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SHORT-PULSE ACCELERATION IN A
RACETRACK MICROTRON

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Electron pulses of a duration much shorter than the time constant of the linear accelerator have been accelerated in a racetrack microtron (RTM). As the pulses are short, part of the rf energy stored in the linac may be utilized so that the instantaneous beam power can well exceed the rf drive.

The experiments were made with the microtron described in ref. 1.

1.a. Experiments with short injection pulses

In these experiments, electron pulses of about 45 ns duration and 30 keV energy were injected from the diode electron gun into the linear accelerator. The linac was fed by rf pulses sufficiently long to ensure that the microwave fields had reached steady conditions before the injection took place.

After acceleration through 15 orbits to 50 MeV the extracted electron pulses were about 25 ns (FWHM) long and almost triangular in shape as shown in Fig. 1. The operation was very stable indeed.

The figure also contains the central part of a (positive) pick-up signal from the linac showing how the rf fields sag during acceleration of the heavy load and the recovery of the fields after the electrons have left the accelerator. (As the electron current is measured outside the microtron this pulse is delayed as compared to the linac response.)

Fig. 1. Oscillogram demonstrating short-pulse acceleration to 50 MeV

Horizontal scale: 100 ns/div.

Upper trace: Electron current, 10 mA/div.

Lower trace: Linac voltage, arbitrary scale.

The maximum current attained (peak of the triangle) at 50 MeV was 60 mA corresponding to a peak beam power of 3 MW, while the klystron output was 1.9 ± 0.15 MW; the uncertainty mainly arising from measurements of large attenuation factors.

This power, though partly spent on waveguide losses and mismatch reflexions, is much higher than what is needed for driving the accelerating voltage to the upper limit of the interval of stable phases (corresponding to a resonant phase of 122.5° ; see for instance ref. 2). The electrons in the initial part of the injection pulse therefore experience a linac voltage being too high and go lost. Nevertheless, they load the linac so that the voltage decreases and thus the rest of the electrons can be stably accelerated.

1.b. Estimation of the maximum electron pulse charge

Swain and Scott have shown (ref. 3) that even rather long $\pi/2$ -mode standing wave linacs rapidly respond to transients. Therefore, in this simple treatment, the short (25 cm) side-coupled linac of the actual RTM will be regarded as a single resonator concerning the transient behaviour.

The power absorbed by the linac is used for covering ohmic losses in the structure, increasing the oscillating rf energy, and accelerating electrons. Under resonance this is:

$$P_a = P_{str} + \frac{dW}{dt} + P_e = \frac{V^2 G}{2} + \frac{QG}{\omega} V \frac{dV}{dt} + \frac{I_e V \sin \phi_s}{2} . \quad (1)$$

Here V is the linac voltage, G its shunt conductance, and $Q = \omega W / P_{str}$ the unloaded Q -value. (The standard indices sh for G and o for Q and ω are omitted for simplicity.) The phase of the electron current load, I_e , is supposed to coincide with the synchronous phase, ϕ_s , of the accelerating voltage.

The equation can be written in a simplified way:

$$P_a = P_{str} (1+\gamma) = \frac{V^2 G}{2} (1+\gamma) . \quad (2)$$

On the other hand, neglecting all reactive components due to a possible detuning or to the moderate phase difference between beam current and linac voltage,

$$P_a = P_{str} \frac{\beta_o}{\beta} , \quad (3)$$

where β_o and β is the unloaded and loaded coupling coefficient respectively.

The last two equations give

$$\beta = \frac{\beta_o}{1+\gamma} . \quad (4)$$

The absorbed power can also be expressed in terms of the incident power and the reflexion coefficient:

$$P_a = P_i (1-\rho^2) = P_i \frac{4\beta}{(1+\beta)^2} , \quad (5)$$

which, together with the equations (2) and (4), gives

$$\sqrt{2P_i \beta_o G} = \frac{VG}{2}(1 + \beta_o + \gamma). \quad (6)$$

According to Eqs. (1) and (2) this is:

$$2\sqrt{2P_i \beta_o G} = V(1 + \beta_o)G + 2\frac{QG}{\omega} \frac{dV}{dt} + I_e \sin \phi_s. \quad (7)$$

This last expression can be illustrated by the following equivalent scheme:

Fig. 2. Scheme equivalent to Eq. (7).

$$I_g = 2\sqrt{2P_i \beta_o G}, \quad Y_o = \beta_o G, \\ C^G = QG/\omega, \quad I_b = I_e \sin \phi_s.$$

The equation (7) can now be simplified:

$$\frac{dV}{dt} + \frac{(1 + \beta_o)G}{2C} V = \frac{I_g - I_b}{2C}. \quad (8)$$

With the time constant, $\tau = 2C/[(1 + \beta_o)G]$, and the initial linac voltage, $V_o = I_g/[(1 + \beta_o)G]$, this becomes:

$$\frac{dV}{dt} - \frac{V_o - V}{\tau} = - \frac{I_b}{2C}. \quad (9)$$

In the case of a heavy load of short duration, the second term of Eq. (9), corresponding to the power fed to the

electrons directly from the rf source, is much smaller than the other ones. It may therefore be linearized in order that an integration over the time of interest yields

$$\Delta V + \frac{\Delta V/2}{\tau} T = - \frac{1}{2C} \int_0^T I_b dt. \quad (10)$$

The linac is loaded during a time, T , approximately equal to the time each electron spends in the microtron plus the electron pulse duration.

Insertion of the original symbols finally gives

$$\int_0^T I_e \sin \phi_s dt = -\Delta V \frac{G}{2} \left[\frac{4Q}{\omega} + T(1+\beta_o) \right], \quad (11)$$

where

$$T = T_{acc} + T_p \text{ as stated.}$$

Now, I_e is the first Fourier component representing the sharply bunched electron load of the linear accelerator and thus twice the bunch current averaged over the rf period. In a machine with M orbits the linac is loaded by the beams from, on the average, $M \cdot T_p / T$ of the orbits woven into each other, and therefore

$$I_e = 2 k M \frac{T_p}{T} I_p. \quad (12)$$

Here I_p is the beam current actually measured and k the power ratio between total and useful beam load. $k > 1$ as electrons are lost during the first revolutions.

Combining Eqs. (11) and (12) and replacing k and $\sin \phi_s$ by their average values gives the wanted formula, ready for computation:

$$\int_0^T I_p dt = \frac{-\Delta V \cdot G \left[\frac{4Q}{\omega} + T(1+\beta_o) \right]}{4M \langle k \rangle \langle \sin \phi_s \rangle}. \quad (13)$$

In the actual RTM this means that $\int_0^T I_p dt \approx 1.8 \cdot 10^{-9}$ As under the following assumptions:

Energy gain per turn: 3.33 MeV

Transit time factor: 0.90 (25 mm gaps)

ΔV corresponding to $122,5^\circ > \phi_s > 90^\circ$

$G = 10^{-6}/15$ mho

$Q = 12 \cdot 10^3$

$\omega = 2\pi \cdot 3 \cdot 10^9$ s⁻¹

$T = (85+25) \cdot 10^{-9}$ s

$\beta_0 = 3,2$

$M = 15$

$\langle k \rangle \approx 1.25$ (i.e. the same as for long pulses in this RTM)

$\langle \sin \phi_s \rangle \approx \frac{1}{2} (\sin 122,5^\circ + \sin 90^\circ)$

The true value of $\langle k \rangle$ and the limits of the synchronous phase under transient conditions are not known; the estimation is thus rough. Anyhow, it gives an idea of the pulse currents which can be attained.

Dividing the calculated pulse charge by the FWHM pulse duration gives the peak pulse current $I_p \approx 70$ mA as compared to the experimental value of 60 mA. Not very much more is likely to be found.

2. Experiments with long injection pulses

In a previous experiment, still at 50 MeV electron energy, 60 ns pulses of up to 44 mA intensity were obtained simply by specific trimming of the microtron.

The injection pulse is delayed, so that the linac voltage has reached a very high value when the injection starts. During build up of the injection current and voltage the increasing load gradually lowers the linac voltage till, suddenly, it reaches the upper limit of the stable interval. Then the load rapidly increases as more and more orbits are filled, and in a short time the linac voltage falls to and beyond the lower stability limit, where the acceleration ceases. In this way a short pulse is accelerated.

Now, if the rf pulse is long enough, the linac voltage will recover in the absence of the load from all the orbits and therefore enter into the stable interval from below, so that the acceleration process can start again. A new, less intense, electron pulse will be created and so on. This mechanism allows a few pulses of decreasing current to be accelerated until the linac voltage eventually reaches a steady value near the lower limit of the stability interval.

The process described is illustrated in Fig. 3, which shows the time variation of the injection current, the linac voltage, and the accelerated electron pulses respectively.

In order to reach 40 mA peak current at 50 MeV, i.e. 2 MW beam power, the necessary rf gross power was lower than 2.2 MW.

Fig. 3. Typical waveforms during short-pulse acceleration with long injection pulses.

Upper curve: Injection current.

Central curve: Linac voltage.

Lower curve: Current in accelerated beam.

Broken curves are resulting from rf pulses of full length, continuous curves from rf pulses shortened to give just one accelerated pulse.

The experiments reported here underline the great versatility of the racetrack microtron, whose compactness, moderate cost, and flexibility make it a very attractive accelerator.

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The experiments were made with the 55 MeV microtron at the Royal Institute.

Key words: Microtron, Racetrack microtron, Nanosecond pulses, Stored rf energy, Linear accelerator