STUDIES OF ELECTRON LINAC BEAM POSTACCELERATION IN A CHAIN OF PASSIVE CAVITY STRUCTURES

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Introduction

Traditionally, the energy of electron linacs can be raised by increasing the number of accelerating sections and their RF power supply systems, which is rather laborious and costly procedure. Therefore, it seems important to search for simpler and more effective methods of increasing the energy of the existing accelerators. One way of these efforts resides in further perfection of accelerating structures and their RF sources.[1-4] The potentialities of these methods are restricted by electrical breakdown of RF linac components. Another way is connected with energy exchange between the beam particles during the pulse in passive structures.[5-7] It is just the experimental studies of this method that are discussed in the present report.

Excitation of Accelerating Fields

The essence of the method under study consists in the excitation of oscillations by the linac beam in a passive cavity structure tuned to the bunch repetition frequency ω_0 or its harmonic. As a result, there arise such phase conditions that some part of the particles gets entrapped into the accelerating field and acquires an additional energy.

In this work a chain of TM_{010} cavities connected by below cutoff waveguides (b.c.w.) was used as a passive structure. When the electron beam of radius a travels along a cylindrical cavity tuned to the n^{th} harmonic of the bunch repetition frequency, it excites there an electrical field with a steady-state value given by

$$E_0 = \frac{8 I_0 Q_n \omega_0 n}{\nu^2 c^2 J_1^2(\nu)} \cdot \frac{\sin\alpha}{\alpha} \cdot \frac{\sin\left(\frac{n\Delta\phi}{2}\right)}{\frac{n\Delta\phi}{2}} \cdot \frac{2J_1(2\pi n \frac{a}{\lambda})}{2\pi n \frac{a}{\lambda}} \qquad (1)$$

where I_0 is the pulse current, $\Delta\phi$ is the bunch width at the accelerator frequency, c is the light-wave velocity, $\lambda = 2\pi c/\omega_0$, $\alpha = n\pi d/\lambda$, Q is the quality factor of the cavity, which is known for the TM_{010}-type oscillations to be

$$Q_n = \frac{A}{\sqrt{n}(1+\frac{R}{d})} \qquad (2)$$

R, d are, respectively, the radius and longitudinal size of the cavity, A is the constant.

Taking into account that at $\lambda \approx 10$ cm, $n \leq 4$ the last term in Eq. (1) is nearly unity, we obtain the following expression for the mean accelerating gradient

$$\frac{\Delta\mathcal{E}}{\ell + d} = \frac{16 I_0 A \omega_0 e}{\nu^2 J_1^2(\nu) c^2} \cdot \frac{\sin^2\alpha}{(d+n\beta)(2d+\nu)} \cdot \frac{\sin\left(\frac{n\Delta\phi}{2}\right)}{\frac{\sqrt{n}\Delta\phi}{2}} \qquad (3)$$

where $\beta \equiv \pi\ell/\lambda$, ℓ being the length of each b.c.w. between the cavities. Using this formula one can obtain the optimum $n = n_{opt}$ and $d = d_{opt}$ values, at which the accelerating gradient is maximum. The calculated values of d, n and the accelerating gradient are listed in the table for two β values: 0.17 and 0.35.

Table 1

$\Delta\phi$ (rad)		0.2	0.3	0.5	0.7	1.0
$\beta = 0.17$	n_{opt}	4.85	4.0	2.9	2.3	1.75
	d_{opt} (cm)	0.72	0.88	1.15	1.69	1.66
	$\frac{\Delta\mathcal{E}}{(d+\ell)I_0}\left(\frac{\text{MeV}}{\text{cm}\cdot A}\right)$	1.06	1.02	0.95	0.92	0.8
$\beta = 0.35$	n_{opt}	2.9	2.65	2.15	1.75	1.45
	d_{opt}(cm)	1.22	1.21	1.78	1.75	3.41
	$\frac{\Delta\mathcal{E}}{(d+\ell)I_0}\left(\frac{\text{MeV}}{\text{cm}\cdot A}\right)$	0.77	0.76	0.73	0.7	0.64

Since n can be only an integer, then the integral n values lying close to the ones listed in the table should be taken as optimum. It is for these values that d_{opt} and $\Delta\mathcal{E}/(d+\ell)I_0$ were calculated. It is seen from the table that generally n_{opt} values lie within the range from two to five, whereas for d_{opt} this range is from 0.7 to 2 cm. The accelerating gradient may reach relatively high values. For example, for $\beta = 0.17$, $\Delta\phi = 0.2$, $I_0 = 400$ mA, we have $\Delta\mathcal{E}/(d+\ell) \simeq 430$ keV/cm.

The experiment on the excitation of accelerating fields was performed as follows. The electron beam from the S-band linac[8] LU-40 was transmitted along the axis of the chain of 7 passive, loosely bound, cylindrical cavities tuned to the second harmonic of the bunch repetition frequency ($n = 2$). The cavity Q-factor was measured to be 10^4, $\beta = 0.35$.

The beam-excited electric field value was determined from electron energy losses, and also, from RF measurements.

During the experiments we measured the field and the energy of the particles that travelled along the cavity sequence versus the beam pulse current. First, the electron energy was measured for detuned cavities, which were then tuned to the $2\omega_0$ frequency and the energy measurements were repeated. By this way we could determine the energy losses in the cavities. Simultaneously, studies were made of the envelope of the beam-excited RF signal. As the beam current increased up to 200 mA, there occurred break-downs which disappeared after minor RF processing for different currents up to 400 mA.

The measured energy losses are shown in Fig. 1 together with the results of calculations by Eq. (3) for $\Delta\phi = 0$ and 0.7 rad. The figure shows good agreement between the measured and calculated data for $\Delta\phi = 0.7$ rad, the latter being a typical value of the accelerator. The highest energy losses at $I_0 = 400$ mA were found to be 4.6 MeV, which corresponds to a mean energy loss rate of 240 keV/cm and a maximum loss rate in each cavity of $\sim$ 330 keV/cm. In this case the highest field gradient on the axis was above 400 kV/cm (the difference between these quantities was due to the $\sin\alpha/\alpha$ factor). Figure 2 shows the measured energy losses as a function of the excited RF signal during the pulse. This function is also in agreement with the calculations.

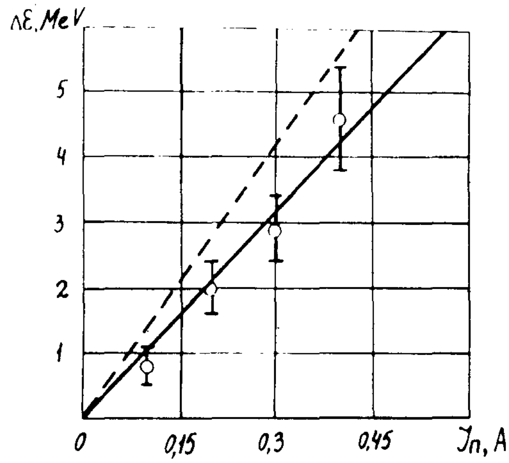

Fig. 1. Energy losses $\Delta\mathcal{E}$ versus the beam current I_0. The dots show the experimental data. The dashed and solid curves were calculated for $\Delta\phi = 0$ and $\Delta\phi = 0.7$ rad, respectively.

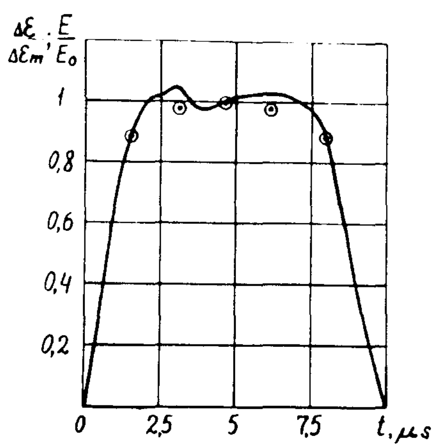

Fig. 2. Experimental time dependence of energy losses $\Delta\mathcal{E}/\Delta\mathcal{E}_M$ (dots) and the SRF field amplitude E/E_0 in cavities.

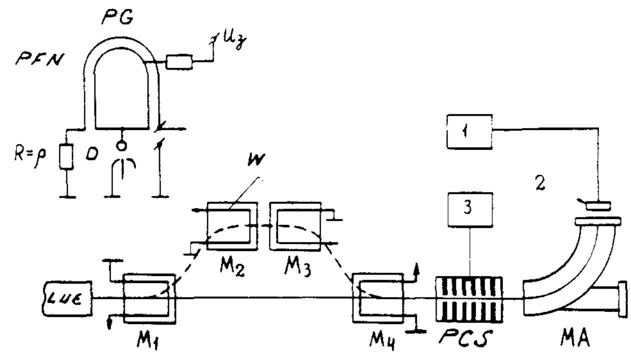

Fig. 3. Experimental arrangement. MA: magnetic analyzer of particle energy; PCS: passive cavity structure; M_1, M_2, M_3, and M_4: deflector magnets; LUE: linear accelerator; PG: pulse generator; PFN: pulse forming network; ρ: PFN wave impedance; R: loading impedance; D: discharger; W: magnet windings. 1: oscillograph; 2: Faraday cup; 3: meter of beam-induced SRF signals.

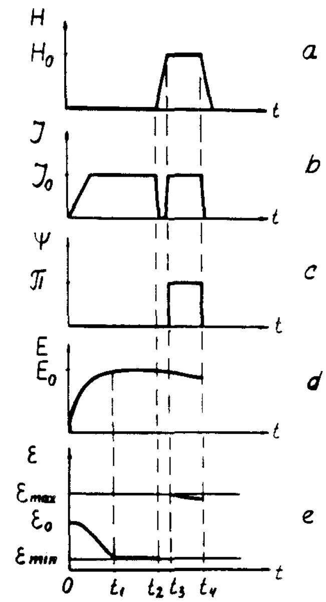

Fig. 4. Time-ordered diagram of: the magnetic field H in deflector magnets (a); beam current I in the passive cavity structure (b); particle phase with respect to the RF field in the passive cavities (c); electric field E amplitude in the passive cavities (d); the particle energy $\mathcal{E}$ (e).

Experiments on Phase Shift and Postacceleration of the Beam

The beam-excited field in the passive cavities naturally decelerates the beam. To accelerate the beam particles, it is necessary to have them phase shifted by 180°. This can be achieved by extending the particle trajectory using a system of pulsed magnets.[5] The advantage of this method is its fast action and, for this reason, it can be applied in our experiments.

The experimental system is shown schematically in Fig. 3. A chain of seven passive cavities described in the previous section was used as a passive cavity structure. The phase shift of the particles was accomplished by means of a short-pulse deflector system involving four ferrite magnets M_1, M_2, M_3, and M_4, which were fed from the pulsed generator. The magnetic field pulse length was 100 nsec.

The time-ordered diagram of the accelerating field excitation, phase shift and postacceleration is shown in Fig. 4. At the initial time $t = 0$ the deflector is in the switched-off position. To the moment when the deflector is on ($t = t_2$), the beam passes along the accelerator axis through the cavities (Fig. 4b), excites an electric field there (Fig. 4d) and loses its energy (Fig. 4e). At the time t_1 the field in the cavities reaches its maximum steady-state value E_0, while the particle energy decreases to the minimum value of $\mathcal{E}_{min}$. At $t = t_2$ the magnetic field in the deflector starts to rise (Fig. 4a). During the rise time ($t_2 < t < t_3$) the magnet M_1 deflects the beam so that it does not get into the passive cavity structure, on the other hand, the magnetic field value is insufficient to transport the beam throughout the deflector system. Therefore, at $t_2 < t < t_3$ the beam current in the passive cavities is zero (Fig. 4b) and the field there somewhat decreases at the expense of the final Q-factor. Since the duration of the rise time is much shorter than the time constant of the cavities ($2Q/n\omega_0$), then this falloff is insignificant. At the time $t = t_3$ the magnetic field in the deflector reaches its maximum (Fig. 4a) and the beam emerging from the deflector comes into the cavities (Fig. 4b) in the accelerating phase of the RF field $\psi = 180°$ (Fig. 4c) and is postaccelerated (Fig. 4e).

Experiments on postacceleration were performed at a pulse current of 200 mA. The developed technique of the beam transport ensured a 100% transmission of the beam through the deflector system for 100 ns, and the accelerated pulse current was also 200 mA.

Figure 5 shows: the measured energy spectrum of the accelerator beam with detuned resonators (curve 1), the spectrum of the beam decelerated in the passive cavities (curve 2) and the spectrum of the postaccelerated beam that passed through the deflector (curve 3). It is seen from the figure that the particle energy increased by ~ 1.8 MeV at the expense of energy losses by other particles (~ 2 MeV). The 0.2 MeV difference is due to some field decrease in the cavities during the magnetic field buildup in the deflector magnets. Somewhat lower energy losses in this experiment are explained by a larger bunch width. It is also seen from Fig. 5 that the spectrum width remains practically the same for the beam postacceleration regime. Thus, the deflector system changes little the phase width of the bunch.

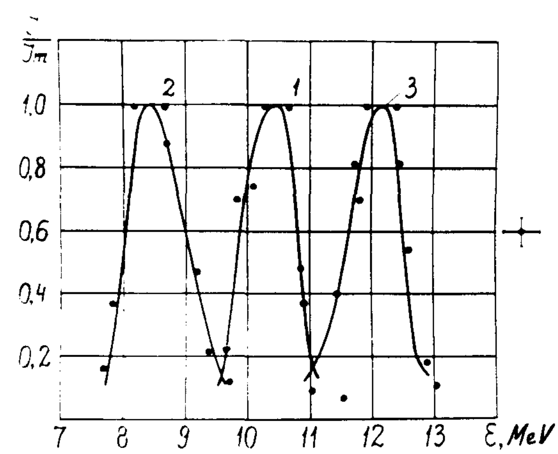

Fig. 5. Energy spectra of: 1: accelerator beam; 2: beam that lost its energy in passive cavities; 3: beam accelerated in passive cavities.

Conclusion

The results obtained show the postacceleration of linac beams through a chain of passive cavities to be a promising and feasible method. With a beam pulse current of 400 mA, a maximum intensity of the accelerating field above 400 kV/cm was obtained. The beam particles were quickly phase shifted by 180° due to the extension of the beam trajectory by a deflector system, which also ensured a 100% current transfer. An effective postacceleration of the beam has been realized.

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