A Conceptual Design of a One-Section Linac Using RF-Energy Compression

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Abstract

The basic feasibility of a proposal to simplify the conventional low energy rf electron linear accelerator (linac), is considered. The design suggested foresees replacement of the traditional high power systems of external rf generator and modulator by a more passive switched energy storage system. The proposed conception of a compact linac is based on advanced rf-energy compression techniques and an efficient self-excited oscillation in a special accelerating/oscillating linac structure. The principal relations and performance estimations for such a linac are presented.

1. INTRODUCTION

To realise a more compact linac design we can combine the processes of acceleration and rf-generation in the same linac structure. In contrary to similar proposals [1,2] we consider the processes being separated in time. In this case we need only one e.b. source, almost conventional type of structure and an rf-energy compression (REC) system (instead of a klystron) for energy storage and power increasing. This proposal is aimed to facilitate the limitations on sizes, weight and pulse rate associated with using of a high power klystron and modulator. The main purpose of the paper is to show the feasibility of low energy linac combining rf-generation and acceleration processes at the same injected beam energy and using of rf-compression technique developed for high energy linear colliders.

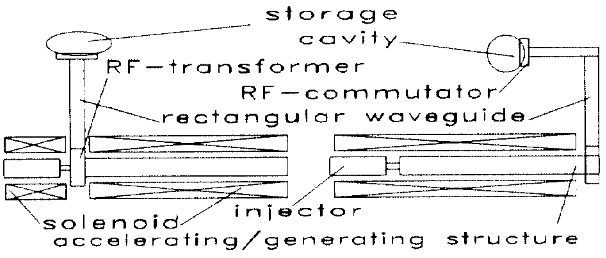

Figure 1. The compact linac schematic layout for the case of the acceleration by the forward (a) and backward wave (b).

2. PERFORMANCE PRINCIPLE AND MAIN CONDITIONS

In the Figure 1 we can see the schematic layouts of the linac proposed. The first type of structure (a) corresponds to a negative mutual inductance between structure cells for the last L_3 subsection, the second (b) - to a positive one. The rf commutator contains an auxiliary modulator (it is not shown) to control the external Q_e of the storage cavity. During the period of rf-energy generation the low-voltage injected beam interaction with the synchronous backward space harmonic of the last L_3 subsection causes self-excited oscillation in this section similar to that in travelling-wave cascade TWT-BWO generating tubes. The rf-commutator provides close to critical coupling between external cavity and slow-wave structure during this period t_g of rf-energy storage. Then rf-commutator is switched rapidly in order to produce strong coupling between the cavity and linac structure. This results in backward compressed rf-energy flow and linac structure filling during the period t_u.

The beam, entering after the filling of the section by the compressed rf-energy, interacts with the fundamental harmonic of the structure as in a conventional travelling wave one-section linac with bunching in the first subsection L_1, bunching and acceleration in the second one, L_2 and acceleration in the last subsection, L_3. To ensure capture and acceleration of the continuous injected beam it is necessary to ensure relevant accelerating field amplitude and phase velocity profiles along the section which are typical for a (one-section) waveguide linac (e.g., see ref. [3] and Fig. 3).

Using TWT theory relationships and Brillouin diagrams (see Figure 2) for the case of backward wave generation we can derive the main conditions for effective rf energy generation, storage and outcoupling:

$$\begin{aligned}
&\beta_b \approx \beta_{ph0} \approx \theta / (2\pi - \theta), \\
&I_b = (2 \div 5) I_s, \\
&C \approx 0.1\text{-}0.2, \\
&|\chi_g - 1|^2 << 1,\ |\chi_g - 1| \approx 2|\Gamma_2|, \qquad (1) \\
&t_c << t_f,\ \chi_u >> 1, \\
&t_p << t_f \approx t_u,
\end{aligned}$$

where β_b, β_{ph0} are the phase velocities related to the speed of light c for the injected beam and fundamental harmonic in the first subsection L_1, $\theta=2\pi D/\Lambda$ is the acceleration mode for the last subsection L_3 with period D, Λ is the waveguide wavelength, I_b is the beam current, I_s is the threshold current, $C=(I_b R_c / 2\gamma(\gamma+1)V_b)^{1/3}$ is TWT gain parameter, R_c is the coupling impedance for the non-zero (-1) harmonic, Γ_1, Γ_2 are the reflection coefficients for the space harmonic near the section endpoints, χ_g is the coupling factor during rf -power generation regime which is close to critical value, t_c is the commutation period when the RF commutator changes the value of coupling between the cavity and linac section, t_f is the section filling time, t_p is the accelerated beam pulse length, χ_u is the coupling factor during the period of the stored energy coupling out of the storage cavity. For the experiment [3] I_b/I_s ratio is close to 3.7 and the threshold current is defined by the conventional BWO tube theory and high efficiency, η_g >30%, may be achieved provided the reflections are optimal.

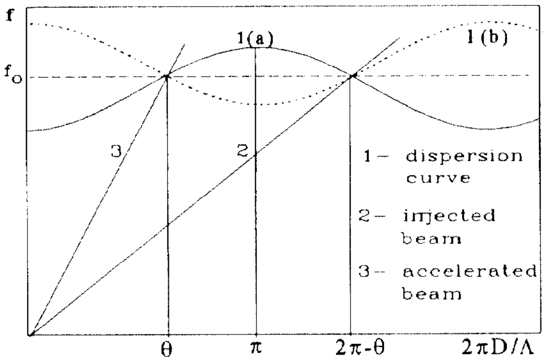

Figure 2. Brillouin diagrams for the cases of the negative (a) and positive (b) mutual coupling inductance between structure cells.

In the case (b) (see Figures 1b, 2) we have the situation similar to a travelling-wave tube supplied by a feedback loop. The loop may be provided by either an external waveguide feedback loop or internal reflections in the section. Neglecting beam-wave interaction in the subsections L_1, L_2 we can define the threshold current in the same way as for the regenerating TWT: $G_{TWT}|\Gamma_1\Gamma_2|^2 \geq 1$, where G_{TWT} is TWT equivalent power gain for the subsection L_3. Note, unlike a conventional TWT, the self-excited oscillation can take place also in the case $\Gamma_1 = 0$, $\Gamma_2 \neq 0$ due to beam interaction with the fundamental harmonic of the reflected wave from the coupler side. In this case we have preliminary bunching in the subsection L_1 by the backward wave before TWT amplification in the subsection L_3.

3. ESTIMATIONS OF THE COMPACT LINAC PARAMETERS

Two kinds of structure were considered for the L_3 subsection: circular disk loaded waveguide (DLWG) for the variant (a) and jungle gym bar-loaded (JG) structure for the variant (b).

Three sets of structure parameters are listed in the Table 1: (a_1) and (a_2) variants were chosen with the help of [4] for the DLWG structure and (b) variant corresponds to the JG structure [5].

Table 1. Parameters of the oscillating/accelerating structure used for estimations

Parameter Variant	θ	Aperture, a/λ	Disk thickness t/λ	Shunt imped. $\lambda R_s/Q$, Ohm	Internal radii ratio a/b	Attenuation $\alpha\lambda^{3/2}m^{1/2}$	R_C, Ohm	β_{gr}, 10^{-3}
a_1	π/2	.0774	0.038	653	0.2	0.02	139	5.48
a_2	2π/3	0.09	0.095	710	0.233	0.04	1140	3.1
b	π/2	0.075	-	1000	-	0.032	41	-70.

To estimate the energy gain we have assumed that during the period t_u of using the stored rf energy the rf power filling the section decreases as $\exp(-2\pi t f_0(1+\chi_u)/Q_0)$ neglecting the pulse leading edge and commutation times. In addition we neglected phase slippage between the beam and the wave in L_3 subsection, energy increasing in the L_1, L_2 subsections and beam energy radiation losses in higher order frequency bands. Then the unloaded energy gain is:

$$W_l = 2B\frac{1-e^{-\delta}}{\sqrt{\delta}}\sqrt{\pi c\frac{R_s}{Q}W_{st}\eta_{oc}\frac{L_3}{\lambda}}, \qquad (2)$$

where $\delta = \pi t_f f_0(1+\chi_u)/Q_0$ describes the ratio between filling time and e-folding time of the stored energy outcoupling, Q_0 is the storage cavity figure of merit, W_{st} is the radiation from the strongly overcoupled cavity, $W_{st} = I_b V_b t_g \eta_g \eta_{st}$, $\eta_{st} = (1-\exp(-2\mu))/2\mu$, is the storage efficiency, $\mu = \pi t_g f_0(1+\chi_g)/Q_0$, f_0 is the operating frequency, η_{oc} is the efficiency of the rf-energy commutation and radiation outcoupling processes, and B is the coefficient taking into account rf losses in the waveguide structure:

$$B = \frac{1-e^{-(\delta+\alpha L_3)}}{\delta+\alpha L_3}\Big/\frac{1-e^{-\delta}}{\delta}.$$

Now we can find from (2) the relationship for definition the optimum section length: $\delta \approx 1.25$. The averaged over beam pulse accelerated beam energy with taking into account beam loading: $W_{av} = W_l\,(1-K/2)$, where $K = q/q_{max}$, q is the total accelerated pulse charge,

$$q_{max} = \frac{W_l\,/\,L_3}{\pi f R_s\,/\,Q}.$$

The overall compact linac efficiency is defined as $\eta = \eta_g\eta_{st}\eta_{oc}2K(1-K/2)\exp(-2\alpha z)$ and as well as energy gain depends appreciably on the storage cavity quality factor Q_0.

In the Table 2 linac parameters are presented for $\lambda = 10$cm, $\eta_{oc} = 74\%$, $\delta = 1.25$, $K = 0.8$. For extremely high power regimes the limitations imposed by the cooling system are neglected. It can be seen from the table that we used close to limiting parameter values for REC system (see refs. [6-8]): high efficiency $\eta_{oc} > 70\%$, high rf energy compression factor $r = \eta_{oc}P/P_g \approx \chi_u$ (P_g is the rf-power of oscillation, P is the accelerating travelling wave power) of the order of tens and pulse rate frequency close to ultimate value 100kHz. However, the values of rf energy stored (of the order of joules) are far from limiting values (hundred joules).

Note, structure (b) variants require high perveance ($\approx 10\mu$ A/V$^{3/2}$) beams which can be obtained in magnetron injection guns or toroidal guns for hollow beams. Brillouin field value (for the generating stage) at beam radius $r_b = 0.7$cm is about 0.15T. The beam confinement with such parameters presents a more difficult problem in our case of small structure apertures than for similar industrial linacs.

For the accelerating stage we have to verify that the bunching and focusing forces are greater than corresponding deleterious bunch space charge forces.

Table 2. Estimated parameters for the compact linac

Variant	a_1	a_1	a_2	b	b
L_3, m	1.6	1.6	1	1.6	1.6
t_f, μs	1	1	1.1	0.08	0.08
I_b, A	9	9	3	90	90
V_b, kV	40	40	100	40	40
Q_0 , $\cdot 10^5$	3.0	6.0	3.0	5.0	1.0
W_1 , MeV	10.2	11	6	17.3	24.5
Wav, MeV	6.1	6.6	3.6	10.4	14.7
Pulse length t_p, ns	9.2	10	24	1	1.5
$r = \eta_{oc}P/P_g \approx \chi_u$	40	81	36	87	173
ν, kHz	40	16	50	100	100
Beam power, kW	20.3	10	30	96	180
$\eta_{REC} = \eta_{oc}\eta_{st}$, %	37	19	55	19	19
Linac efficiency η, %	5.6	3	8.3	5.4	6

Accelerating (bunching) field amplitude E (E = 100kV/cm was taken, see Table 2) is equal to longitudinal debunching space charge field when the peak bunch current I_p is close to 200A. We see that in this case we have to use another (klystron) prebunching (instead of waveguide bunching as in (a) variants) because of lack of an enough reserve for stable bunching, unlike the (a) variants where $I_p/I_b \approx 6$. The minimum solenoidal field required for the beam confinement can be defined in the usual way:

$$\Omega_L^2 = \frac{E\lambda\cos\varphi}{mc^2/e}\frac{\pi}{\beta_{pho}}\left(\frac{c}{\lambda}\right)^2\frac{1-\beta_z\beta_{pho}}{\gamma} + \frac{I_p}{I_A\gamma^3}\left(\frac{c}{r_b}\right)^2\frac{\lambda}{r_b},$$

that gives $B_z = 0.3$T at $\beta_z = \beta_{pho} = 0.37$ and I_p=400 A.

Time-dependent calculations were undertaken to confirm and specify the estimations given in the first column of the Table 2. The modified code [9] used takes into account non-steady beam loading, accelerating wave propagation in the tapered section and longitudinal space charge effect. One of the most hard problem was to find the optimum section parameters presented in the Figure 3:

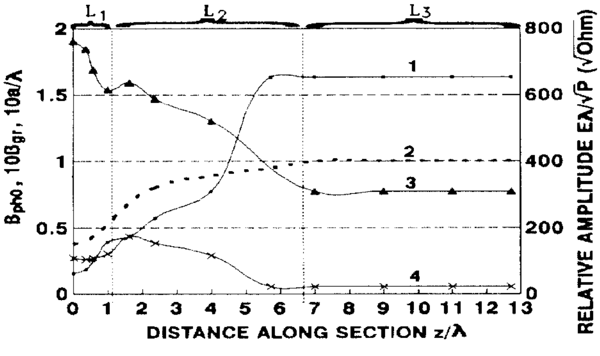

Figure 3. The parameters of the optimised DLWG tapered structure plotted along the section: relative accelerating field amplitude (curve 1), relative phase velocity for the fundamental harmonic β_{ph0} (curve 2), iris relative radius a/λ (curve 3) and relative group velocity (4)

4. SUMMARY

1. The conception proposed of the compact linac can give a considerable reduction of the weight and sizes for the linac facility (more than 2.5 times) due to elimination of conventional high power systems of rf-generator and modulator.
2. Combining of the structure proposed and rf-energy compression system can allow us to obtain high levels of the beam average power because the rf-energy commutation may be one or two orders faster than electric high voltage energy commutation (conventional modulator).
3. The linac proposed can have overall wall plug efficiency comparable with that for similar industrial linacs. Power supply required is 40-120kV range d.c. source. Some versions of such a linac are potentially applicable in various brunches.
4. The compact linac development requires further optimisation for the two-purpose generating/accelerating structure as well as efficiency and reliability enhancement for rf energy compression system.
5. The linac can be considered as a compact injector for single-pass FEL and especially Multi-Cavity [10] (MC) FEL of infra red-millimetre wavelength range. A functional linear integration scheme [11] of a compact FEL needs a special RF-compression system to provide high enough energy, peak current and narrow energy spectrum

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