THE RESONANT WAKE FIELD TRANSFORMER CONCEPT FOR PARTICLE ACCELERATION

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Abstract

In a modified version of the *Wake Field Transformer*, which we call the *Resonant Wake Field Transformer*, a train of many bunches in a hollow driver beam excites the transformer cavity. The accelerator consist of a pulsed, low frequency driver and a transformer. The driver may be a pulsed, normal conducting cavity structure, a superconducting cw structure or an induction accelerator. The hollow driver beam passes through the cavity with a timing such that the energy distribution over the bunches is a linear ramp. Subsequently, this bunch train excites a high frequency wake field transformer resulting in a field strength of 100 MV/m generated on axis. This scheme combines the features of the relativistic klystron with those of the wake field transformer concept. The major advantage of such a system is the relatively low charge density in the driving beam bunches, which corresponds to numbers actually achieved in the DESY experiment.

Introduction

For e^+-,e^--linear colliders, new acceleration techniques are necessary to create the desired high accelerating gradients of more than 100 MeV/m. The principle of using transient wake fields [1] and the *Wake Field Transformer* experiment at DESY have been described in detail in other papers ([2] and references therein).

In a special *Wake Field Transformer*, a hollow driving beam (ring) of high charge (1 μC), with a small ring thickness of 4 mm and diameter of 10 cm excites wake fields which are spatially focused to the centre. Inside this transformer, a high energy beam can be accelerated with a gradient of up to 200 MeV/m. In translating this idea into an experiment at DESY, we achieved a lower charge divided into six somewhat longer bunches. With this, the first measured accelerating gradient of 8 MeV/m was more than the expected value for one bunch ($q \approx 100\,\mathrm{nC}$). This can be explained by the resonant superposition of the wake fields of all six bunches. The combination of resonant energy accumulation together with the transformer idea may be called another kind of a *Relativistic Klystron* [3,4,5]. One advantage of the resonant transformation scheme is the relatively low charge density necessary which has already been achieved in the experiment. The combination of rf-output and beam acceleration in the same cavity avoids phasing problems. With solenoid focusing, a large energy spread of the driving beam can be accepted. The idea of resonant excitation has initiated many activities for producing more bunches experimentally as well as designing and optimizing a *Resonant Wake Field Transformer*, the topic of this paper.

Theoretical Considerations

Many proposed acceleration techniques for a future 1-TeV linear collider make use of a driving beam to excite rf fields for a high gradient linac. Before we discuss the *Resonant Wake Field Transformer*, let us consider the general scheme shown in Figure 1.

A driving beam consisting of a train of N bunches with charge q is first generated by a preaccelerator with frequency $f_0 = 1/\Delta t$, and is further accelerated in a cavity with frequency f_1, quality factor Q_1, loss parameter per unit length k_1',[1] and total length L_1 (these parameters characterize the cavity completely [6]). Then the driving beam is decelerated in a second cavity, with parameters f_2, k_2', Q_2 and L_2, where it excites rf fields, that accelerate the main beam up to the final energy of 1 TeV.

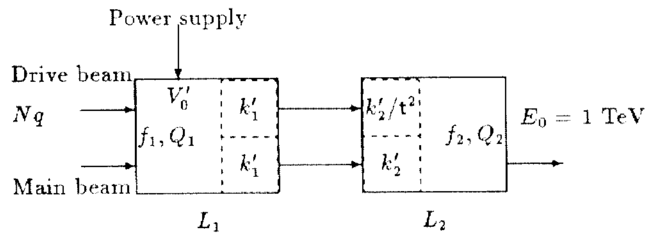

Figure 1 : General scheme of a colinear, two-beam system. A driving beam consisting of a train of N bunches with charge q is accelerated in the first cavity with frequency f_1, loss parameter per unit length k_1' and total length L_1. Then the drive beam is decelerated in a second cavity with parameters f_2, k_2'/t^2, Q_2 and L_2, where it excites rf fields, accelerating the main beam up to 1 TeV. The loss parameter on axis is k_2', and t is the transformer ratio.

The m-th bunch enters the first cavity at time $t_m = t_0 + m\Delta t$, and injection phase $\phi_m = \phi_0 + m\Delta\phi$. So for a given phase shift $\Delta\phi$ from one bunch to the next, f_1 has to be chosen as $f_1 = (1 + \Delta\phi/(2\pi))/\Delta t$. We assume that the first cavity is raised up to a voltage V_0' by a power supply before the first bunch enters the cavity.

Then the (complex) voltage in the first cavity as a function of the bunch number is given by :

$$V_1'(m) = V_0'\exp(i\phi_0 + im\Delta\phi)\exp(-m\Delta t/\tau_1) - 0.5V_{1B} - V_{1B}\sum_{n=1}^{m-1}\exp(in\Delta\phi)\exp(-n\Delta t/\tau_1) \quad (1)$$

With $\omega_1 = 2\pi f_1, \tau_1 = 2Q_1/\omega_1, V_{1B} = 2k_1'q$.

The actual accelerating voltage, seen by the m-th bunch is:

$$V_B'(m) = Re[V_1'(m)] - qk_{par}'(\sigma) \quad (2)$$

The parasitic loss parameter $k_{par}'(\sigma)$ [6] characterizes the losses to higher modes in the driver cavity which depend on the rms bunch length σ .

The energy transfer efficiency from the first cavity to the driving beam is given by the energy in the beam bunches divided by the energy stored in the driver cavity before the driving beam enters it:

$$\eta_{1\to B} = q\sum_{m=1}^{N} V_B'(m)/W_0' = 2\alpha\ (1/N)\sum_{m=1}^{N} V_B'(m)/V_0' \quad (3)$$

$W_0' = V_0'^2/4k_1'$ is the stored energy per unit length before the driving beam enters the first cavity, and the transient beam loading parameter α is defined as $\alpha = 2k_1'Nq/V_0'$ [7]. If $\alpha = 1$ and parasitic losses are neglected, a driving beam consisting out of only one bunch injected at phase $\phi_1 = 0$ would take all the stored energy out of the cavity.

In order to achieve a high decelerating voltage in the second cavity, we choose f_2 as a higher harmonic of $1/\Delta t$, i.e. $f_2 = h/\Delta t$ with $h \in \mathbb{N}$. Thus all bunches are injected at phase 0

[1] The prime ′ always indicates that the considered quantity is taken per unit length

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into cavity 2. The corresponding deceleration voltage seen by the driving beam bunches in the second cavity is given by:

$$V'_{dec}(m) = 0.5V'_{2B} + V'_{2B}\sum_{n=1}^{m-1}\exp(-n\Delta t/\tau_2) \qquad (4)$$

With $\omega_2 = 2\pi f_2, \tau_2 = 2Q_2/\omega_2, V'_{2B} = 2q(k'_2/t^2)$.

If k'_2 is the loss parameter of the main beam (i.e. on axis of the Wake Field Transformer) and t the transformer ratio from the driving beam to the main beam, the voltage induced by one bunch is $V'_{2B} = 2q(k'_2/t^2)$.

The length ratio L_1/L_2 is optimally chosen with respect to the condition :

$$L_1 q V'_B(m) \geq L_2 q V'_{dec}(m) \qquad \forall m \qquad (5)$$

(i.e., all bunches must be accelerated at least the same amount that they are decelerated in the transformer)

Figure 3 shows an example of a plot of V'_B and $(L_2/L_1)V'_{dec}$ versus the bunch number after the length ratio L_2/L_1 has been adjusted.

The overall efficiency η_W of the energy transport from the first cavity via the driving beam into the second cavity is given by the formula :

$$\eta_W = q\sum_{m=1}^{N} L_2 V'_{dec}(m)/(L_1 W'_0) \qquad (6)$$

$\eta_W L_1 W'_0$ is the useful energy in the driving beam. The total length of the linac can be calculated from the desired energy E_0 and the gradient $V'_{acc} = V'_{dec}(N) \times t$ in the second cavity. The power supply has to provide the energy per pulse:

$$W_0 = \frac{1}{\eta_W}\frac{(E_0/e)V'_{acc}}{4k'_2} \qquad (7)$$

Note that this equation holds for any type of linear accelerator.

Since the overall efficiency η_W can only be calculated numerically, a computer code has been written which carries out all the sums in the equations 1,...,6, and calculates the energy transfer efficiency η_W. Furthermore, the lengths L_1 and L_2 are determinated for a given final energy of $E_0 = 1$ TeV for the main beam.

The input parameters are : $f_1, Q_1, k'_1, h, Q_2, k'_2, k'_{par}(\sigma)$, t, which depend on the geometric shape of the cavities, and the bunch length σ. Additional parameters are E_0, the desired final energy of the main beam, V'_0, the voltage delivered by a power supply, α, the normalized bunch charge, $\beta_2 = n\Delta t/\tau_2$, the total beam pulse length in units of τ_2, and the injection phases ϕ_0, ϕ_{max} of the first and of the last bunch.

After one has decided which parameters should be kept constant, the computer code can be used to find an optimal parameter set. In the next section, we consider such examples.

To get more insight into the dependence of the various quantities, we can derive an ideal efficiency by neglecting the losses in the cavities (i.e. $Q_1 \to \infty, Q_2 \to \infty$) and going to the limit $N \to \infty$ with finite $q_{total} = Nq$ and $\Phi = N\Delta\phi$. Under these assumptions we obtain for the overall energy transfer efficiency (if the first bunch is injected at phase $\phi_0 = 270°$) :

$$\eta_W = \alpha(1 - \alpha/\Phi)\sin\Phi \qquad (8)$$

Under these assumptions, the optimal value for η_W is:

$$\eta_{W_{opt}} = \max_{\alpha,\Phi}\eta_W(\alpha,\Phi) = 0.454 \qquad (9)$$

$\eta_{W_{opt}}$ is reached for $\alpha = 1.014, \Phi = 116.24°$. (The max is taken over the range $\alpha \geq 0, \Phi \in [0,\pi]$.)

Example parameter set for a 1-TeV linear collider

Following the previous theoretical discussion of a general scheme for a colinear two-beam system, we now turn to our *Resonant Wake Field Transformer Concept*. The aforementioned computer code has been used to calculate two example parameter list for a 1-TeV linear collider.

As input parameters, we mainly used experimentally verified data. A hollow beam is used as a driving beam for the Wake Field Transformer which forms the second cavity section. A charge per bunch $q \leq 100$ nC was already achieved experimentally in the stage-1 Wake Field Transformer experiment.

Both examples have a frequency of 30 GHz in the *Resonant Wakefield Transformer.* The parameters of the transformer were calculated by computer simulations with the program URMEL [8]. Figure 2 shows a plot of the electric field in two cells of the transformer.

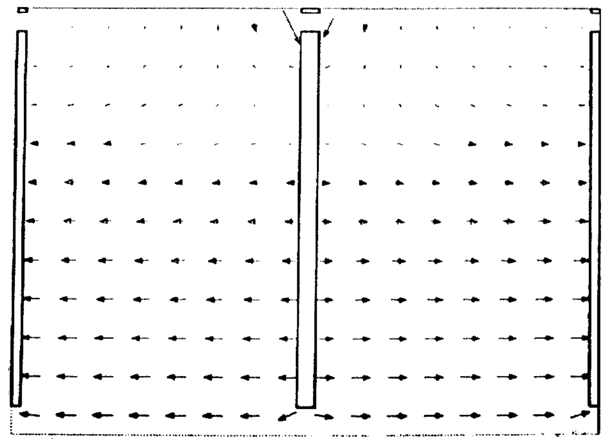

Figure 2: *Electric field of a 30 GHz mode in the Resonant Wake Field Transformer.*

We have chosen two cases which have fundamentally different driver cavities.

a) Example with f_1 = 300 MHz and f_2 = 30 GHz

Table 1: Example parameter set with a high harmonic ratio between the Resonant Wake Field Transformer and the driving linac.

	Driving Cavity		Wake Field Transformer
f_1	300 MHz	f_2	30 GHz
Q_1	50000	Q_2	4700
k'_1	0.206 V/pCm	k'_2	1720 V/pCm
		t	67
Remaining parameters			
	with parasitic losses $k'_{par}(\sigma = 0.6mm) = 1.53$ V/pCm		without parasitic losses
E_0	1 TeV		1TeV
L_1	6547 m		5041 m
L_2	8018 m		7871 m
V'_0	4 MV/m		4 MV/m
W_0	127 kJ		98 kJ
q	211 nC		211 nC
N	23		23
η_W	0.14		0.18

As a first observation, one finds a relatively low efficiency η_W when the actual unavoidable parasitic losses are included. This is mainly due to the short bunches creating strong, higher order mode losses in the driver. The bunch length was optimized although it usually ends up not longer than $\sigma \approx 0.05 \times \lambda_2$, otherwise the accelerating mode in the transformer is not efficiently excited.

A second problem arising from the large harmonic number is that only a few bunches spaced at the driver wavelength fit into one damping time of the transformer ($Q_2/(\pi h)$ bunches per $\beta_2 = 1$). The efficiency is high only if $N \ll Q_2/(\pi h)$. But $N \ll 16$ yields a relatively high charge per bunch and thus increases parasitic losses. Note that the total charge for any two-beam scheme is about the same and of the order of a few μC.

b) Example with f_1 = 3 GHz and f_2 = 30 GHz

In a second case, we use a higher driver frequency and avoid all the instrinsic problems of large frequency ratios. Parameters are show in Table 2. As can be seen, the efficiency is almost doubled in the realistic case including parasitic losses. Parasitic losses are negligible and the charge per bunch is significantly lower.

Assuming that the driving linac is of the SLAC-type, the total klystron power per linac is approximately 4 to 5 times the power of all the SLC linac klystrons.

Table 2: Example parameter set with a low harmonic ratio between the Resonant Wake Field Transformer and the driving linac

Driving Cavity		Wake Field Transformer	
f_1	3 GHz	f_2	30 GHz
Q_1	16500	Q_2	4700
k'_1	20.6 V/pCm	k'_2	1720 V/pCm
		t	67
Remaining parameters			
	with parasitic losses		without parasitic losses
	$k'_{par}(\sigma = 0.6mm) = 153$ V/pCm		
E_0	1 TeV		1TeV
L_1	367 m		335 m
L_2	10539 m		10552 m
V'_0	100 MV/m		100 MV/m
W_0	44.5 kJ		40.6 kJ
q	33 nC		33 nC
N	74		74
η_W	0.3		0.33

Figure 3 shows for this example the voltage V'_B and $L_2/L_1V'_{dec}$ versus the bunch number without parasitic losses (cf. also equation 5).

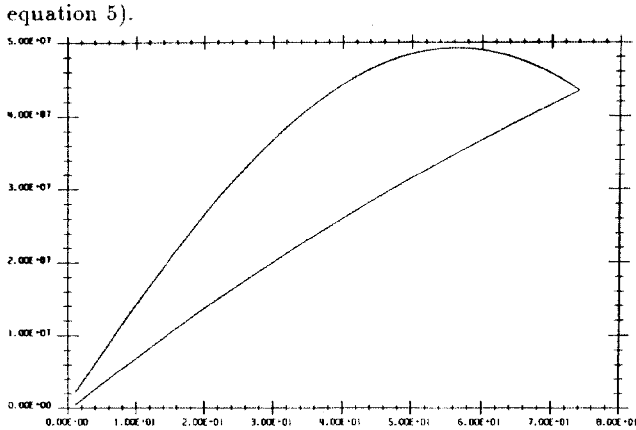

Figure 3: V'_B *and* $L_2/L_1V'_{dec}$ *versus the bunch number*

A 1-GeV test accelerator

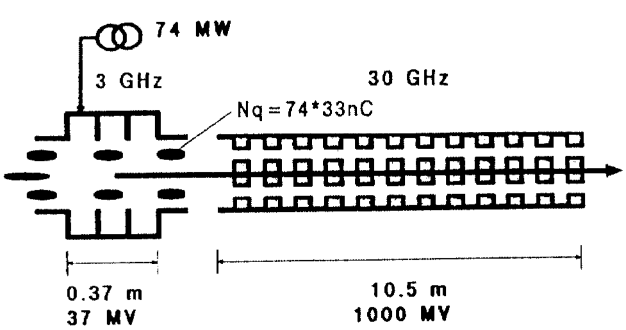

Figure 4: *1 GeV test accelerator with a low harmonic ratio between the transformer and the driving linac.*

Figure 4 shows a realistic, small scale test unit that could readily be built using existing rf equipment. It would use a driving beam with bunches of a quality as that achieved in the stage-1 Wake Field Transformer experiment [2].

Concluding remarks

A modified version of the *Wake Field Transformer*, which we call the *Resonant Wake Field Transformer*, is proposed as a scheme for a colinear, two-beam 1-TeV collider. The accelerator units consist of a driver linac and a transformer, where a field strength of 100 MV/m will be generated on axis. The major advantages over other two-beam schemes is that there is no separate rf extraction structure necessary and thus no timing problem. Based on theoretical studies, valid for any two beam system, example parameter sets are calculated for this concept. We used experimentally verified data for the first cavity section and the charge per bunch. Preliminary investigations show that large ratios of the frequencies have severe problems once true parasitic mode losses are taken into account. The example uses standard S-band equipment and could be readily tested in a small scale experiment.

Acknowledgement

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