure shown in Fig. 2 is adopted. In order to reduce the machining workload and simplify the microwave measurement, a constant phase velocity and constant impendence structure are adopted. To constrain the emittance growth caused by short-range wakefields

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and keep higher accelerating efficiency, the group velocity is chosen to be 0.03 with $\beta_\varphi = 1$.

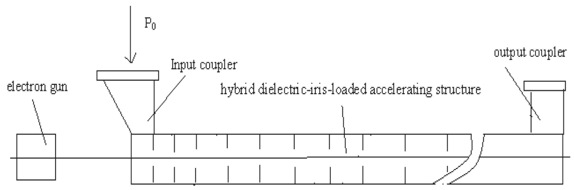

Fig. 2. Sketch of compact accelerator.

The equations about electric longitudinal dynamics along z axis for the accelerating structure are recalled here:

$$\frac{\mathrm{d}\gamma}{\mathrm{d}z} = \frac{eE}{mc^2}\cos\varphi\,, \tag{1}$$

$$\frac{\mathrm{d}\varphi}{\mathrm{d}z} = \frac{2\pi}{\lambda}\left[\frac{1}{\beta_\varphi} - \frac{1}{\beta}\right]. \tag{2}$$

Here $\beta = \sqrt{\gamma^2-1}/\gamma$, β is the relative velocity of electron, z is the longitudinal position, γ is the relative energy, E is the accelerating gradient, φ is the phase, c is the velocity of light, m is the mass of electron, β_φ is the phase velocity, and λ is the wavelength.

The RF power distribution along the linac section and the accelerating electric field can be expressed by:

$$\frac{\mathrm{d}P}{\mathrm{d}z} = -2\alpha P - i_b E\,, \tag{3}$$

$$E = \sqrt{2\alpha R_s F}\,, \tag{4}$$

Here P is the RF power, α is the attenuation per unit length of structure, R_s is the shunt impedance, and i_b is the beam current.

Based on the above equations, the phase velocity and numbers of cavities and the accelerating gradient of accelerator cavities can be determined to get high energy gain, low energy spread and high capture efficiency through large numbers of calculations under the conditions of the given RF power input, voltage input of the electron gun and beam current.

3 Calculation results

We assume the voltage input of the electron gun is 50 kV, the RF power input is 20 MW and the pulse beam current is 100 mA. The values of optimized β_φ (0.5, 0.85, 1) and the numbers of cells (3, 5 and 162 respectively) for three sections are obtained.

By using electromagnetic code such as MAFIA, the attenuation per unit length of structure α, the shunt impedance R_s, the quality factor Q, the group velocity β_g and the phase velocity β_φ are got by optimizing the dimensions of the cavities. The structure parameters and performance parameters for the three sections are given in Table 1 and Table 2.

Table 1. The structure parameters of accelerator cavities.

type	t/mm	a/mm	b/mm	d/mm	h/mm	No.
#1	3	4.66	6.796	4.374	2	3
#2	1	4.56	5.560	7.435	2	5
#3	1	3.23	5.226	8.747	2	162

Table 2. The performance parameters of accelerator cavities.

type	β_φ	α	R_s	Q	β_g	Es/Ea
#1	0.5	0.49	8.13	2497.3	0.10	1.65
#2	0.85	0.151	64.28	5298.4	0.15	1.01
#3	1	0.907	56.73	4393.8	0.03	1.09

Using Eqs. (1)—(4) and MATLAB code, we can get the variations of residual power, which are shown in Fig. 3. Using Eq. (4), one can get the accelerating gradients along the accelerator tube. The maximum accelerating gradient at the 9$^{\text{th}}$ cell is 45 MV/m which is much larger than the accelerating electric field (12.6 MV/m) of the 1$^{\text{st}}$ cell through calculations.

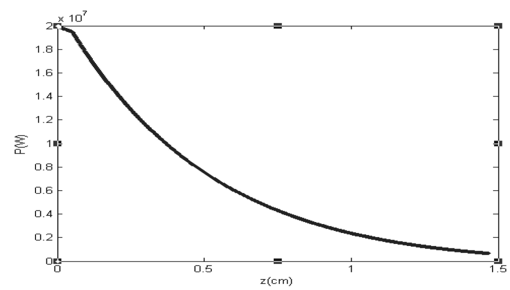

Fig. 3. The residual power variation along z axis.

We suppose the initial spots diameter is 2 mm of the input beam from electron gun, the phase distribution from $-\pi$ to π is uniform and the energy spread is equal to zero. To control the transverse beam losses, proper focusing coils are added. The optimized magnetic field distribution of these coils by using PARMELA is shown in Fig. 4. 13000 sample electrons are used to do the beam dynamics simulations with the input beam current of 250 mA. The space charge effect is taken into account in the PAMELA code. Beam spectra at the exit of the accelerating tube is shown in Fig. 5 for the examination of the beam quality. At the exit of the accelerating tube the geometrical emittance is small shown in Fig. 5a, the transverse beam diameter is 4 mm shown in Fig. 5b, the phase is bunched near to zero shown in Fig. 5c and the energy spread is about 0.5% shown in Fig. 5d. The beam energy at the end of the linac is 33 MeV. The transverse emittance at the exit is about 5.7 πmm·mrad by calculation.

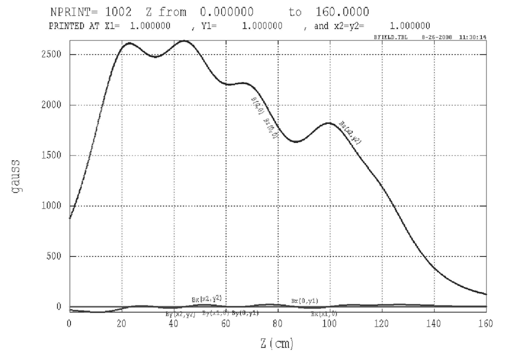

Fig. 4. Magnetic field distribution of focus coils along the lianc.

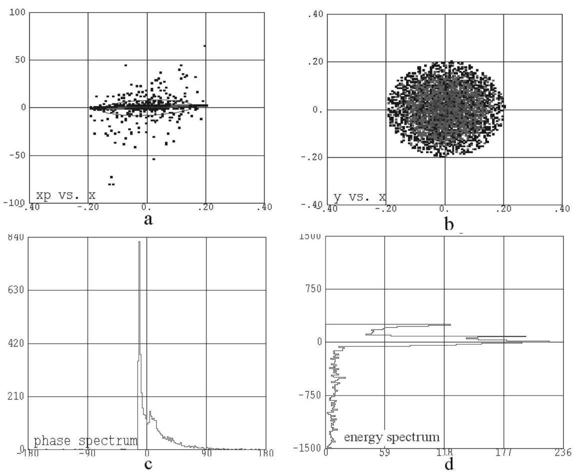

Fig. 5. Beam spectra at the exit of the accelerating tube. (a) x'-x (mrad-cm); (b) x-y (cm-cm); (c) Phase spectrum (degree-particle numbers); (d) Energy spectrum (particle numbers-keV).

Based on the above results, the beam characteristics are shown in Table 3.

Table 3. Critical parameters of X-band 33 MeV TW accelerator.

main parameters	designed value
energy	33 MeV
the length of accelerator tube	1.47 m
structure type	constant impedance
input peak power	20 MW
operation frequency	11.424 GHz
input voltage of electron gun	50 kV
output pulse beam current	100 mA
shunt impedance	56.73 MΩ/m
Q	4393.75
capture efficiency	40%
energy spread	0.5%
emittance	5.7 πmm·mrad

4 Conclusions

With the help of MAFIA code, MATLAB code and PAMELA code, a small and high accelerating gradient X-band (11.424 GHz) hybrid dielectric and iris loaded travelling wave electron linac is theoretically studied. The beam energy is 33 MeV. The capture efficiency is about 40%, the energy spread is about 0.5% and the beam emittance is about 5.7 πmm·mrad under the conditions of the beam current being 100 mA and the electron gun voltage being 50 keV. The length of accelerator tube is 1.47 m.

References

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