A PRELIMINARY STUDY OF A VOLTAGE MULTIPLYING STRUCTURE FOR ELECTRON ACCELERATION

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1. INTRODUCTION

In [1], a double cavity structure has been proposed which is capable of accelerating a short burst of electrons after excitation by a pumping beam of low energy. The structure does not only exhibit an impedance transformation as in the wake – field accelerator [2], [3], but also shows an appreciable measure of pulse compression.

2. PRINCIPLE OF OPERATION

The device consists of two coupled cavities (fig. 1). The cavity traversed by the beam will be referred to as the *interaction cavity*, the other as the *storage cavity*. The accelerating cycle can be divided into three phases:

1. The intensity of the bunched pumping beam is smoothly raised until it reaches its final value I_B. During this time, it transfers energy to the interaction cavity. This cavity stores only a small part of this energy, but transports most of it to the storage cavity, until an equilibrium is reached, when power extracted from the beam only compensates for the cavity losses. The steady state voltage V_B across the interaction cavity and the ratio of the energies stored in both cavities depend on the coupling.

2. The pumping beam is switched off abruptly. This reverses the power flow between the cavities, and the stored energy starts to oscillate back and forth between the two. Half a period of this differential frequency later, all the energy has moved into the interaction cavity. As the voltage across the interaction cavity is proportional to the square root of the energy stored therein, this means a rise of the voltage to a much greater value V_{max}. A voltage gain V_{max}/V_B of 10 to 100 is realistic.

3. The beam to be accelerated is injected as a short burst at this first peak of V_{max}.

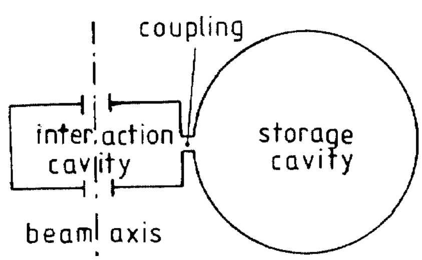

Fig. 1: *Arrangement of cavities*

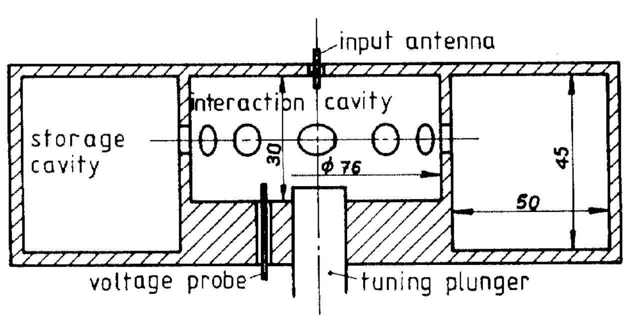

Fig. 2: *Test resonator*

3. EXPERIMENTAL RESULTS

To demonstrate the operation, a model structure has been tested (fig. 2). The interaction cavity is operated in the E_{010} – mode. It is surrounded by the storage cavity, which is shaped as a ring of rectangular cross – section. Its mode can be characterized as the E_{020} – mode of an equivalent cylindrical resonator. Coupling occurs via 12 oval shaped holes of 11 × 7.5 mm. The other dimensions can be taken from the figure. The beam is replaced by a short antenna at the center of the interaction cavity. A second one at the opposite side allows probing of the electric RF field. It is essential that coupling be weak, so that the Q – value of the inner cavity is not too much reduced. Unfortunately, this requirement can only be met imperfectly because of sensitivity problems. Thus Q_i is considerably reduced by the coupling to the probe (to about half its unloaded value). The measured data of the aluminium alloy cavities are

Q of storage cavity: $Q_s = 6000$, of interaction cavity: $Q_i = 2430$
operating frequency: $f_0 = 3$ GHz, frequency splitting: $\Delta f = 6.1$ MHz.

Measurements have been done by a homodyne system. The signal from the voltage probe is mixed with the unmodulated generator signal. Thus the phase of the amplitude relative to the input signal is also available at the mixer output. The result with a square wave modulated input signal is shown in fig. 3. The upper trace is the drive, the lower trace the electric field in the interaction cavity as measured at the mixer output. The voltage overshoot is about 10.

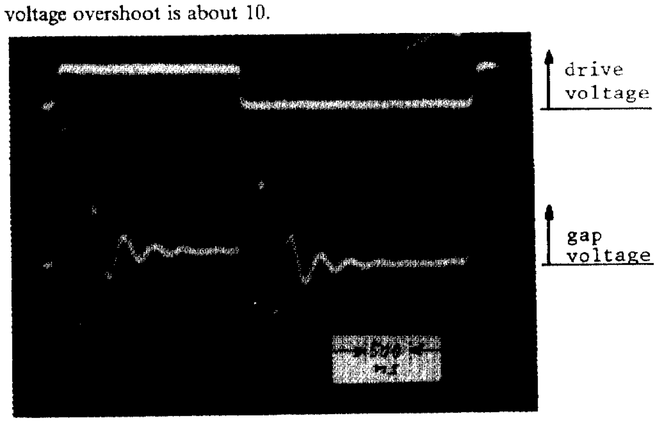

Fig. 3: *Transient behaviour with square – wave modulated signal*

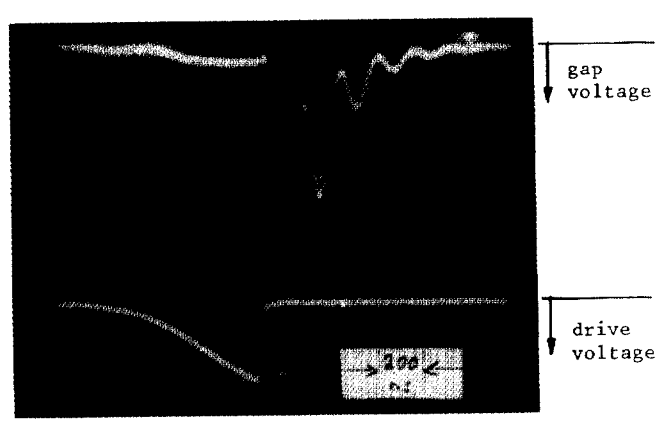

Fig. 4: *Transient behaviour with saw – tooth modulated signal*

It may be worth remarking that the cavity voltage features the 180° phase jump necessary to change from energy absorption to beam acceleration. The beam to be accelerated must therefore be injected with the same phase as the drive beam. Where both beams originate from the same gun, only an intensity change is required.

The first transient voltage peak at beam switch-on is of course undesirable. It is easily eliminated by turning up the drive intensity progressively as shown in fig. 4. The output signal is detected by a square-law detector instead of the mixer, polarity is negative. The upper trace is the detected signal, which is proportional to the negative square of the voltage, and the lower trace is the input wave. It can be seen, that the oscillations during switch-on are completely suppressed.

4. DESIGN CONSIDERATIONS AND POSSIBILITIES

In the following we give some guidelines and formulae for the parameters of the structure.

The two cavities are operated at their (uncoupled) resonance angular frequency ω_0. Coupling makes the energy oscillate between both with the beat angular frequency $\Delta\omega_r = 2\omega_r$ (the envelope of the voltage at one cavity oscillates with ω_r), and the loss is given by an exponential decrement $\sigma = (\omega_0/4)(1/Q_s + 1/Q_i)$ with Q_s and Q_i the Q-values of the storage and the interaction cavity. The interaction cavity should be operated with the maximum energy it can be expected to accept without breaking down. Calling this voltage V_{max}, and the characteristic impedance of the interaction cavity Z_0, this corresponds to a stored energy

$$W_i = V_{max}^2 / (2\,\omega_0 Z_0)\ . \tag{1}$$

A quarter beat period earlier, this energy plus some losses had been stored in the storage cavity, i.e.

$$W_s = W_i\, e^{2\sigma\pi/\Delta\omega_r}\ . \tag{2}$$

If there had been an equilibrium before switching off the beam, the beam would have had to supply only the cavity losses

$$P_B = V_B I_B / 2 = Z_B I_B^2 / 2 = \omega_0 W_s / Q_s\ , \tag{3}$$

if the energy stored in the interaction cavity is neglected. Z_B is the impedance the interaction cavity presents to the beam, i.e. the ratio V_B / I_B. Its value follows from the theory of coupled resonators, and for Q-values not too low it depends on the coupling strength as

$$Z_B \approx \frac{Z_0}{(\Delta\omega_r/\omega_0)^2\, Q_s}\ . \tag{4}$$

To analyze the transient process, we transform the equivalent circuit of the coupled resonators to a low-pass equivalent, i.e. we replace the frequency ω by $\omega - \omega_0$. Thus we regard only the envelope of the RF instead of the RF itself, and the beam becomes a modulated DC current source. The analysis is now performed by Laplace transformation. This yields for the voltage gain V_{max} / V_B ([4]):

$$k_\infty = V_{max} / V_B \approx (\Delta\omega_r / \omega_0)\, Q_s\, e^{-\sigma\pi/\Delta\omega_r}\ . \tag{5}$$

From eqs.(1) to (4) the necessary pumping beam current is

$$I_B \approx (\Delta\omega_r / \omega_0)(V_{max} / Z_0)\, e^{\sigma\pi/\Delta\omega_r}\ . \tag{6}$$

Eq.(5) shows that a large voltage gain k_∞ can be achieved either by a large Q_s or a strong coupling. In the latter case, however, the pumping current must also be made larger, and one has to find a compromise.

For a pillbox, $Z_0 = 242\,\Omega\, h/(\lambda/2) \approx 150\,\Omega$ with h the height of the cavity. Assuming a frequency of 3 GHz, a height of 3 cm, and a maximum RF field of 1 MV/cm, $V_{max} \approx 3$ MV. Fig. 5 shows the required pumping beam characteristics for different values of Q_s, calculated by the exact formulae. Voltage multiplication k_∞ and current I_B of the pumping beam are given as a function of the relative frequency splitting $\Delta\omega_r/\omega_0$. The Q-value of the interaction resonator, which does not appear in the formulae above, is assumed as $Q_i = 14000$.

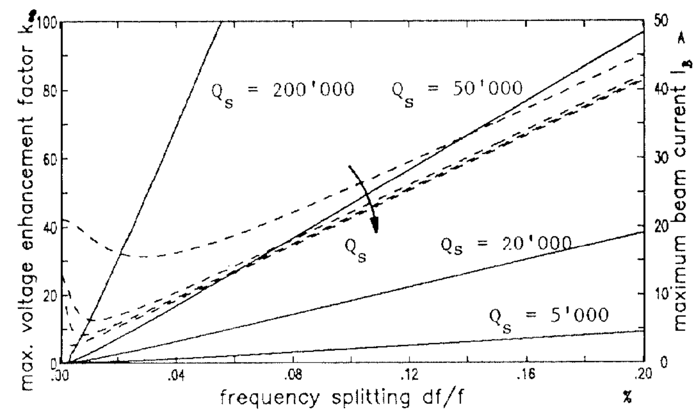

Fig. 5: Voltage enhancement factor and charging beam current ($Q_i = 14000$), ——— k_∞ – – – – I_B

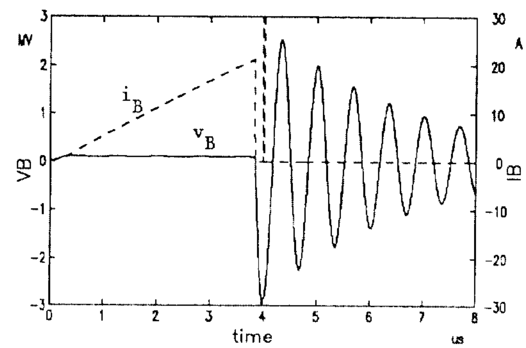

Fig. 6: Cavity voltage and beam current for finite charging time ($Q_i = 14000$, $Q_s = 200000$, $f_0 = 3$ GHz, $\Delta f / f_0 = 10^{-3}$, $k = V_{max}/V_0 = 30$)

Let us now consider a charging time so short that the above mentioned equilibrium is not reached, so that the storage cavity is still being charged when the beam is switched off. During the charging period, the power of the beam feeds the storage cavity and its losses:

$$p_B(t) = \frac{v_B(t)\, i_B(t)}{2} = \frac{dW_s(t)}{dt} + \frac{\omega_0}{Q_s} W_s(t)\ . \tag{7}$$

The beam must not be switched on abruptly, because this would yield an unwanted overshoot like that after switch-off. To avoid this, the beam current $i_B(t)$ must be raised gradually. The voltage drop $v_B(t)$ across the interaction cavity depends on $i_B(t)$ and its derivatives. The exact analytical solution is again evaluated by Laplace transformation, it consists of the superposition of several exponentials. An example is shown in fig. 6.

For the sake of simplicity, this function can be approximated by a linear ramp rising from zero to I_B after the charging time T_c, whereas $v_B(t) = V_0$ does not depend on time. Thus the energy after the charging period is

$$W_s(T_c) \approx \frac{V_0 I_B T_c}{4} \frac{2Q_s}{\omega_0 T_c} \left[1 - \frac{Q_s}{\omega_0 T_c} \left(1 - e^{-\omega_0 T_c/Q_s} \right) \right]\ . \tag{8}$$

After switching off, the same voltage V_{max} is achieved as in the case of infinite charging time (eq.(5), which holds also approximately in this case), it depends only on the maximum drive current I_B. Because the stationary state has not been reached, the drive voltage is $V_0 > V_B$, so that the voltage gain $k = V_{max} / V_0 < k_\infty$. To find the charging time T_c, eq.(8) with

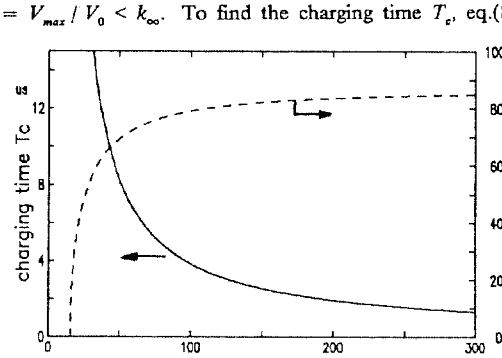

Fig. 7: Charging time and charging efficiency vs. charging voltage (data as in fig. 6; $V_{max} = 3$ MV, $V_B = V_{max}/k_\infty = 15.9$ kV, $I_B = 21.3$ A)

eq.(6) must be equated to eq.(2) with eq.(1). This yields a transcendental equation for T_c:

$$\frac{Q_s}{\omega_0 T_c}\left(1 - e^{-\omega_0 T_c/Q_s}\right) \approx 1 - \frac{V_{max}}{V_0}\,\frac{e^{\sigma\pi/\Delta\omega_r}}{Q_s \Delta\omega_r/\omega_0}\,. \tag{9}$$

Fig. 7 shows the charging time T_c as a function of the voltage V_0 for a practical example.

5. ENERGY CONSIDERATIONS

Concerning the balance of energy, a figure of practical importance is the part of drive beam energy which is available in the interaction cavity when the main beam is injected. It is given by

$$\eta_{d\to c} = \frac{2Q_s}{\omega_0 T_c}\left[1 - \frac{Q_s}{\omega_0 T_c}\left(1 - e^{-\omega_0 T_c/Q_s}\right)\right] e^{-2\sigma\pi/\Delta\omega_r} \tag{10}$$

and is in the order of 70 to 90 %. The first term is the loss whilst the storage cavity is charged, and the exponential term the loss during the energy transport from the storage cavity to the interaction cavity. This efficiency is also shown in fig. 7. Using a superconducting storage cavity yields neglegible loss during charging, but it has no large effect on the flow−back of the energy, because σ is governed by the lower of the two Q−values. The only way for improvement is by reducing the time for this procedure, i.e. the beat frequency and hence the coupling must be large. On the other hand, this leads to a high charging current.

Of the available energy, only a small portion can be extracted by the beam, because beam loading is limited by the acceptable energy dispersion. Thus it would be desirable to make use of the energy remaining in the system. There are two possibilities to do so: Either the next charging period starts immediately after one beat cycle, or a second drive beam is injected, which extracts the energy and returns it to a large superconducting storage resonator, which is part of the drive beam accelerating system. In both cases, timing and shape of the drive beam have to be adjusted such that the voltage is constant.

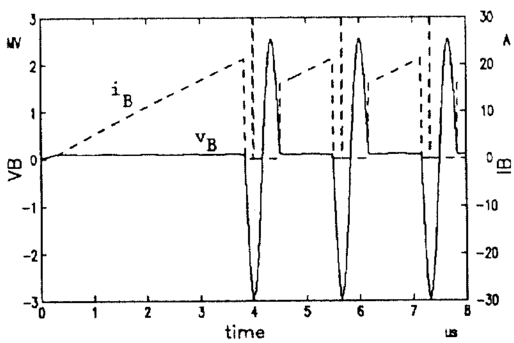

Fig. 8: Cavity voltage and beam current with recharging (data as in fig. 6)

Fig. 8 shows the result of a simulation for the first case. After a quarter beat period, the main beam extracts a certain amount of energy (10% in this example). After one beat period, the drive beam is switched on with a well−defined function of its current versus time. As can be seen, this second charging interval is shorter than the first one because it starts with the residual energy of the first cycle. In a steady state, the pattern of this second cycle will be repeated.

According to eq.(10), one can define a second efficiency concerning the loss between the voltage maximum and the start of the next charging period. As this time is about 3/4 beat period, it is

$$\eta_{c\to d} \approx e^{-6\sigma\pi/\Delta\omega_r} \tag{11}$$

One can also switch on the drive beam half a beat period earlier, with some gain in efficiency, but with the need to reverse phase.

Fig. 8 also shows that the period between the pulses is rather short, in the order of several μs. As the charging current is fixed by eq.(6), the only way to feed the required energy in a longer time is lowering the voltage. This charging voltage is, however, limited to values smaller than V_{max}/k_{co}. Only with superconducting storage cavities pulse intervals as long as 0.1 .. 1 ms can be achieved. In order to keep losses low during the beat oscillation, the coupling constant cannot be considerably reduced, and so the current is still large (eq.(6)). Maintaining a beam current of several amperes,

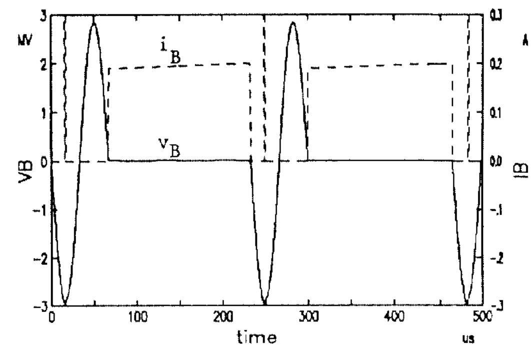

Fig. 9: Cavity voltage and beam current with recharging (superconducting cavities: $Q_i = 10^9$, $Q_s = 10^9$, $f_0 = 3$ GHz, $\Delta f/f_0 = 10^{-5}$, $k = V_{max}/V_0 = 300$)

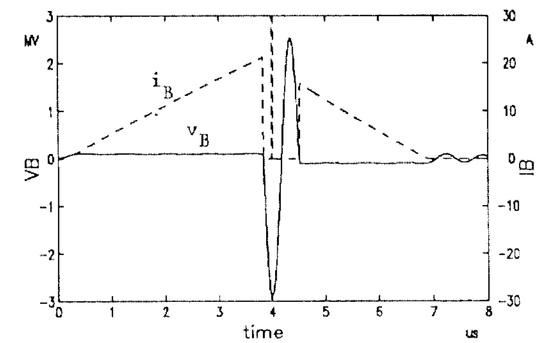

Fig. 10: Cavity voltage and beam current with deceleration (data as in fig. 6)

even if it does not deliver much power, in a nearly CW mode may, however, be inefficient. This can be avoided by also making the interaction cavity superconducting. Then all losses are neglegible, and one can make the coupling so weak that a drive beam current of the order of 0.1 A is sufficient. An example is given in fig. 9.

The second possibility is to empty the cavities by a second drive burst. Fig. 10 shows how this may work. The drive beam is injected a short time later as in the former case, so that voltage and current are opposite in phase. This means that it extracts power. The residual energy after switching off the drive beam is dissipated, but this is only a neglegible part. Assuming the same efficiency for charging and discharging, we get

$$\eta_{c\to d} \approx \eta_{d\to c}\, e^{-4\sigma\pi/\Delta\omega_r} \tag{12}$$

We can also switch half a beat period earlier with inverted phase. Then $\eta_{c\to d} \approx \eta_{d\to c}$.

The part left from the power of the driving bunches after one cycle is given by the product $\eta_{c\to d}\cdot\eta_{d\to c}\cdot\eta^2_{beam}$, where η_{beam} accounts for the incomplete transition of energy between drive beam and cavity because of the excitation of higher order modes. Assuming $\eta_{beam} \approx 95$ %, the efficiency in the example of fig. 10 is 44 %. If the discharging drive beam is switched on half a period earlier, this figure rises to 56 %. This means that an improvement by a factor of about 2 is possible.

6. CONCLUSION

An accelerating structure was proposed which is fed by a drive beam and stores its energy during a short period. It is then available for acceleration at a much higher voltage level. Thanks to the pulse compression the drive beam current need not be excessively high, it is of the same order of magnitude as that of the accelerated beam. Energy recuperation schemes are possible and allow a power saving of about 50 %.

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