A Short Pulse Two-Beam Accelerator with Energy Recuperation

H. Henke[1]

1) Technische Universitaet Berlin, EN 2,
Einsteinufer 17, D-10587 Berlin

Abstract

In view of the recent results on the high gradient limit at longer RF pulses an old idea is taken up again which allows for very short pulses. It is a two-beam accelerator were the cavities of the drive and main beam are directly coupled such that a beating process can take place. Depending on the frequency and coupling RF pulses below 1 ns are possible. Although the device is essentially a single bunch machine with correspondingly low efficiency, an energy recuperation scheme or a multi-bunch operation can be incorporated which brings the efficiency in the range of 10 % or even above.

1. Introduction

The recent results on the high gradient operation at SLAC and CERN showed very hard limits for the peak surface field in the range of 300 to 400 MV/m, see e. g. [1], [2], [3]. The limiting physical effects are: RF breakdown and pulsed surface heating leading to material fatigue. The steps undertaken to cure the problem are manifold from redesigning the geometry of the structure to the use of other material than copper. Shortening the pulse length down to the range of one nanosecond would certainly be the most effective cure, but then the questions would be how to create such short pulses and how to increase the efficiency of a single-bunch machine.
Here, an old idea is taken up again [4], [5] where very short pulses are possible, even below 1 ns. It is a two-beam accelerator with tightly coupled main and drive beam cavities such that beating between the cavities occur. A first drive bunch deposits energy in the drive cavity. This energy is rapidly transferred to the main cavity through the beat-wave mechanism. After acceleration of a main linac bunch the leftover energy swings back into the drive cavity and is taken out by a second drive bunch. The length of one beating bump can be as low as a few RF cycles and the repetition rate is determined by the time structure of the drive beam. Obviously, such a single bunch machine has a low efficiency. Different measures are possible to increase the efficiency by one order of magnitude. One possibility is to put subsequent drive bunches of much lower charge on an RF phase were the beating is not stopped but continues. Then, the main beam will have multi bunches at a distance of one beat period. Another solution is energy recuperation. The first drive bunch which charges up the drive cavity and the second bunch which empties it pass through a superconducting cavity whose wavelength corresponds to twice the beat period. In that way the first bunch will be reaccelerated and the second decelerated. All the energy left in the coupled cavity system is recuperated.

2. Beat-Wave Transformer Principle

In a two-beam accelerator a high current low energy beam charges up a drive structure. The energy is then transferred to the main accelerating structure in order to accelerate a low current high energy beam, Fig. 1. The drive structure is a low impedance structure and the main structure a high impedance structure, thus the high current drive beam can be transported and a voltage ratio between the two beams is obtained, i. e. the drive beam looses less energy than the main beam gains. The energy transfer between the structures can be done in different ways. Here, a beat-wave process is proposed. This requires a direct coupling between the two structures.

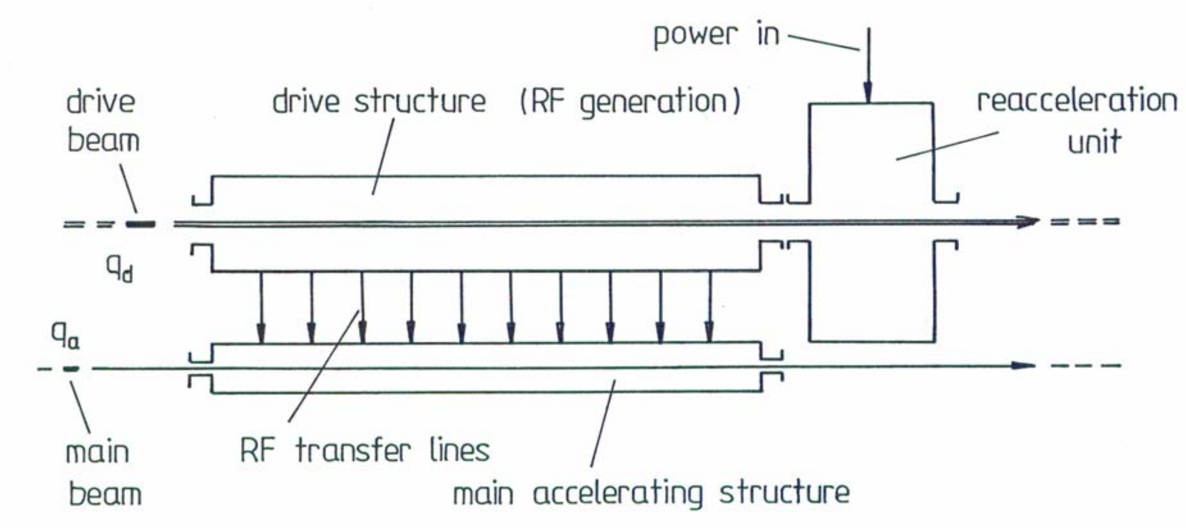

Figure 1: Schematic view of a two-beam accelerator period.

Let us first describe the principle by two tightly coupled resonant circuits, Fig. 2 a. If the uncoupled circuits have a resonance frequency ω and if the coupling strength κ is small, the coupled system has resonances at

$$\omega_0 = \omega\,(1 + \kappa/2)$$
$$\omega_\pi = \omega\,(1 - \kappa/2) \qquad (1)$$

with modes

$$\begin{bmatrix} v_{do} \\ v_{ao} \end{bmatrix} = \begin{bmatrix} D\cos\omega_o t \\ A\cos\omega_o t \end{bmatrix} e^{-\omega t/2Q}, \quad \begin{bmatrix} v_{d\pi} \\ v_{a\pi} \end{bmatrix} = \begin{bmatrix} D\cos\omega_\pi t \\ -A\cos\omega_\pi t \end{bmatrix} e^{-\omega t/2Q}, \qquad (2)$$

where $2/Q = 1/Q_a + 1/Q_d$ determines the Q-value of the system. Now, when one circuit, e. g. the d-circuit, is excited by a current pulse both modes (2) are excited and wringing between the two circuits will take place, Fig. 2 b.

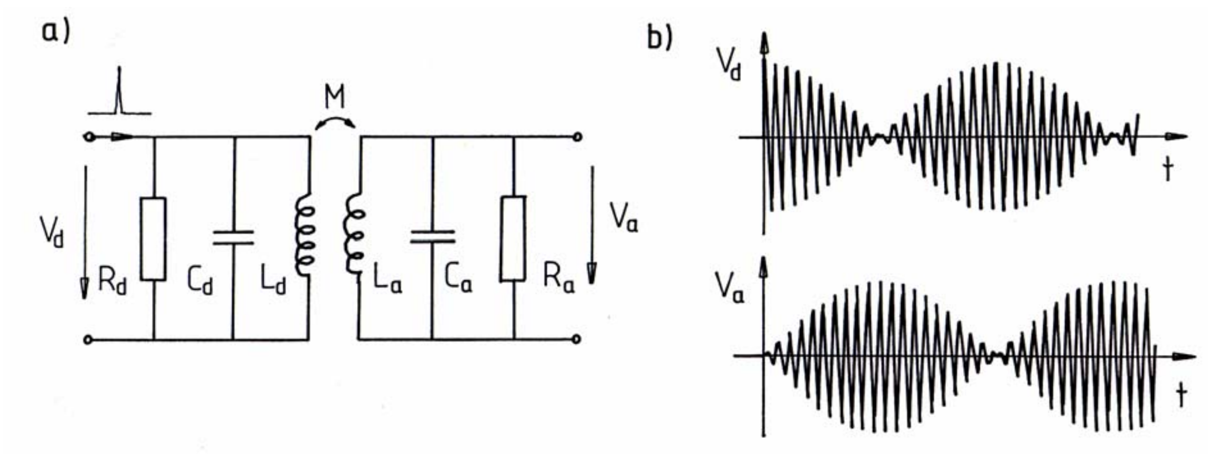

Figure 2: a) Equivalent circuit of two coupled resonators. b) Voltages across the resonant circuits after pulse excitation of circuit d.

In case of a linac two standing wave structures are coupled side-by-side, either every cell or every n-th cell. The structures are operated in a flat π-mode such that no or only very little energy travels in longitudinal direction. A first drive bunch shock excites the drive structure and the beating starts. When all of the stored energy is in the accelerating structure a main bunch can be accelerated and the left-over energy swings back in the drive structure. Now, a second drive bunch, a 180° out of phase, takes the energy out. The structures are completely empty and power was dissipated only during a beat-period which may be as short as a few ten RF cycles. The energy stored in the drive beam can easily be recuperated by passing through a superconducting cavity, Fig. 1, whose wavelength is equal to twice the beat period. If properly phased, the first drive bunch will now be reaccelerated and the second drive bunch decelerated. Different variations of the basic scheme are possible and are mentioned later.

3. Parameter Estimates

Before starting with the device parameters we introduce the loss-factor formalism.

A bunch of charge q going through a cavity looses the energy

$$W_0 = k_0 q^2 = \frac{1}{2} V_0 q \tag{3}$$

in the fundamental mode. Here, k_0 is the loss-factor, V_0 the voltage across the cavity and the factor 1/2 comes from the fundamental beam-loading theorem [7]. From (3) and the definition of R-upon-Q follows

$$\left(\frac{R}{Q}\right)_0 = \frac{V_0^{\,2}}{\omega W_0}$$

$$V_0 = 2k_0 q, \qquad k_0 = \frac{V_0^{\,2}}{4W_0} = \frac{\omega}{4}\left(\frac{R}{Q}\right)_0. \tag{4}$$

Now, let us consider the system of coupled structures. A drive bunch q_d charges up the drive structure and looses the energy

$$W_{tot} = B_d W_d, \tag{5}$$

with the beam-loading enhancement factor

$$B_d = \frac{\text{energy lost in all modes}}{\text{energy lost in fundamental mode}}. \tag{6}$$

From (3), (4) and (5) follows therefore that the bunch experienced the decelerating voltage

$$V_{dec} = \frac{1}{2} B_d V_d \text{ with } V_d = 2k_d q_d \tag{7}$$

and provided the stored energy

$$W_d = k_d q_d^{\;2} \tag{8}$$

in the fundamental mode. After half a beat period

$$\frac{1}{2}T_b = \frac{\pi}{\kappa\omega} \tag{9}$$

the energy will have decayed a little and will be transferred in the main structure

$$W_a = W_d e^{-\pi/\kappa Q} = k_d e^{-\pi/\kappa Q} q_d^2 \tag{10}$$

creating an accelerating voltage

$$V_a = 2\sqrt{k_a W_a} = 2\sqrt{k_a k_d}\, e^{-\pi/2\kappa Q} q_d\,. \tag{11}$$

(11) together with (7) and (4) define the voltage transformer ratio

$$\frac{V_a}{V_{dec}} = \frac{2}{B_d}\sqrt{\frac{k_a}{k_d}}e^{-\pi/2\kappa Q} = \frac{2}{B_d}\sqrt{\frac{(R/Q)_a}{(R/Q)_d}}e^{-\pi/2\kappa Q}\,. \tag{12}$$

With the extraction efficiency, i. e. the fraction of energy taken out by the main bunch,

$$\eta_{ext} = \frac{V_a q_a}{W_a} = 2\sqrt{\frac{(R/Q)_a}{(R(/Q)_d}}e^{\pi/2\kappa Q}\,\frac{q_a}{q_d} \tag{13}$$

we define a transfer efficiency

$$\eta_t = \frac{V_a q_a}{V_{dec} q_d} = \frac{\eta_{ext}}{B_d}e^{-\pi/\kappa Q}\,. \tag{14}$$

It is the ratio of the energy extracted by the main beam to the energy lost by the drive beam.

As an example we take

f = 30 GHz, κ = 0.02,

$$\left(\frac{R'}{Q}\right)_a = 22k\Omega/m,\ \mathrm{Q_a} = 8000,\ \left(\frac{R'}{Q}\right)_d = 300\Omega/m,\ Q_d = 3500$$

and $B_d = 1.01$ which is a reasonable value in a multi-cell structure and for a drive bunch length of about half a wavelength. Then Q = 4870 and $\eta_t = 0.96 \cdot \eta_{ext}$, that is the transfer efficiency equals the extraction efficiency which for linear colliders is in the range of one percent. The voltage transformer ratio is

$V_a / V_{dec} = 16.7$.

4. Energy Recuperation

We repeat the sequence of events as described above. A first drive bunch q_{d1} fills the initially empty drive structure. The deposited energy is transferred into the accelerating structure and a charge q_a is accelerated. The left-over energy, equ. (10) minus the extracted energy, decays further and swings back into the drive structure to a value

$$W_{d2} = \left(1-\eta_{ext}\right) k_d e^{-2\pi/\kappa Q} q_{d1}^2 \tag{15}$$

where it creates a voltage

$$V_{d2} = 2\sqrt{k_d W_{d2}} = 2k_d \sqrt{1-\eta_{ext}}\, e^{-\pi/\kappa Q} q_{d1} \tag{16}$$

Now, a second drive bunch q_{d2} passes the drive structure, 180° out of-phase, and if the charge is right it empties the structure. The condition for the right charge is that the bunch induced voltage should equal Vd_2

$$2k_d q_{d2} = V_{d2}$$

or

$$q_{d2} = \sqrt{1-\eta_{ext}}\, e^{-\pi/\kappa Q} q_{d1}\,. \tag{17}$$

Both structures are empty, see Fig. 3. For energy recuperation, the first drive bunch which was decelerated passes the superconducting recuperation cavity at a positive phase and will be reaccelerated. The second drive bunch which was accelerated passes the cavity half an RF period later and will be decelerated. The voltage envelopes of the structures and the recuperation cavity are shown in Fig. 3. Between pulses the recuperation cavity is charged up to full level by a cw klystron.

The transfer efficiency in that case is the energy extracted by q_a divided by the energy delivered by q_{d1} plus the energy pumped into higher order modes by q_{d2} minus the energy taken out by q_{d2}

$$\eta_{trec} = \frac{V_a q_a}{V_{dec} q_{d1} + \left(B_d - 1\right) k_d q_{d2}^2 - W_{d2}} = \frac{\eta_t}{\Delta} \tag{18}$$

with $\Delta = 1 - \left(\frac{2}{B_d} - 1\right)\left(1-\eta_{ext}\right) e^{-2\pi/\kappa Q}$.

The transfer efficiency with recuperation is $1/\Delta$ times larger than without recuperation. In the example of § 3 with $\eta_{ext} = 0.01$ it is

$\Delta = 0.09$ or $1/\Delta = 11$ and $q_{d2} = 0.96\, q_{d1}$.

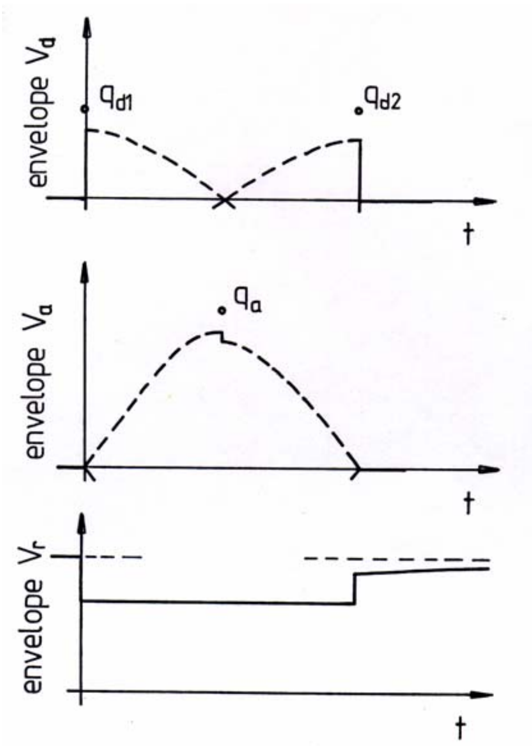

Figure 3: Bunch sequence and voltage envelopes in the drive structure (V_d), accelerating structure (V_a) and recuperation cavity (V_r).

5. Multi-Bunch Operation

Instead of energy recuperation one can also use a multi-bunch operation. A first drive bunch q_{d1} fills the drive structure, while subsequent drive bunches q_{d2}, now at the right phase, replenish just the energy which was taken out by the main bunch and which was dissipated, see Fig. 4.

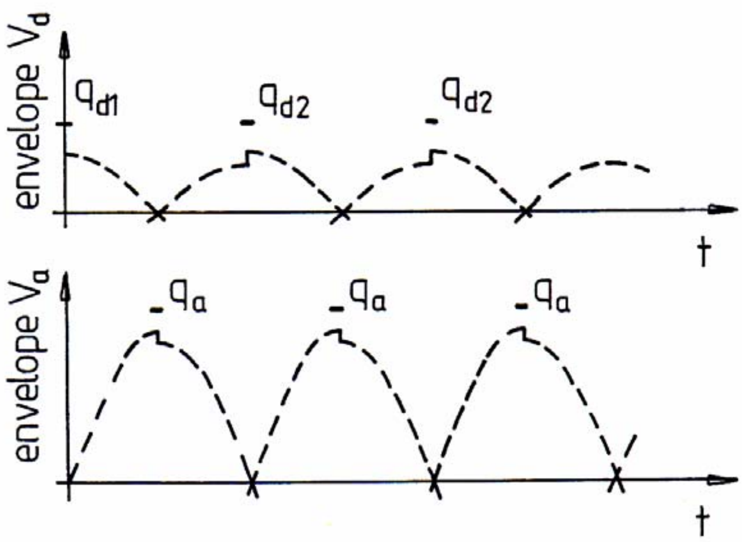

Figure 4: Voltage envelopes in the drive structure (V_d) and accelerating structure (V_a) together with trains of drive and main bunches.

The task of the drive bunches q_{d2} is to bring the voltage V_{d2}, equ. (16), back to its original value $V_{d1} = 2k_d q_{d1}$, that is

$$2k_d q_{d2} = V_{d1} - V_{d2} = 2k_d \left(1 - \sqrt{1-\eta_{ext}}\, e^{-\pi/\kappa Q}\right) q_{d1}$$

or

$$q_{d2} = \left(1 - \sqrt{1-\eta_{ext}}\, e^{-\pi/\kappa Q}\right) q_{d1}. \tag{19}$$

Now, in case of N main bunches the transfer efficiency is the ratio of the energy taken out by the main bunches over the energy delivered by q_{d1} plus the energy delivered by N-1 bunches q_{d2} into the fundamental mode and into the higher modes

$$\eta_{tmb} = \frac{N V_a q_a}{V_{dec} q_{d1} + (N-1)\left[V_{d2} + \frac{1}{2}(V_{d1} - V_{d2})\right] q_{d2} + (N-1)(B_d - 1) k_d q_{d2}^2} = \eta_t \frac{N}{1 + (N-1)\Delta} \tag{20}$$

with

$$\Delta = \frac{1}{B_d}\left[1 - (1-\eta ext) e^{-2\pi/\kappa Q} + (B_d - 1)\left(1 - \sqrt{1-\eta_{ext}}\, e^{-\pi/\kappa Q}\right)^2\right].$$

Again, for the example in § 3 and for $\eta_{ext} = 0.01$, we obtain

$q_{d2} = 0.037\ q_{d1}$, $\triangle = 0.071$,

which in case of 50 bunches yields $\eta_{tmb} = 11.2\ \eta_t$. A pure multi-bunch operation results in about the same as a single-bunch machine with energy recuperation. But still due to the beating process with a continuously changing field level and the standing wave operation high gradients might be easier achievable than in a standard multi-bunch travelling wave machine.

6. Train of Drive Beam Bunchlets

The scheme as described above has one big problem that is the energy spread in the drive bunches. If one charges the drive structure with a single bunch up to a voltage V_d this voltage appears as an energy spread along the bunch.

Fortunately, it turned out [6] that a train of drive bunchlets excites the beating process very much in the same way as a single bunch. While the bunchlets slowly charge up the drive structure the beating starts already and when the voltage in the accelerating structure is at its peak value V_d is zero, Fig. 5. At that instant the charge in the drive bunchlets is slightly reduced, as can be seen from i_d in Fig. 5, in order to match better the lower stored energy. Then, the energy swings back and creates a V_d 180° out of phase. The envelope of V_d is very closely sinusoidal, within a few percent. That means, the first half of the train of drive bunchlets is decelerated and the second half accelerated. If the sinusoidal variation of V_d fits the wavelength in the superconducting recuperation cavity a high degree of energy recovery can be achieved. The energy spread along the bunchlets is now only given by the differential voltage increase between bunches. Other advantages are

- a reduced peak current
- an additional factor of 2 in the voltage transformer ratio
- a clearer drive beam spectrum and therefore a reduced B_d.

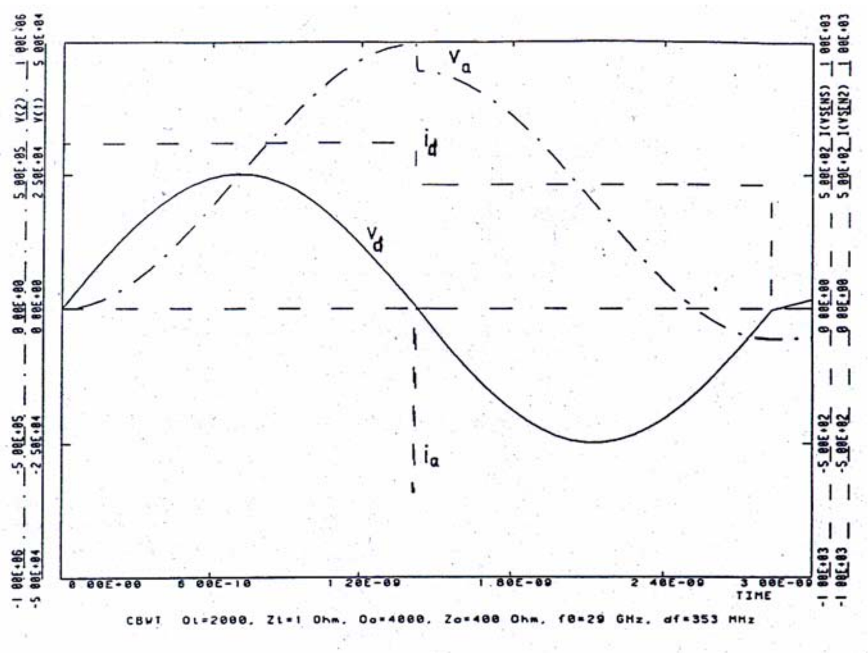

Figure 5: Envelopes of structure voltages and drive beam current.

References

[1] C. Adolphsen, SLAC-PUB-9906, Sept. 2003.
[2] H. H. Braun, S. Döbert, I. Wilson and W. Wuensch, CLIC Note 576, June 2003.
[3] W. Wuensch, CLIC Note 593, March 2004.
[4] H. Henke, CERN-LEP-RF/88-04 and CLIC Note 59, March 1988.
[5] H. Henke, CERN-LEP-RF/88-55 and CLIC Note 81, November 1988.
[6] Ch. Schieblich, CERN/PS 89-34 and CLIC Note 94, April 1989.
[7] P. B. Wilson, SLAC-PUB-2884, February 1982.