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RESEARCH ON ELECTRON LINEAR ACCELERATORS WITH TRAVELING WAVE RESONATORS

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Abstract

The principle of electron linear accelerators with traveling wave resonators is described. The characteristics of this type of accelerator are analysed and calculated by means of the theory of the traveling wave resonator. To make this type of accelerator realistic, the simplified rf resonant ring is presented. A model has been tested at the low power. The measure results agree with the theory.

Finally, a design example is presented. When a 2MW magnetron is used as a power source, the length of the accelerator structure is 300 mm or so, and the pulse current is 150 ma, the electrons will be accelerated to 4 Mev.

1 Introduction

It is well known that if general rf feedback is employed on a traveling wave accelerator[1,2,3], a hybrid is used as a bridge of rf feedback, the attenuation of the accelerator structure is about 3 db, and if the phase is suitable, the field strength in the accelerator structure will be increased about 1.4 times. Therefore, the length of the accelerator structure can be shortened, while its effectiveness is kept constant.

If the length of the accelerator structure is shortened still further, the attenuation of the circuit of feedback is decreased still further, and when the electric length of the circuit is an integral number times the wavelength, the field strength may be raised two or three times, or even higher. This device is called the electron linear accelerator with the traveling wave resonator.

2 The traveling wave resonator[4]

The traveling wave resonator is an interesting microwave element. Under the condition of pure traveling wave, higher field strength can be acquired.

The traveling wave resonator may be qualitatively examined with the aid of Fig.1. A wave progressing from the signal source is partially coupled into the ring through a directional coupler.

Suppose that the voltage coupling coefficient of the directional coupler is C, the total length of the ring is ℓ, the voltage transmission coefficient of the transmission line is T, and the phase constant of the transmission line is β, two properties of the ring circuit can be derived. The forward wave in the ring, that is the wave out of port 4, a_4, normalized with respect to the input at port 1, a_1, can be written as follows

$$\frac{a_4}{a_1} = j\frac{c}{1-T\sqrt{1-c^2}\,e^{-j\beta\ell}} \tag{1}$$

When $\beta\ell = 2n\pi$ (n=0,1,2,......) equation (1) is maximized. The ratio a_4/a_1 is called the field multiplication factor, M, and at resonance

$$M = \frac{c}{1-T\sqrt{1-c^2}} \tag{2}$$

It can be shown that the optimum occurs when $C=\sqrt{1-T^2}$, and (2) becomes

$$M_{opt} = \frac{1}{\sqrt{1-T^2}} = \frac{1}{C_{opt}} \tag{3}$$

The wave transmitted through coupling section to the load, that is the wave out of port 2, a_2, normalized with respect to the input at port 1, a_1, can be written as follows

$$\frac{a_2}{a_1} = \sqrt{1-c^2} - \frac{c^2T}{1-T\sqrt{1-c^2}} \tag{4}$$

When $C = \sqrt{1-T^2}$, and (4) becomes $a_2/a_1 = 0$.

As the ring has some reflection, its reflectance is Γ, the result for the forward wave in the ring normalized to the input at port 1, a_1 , becomes

$$\frac{a_4}{a_1} = jc\frac{1-T\sqrt{1-c^2}\,\sqrt{1-\Gamma^2}\,e^{-j\phi}}{1-2T\sqrt{1-c^2}\,\sqrt{1-\Gamma^2}\,e^{-j\phi}+(1-c^2)T^2e^{-j2\phi}} \tag{5}$$

For this case, the field multiplication factor is a rather complicated function of ring loss, electric length, coupling and reflection coefficient.

3 The accelerator

In order to utilize the traveling wave electric field in the resonator to accelerate electrons, a section of a traveling wave accelerator structure (disk-loaded waveguide) is inserted into the resonant ring. A phase shifter and an impedance matcher are inserted into the ring too, in order to adjust the phase of circuit and to match the impedance respectively. A variable directional coupler is employed in order to adjust coupler to optimum the coupling. Its schematic drawing is shown in Fig.2.

Suppose that the rf attenuation in the

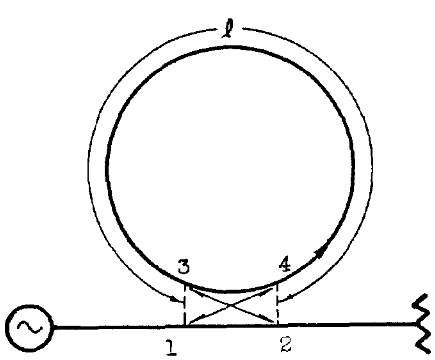

Fig.1

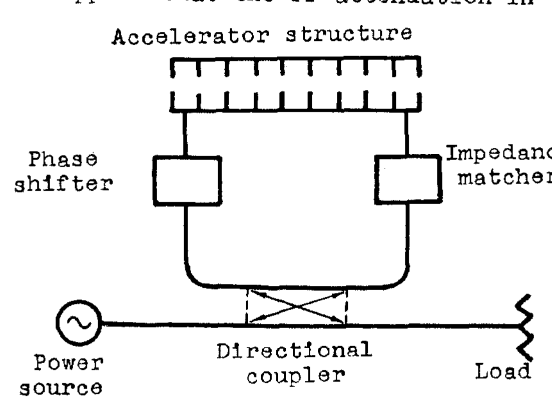

Fig.2

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ring centers on the accelerator structure, i.e. the rf attenuations of other elements in the ring are negligibly small compared to the rf losses in the wall of the accelerating structure. Assuming that the attenuation constant of the accelerator structure is α, the length of the accelerator structure is L, then the total rf attenuation in nepers in the accelerator structure is τ, $\tau=\alpha L$, the voltage transmission coefficient of the ring is T, $T=\exp(-\tau)$. Using equation (3) M can be expressed as

$$M = \frac{1}{\sqrt{1-e^{-2\alpha L}}} = \frac{1}{\sqrt{1-e^{-2\tau}}} \qquad (6)$$

Therefore, under negligible beam loading condition, for the constant impedance accelerator structure the energy gain V can be written as

$$V = ME_oL\left(\frac{1-e^{-\tau}}{\tau}\right)$$
$$= P_s r L \;\frac{2\tau}{\sqrt{1-e^{-2\tau}}}\left(\frac{1-e^{-\tau}}{\tau}\right) \qquad (7)$$

where $E_o = \sqrt{2P_s\alpha r}$, Ps is the power from the external power source, r is the shunt impedance per unit length. When the electron current is significant, the reduction in available energy due to beam loading must be taken into account. In this case, the energy gain Vb is given by

$$V_b = M_bE_oL\;\frac{1-e^{-\tau}}{\tau} - i r L\left(1-\frac{1-e^{-\tau}}{\tau}\right) \qquad (8)$$

where i is the peak beam current and Mb is the field multiplication factor under beam loading condition. The field multiplication factor Mb decreases with increasing i. It can be obtained by repeating the iteration.

For various parameters of the accelerator structure, when the input power is 2 MW, the calculated energy gains are given in table 1.

One can see that the energy gain Vb increases slightly with increasing α and r with the given length of the accelerator structure.

The fractional losses of energy caused by a small change in frequency have been calculated and are listed in table 2. It shows that a higher value of α will result in larger loss of energy, with the given frequency shift δf.

The fractional losses of energy caused by a small refrection in the ring have been calculated and are listed in table 3. It shows that lowering the value of α will result in a serious loss of energy.

According to the preceding analyses, when the parameters of the accelerator structure

Table 1

	α (neper/m)	r (MΩ/m)	L (m)	τ (neper)	Eo (MV/m)	M	V (Mev)	i (A)	Mb	Vb (Mev)
1	0.489	59.35	0.1	0.0489	10.774	3.27	3.44	0.2	2.78	2.90
	0.489	59.35	0.2	0.0978	10.774	2.37	4.87	0.2	1.92	3.82
	0.489	59.35	0.3	0.1467	10.774	1.98	5.97	0.2	1.56	4.43
2	0.288	57.30	0.1	0.0288	8.124	4.22	3.38	0.2	3.59	2.86
	0.288	57.30	0.2	0.0576	8.124	3.03	4.78	0.2	2.43	3.77
	0.288	57.30	0.3	0.0864	8.124	2.51	5.86	0.2	1.94	4.38
3	0.179	55.15	0.1	0.0179	6.283	5.33	3.32	0.2	4.53	2.81
	0.179	55.15	0.2	0.0358	6.283	3.80	4.69	0.2	3.04	3.73
	0.179	55.15	0.3	0.0537	6.283	3.13	5.71	0.2	2.41	4.33
4	0.120	53.00	0.1	0.0120	5.044	6.49	3.25	0.2	5.53	2.77
	0.120	53.00	0.2	0.0240	5.044	4.62	4.60	0.2	3.70	3.69
	0.120	53.00	0.3	0.0360	5.044	3.79	5.63	0.2	2.91	4.27
5	0.084	51.05	0.1	0.0084	4.142	7.74	3.19	0.2	6.18	2.72
	0.084	51.05	0.2	0.0168	4.142	5.50	4.52	0.2	4.41	3.61
	0.084	51.05	0.3	0.0252	4.142	4.51	5.53	0.2	3.46	4.21
6	0.055	48.00	0.1	0.0055	3.325	9.56	3.09	0.2	8.20	2.65
	0.055	48.00	0.2	0.0110	3.325	6.78	4.38	0.2	5.47	3.52
	0.055	48.00	0.3	0.0165	3.325	5.55	5.36	0.2	4.28	4.11

Table 2

	α (neper/m)	L (m)	τ (neper)	Vg/C	f (MHz)	δf (MHz)	$\delta\theta$ (degree)	Mb'*	Vb'* (Mev)	$\frac{Vb-Vb'}{Vb}$ %
1	0.489	0.3	0.1467	0.0048	2856	0.3	-23.52	1.39	3.94	11.2
2	0.288	0.3	0.0864	0.0079	2856	0.3	-14.25	1.79	4.03	8.1
3	0.179	0.3	0.0537	0.0124	2856	0.3	-9.03	2.27	4.08	5.2
4	0.120	0.3	0.0360	0.0181	2856	0.3	-6.15	2.79	4.09	4.2
5	0.084	0.3	0.0252	0.0254	2856	0.3	-4.35	3.35	4.08	3.1
6	0.055	0.3	0.0165	0.0389	2856	0.3	-2.79	4.19	4.03	2.0

* Mb' and Vb' are Mb and Vb respectively under the frequency shift δf condition.

Table 3

	α (neper/m)	L (m)	τ (neper)	Γ	Mb''**	Vb''** (Mev)	$\frac{Vb-Vb''}{Vb}$ %
1	0.489	0.3	0.1467	0.05	1.55	4.40	0.7
2	0.288	0.3	0.0864	0.05	1.89	4.28	2.2
3	0.179	0.3	0.0537	0.05	2.26	4.06	6.0
4	0.120	0.3	0.0360	0.05	2.53	3.71	13.0
5	0.084	0.3	0.0252	0.05	2.64	3.20	23.9
6	0.055	0.3	0.0165	0.05	2.44	2.33	43.3

** Mb'' and Vb'' are Mb and Vb respectively under the refrectance Γ condition.

are chosen, if one desires to relax frequency tolerance, it will be preferable to use a lower value of α, but match of the ring will be more difficult; if one desires to match easily, a higher value of α will be preferable, but high frequency stability will be needed.

4 Simplification of resonant ring

From the above considerations it is obvious that for 4 Mev accelerator the accelerator structure is about 300 mm in length, but the phase shifter and the impedance matcher not only need a large space but also increase the loss in the ring. In order that this type of accelerator has practical values, these difficulties have to be overcome.

To simplify this resonant ring, one may remove the phase shifter and the matcher, and the fixed directional coupler instead of the variable one is used. Its structure is schematically shown in Fig.3.

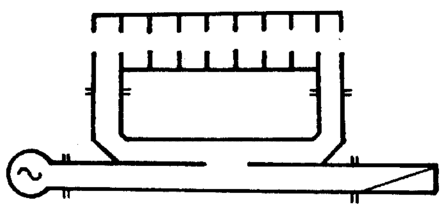


Fig.3

The coupling coefficient of the directional couper may be selected to be near optimum. Changing the length of the waveguide in the ring is used to resonate roughly, and changing the frequency is used to resonate exactly. It is well known that to tune a mismatched ring is not easy. But for the simplified resonant ring, the tuning of the resonant ring may be comparatively convenient.

5 A model test

A section of the traveling wave accelerator, which consists of nine cavities of $2\pi/3$ mode in which phase velocity is equal to the velocity of light and input and output couplers, is inserted into the ring. The V.S.W.R. of this section is 1.03 at the center frequency. The V.S.W.R. is less than 1.10 over 2.6 MHz range.

It has been demonstrated that this simplified resonant ring with the linac (i.e. the linac with the traveling wave resonator) can be resonated convenietly and can be operated stably. At resonance, input, forward and output pulse shape of the ring are shown in Fig.4. The resonant curves of the resonator are shown in Fig.5.

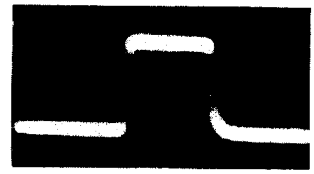
The field multiplication factor M measured is about 3. It depends on the total attenuation of the ring. The lower curve of Fig.5 is the resonant curve when reflection in the ring is increased. A dual peak is appeared.

6 A design example

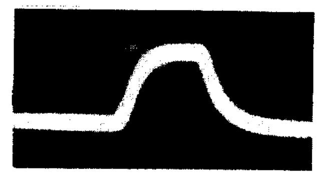
As an example, a 2 MW magnetron is used as a power source to design a 4 Mev electron linac with a traveling wave resonator. A summary of the important design parameters of this linac is as following

Frequency and mode	$f=2856$ MHz $2\pi/3$
Shunt impedance	$r=55$ MΩ/m
Attenuation constant	$\alpha=0.179$ neper/m
Accelerator structure	1 bunching cavity ($\beta=0.7$) + 8 accelerating cavities ($\beta=1$)
Peak rf input power	Ps=1.8 MW
Peak current	i=150 ma
Injecting voltage	Vo=10 Kev
Coupling coefficience of deractional coupler	C=0.4
Beam energy	Vb=4.1 Mev

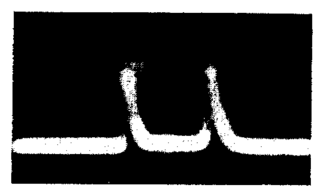
In order to guarantee that the beam does not disperse, the axial magnetic field is used.



Input wave



Ring wave



Load wave

Fig.4

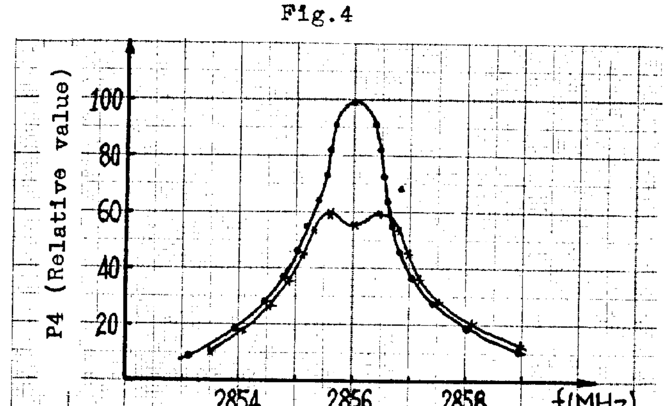


Fig.5

Refernces

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