Longitudinal Beam Dynamics of the RWT - Collider

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Abstract

The proposed Resonant Wake Field Transformer (RWT) Collider is a colinear two-beam system with a hollow driver beam. A train of many hollow beam bunches, accelerated by a superconducting cw structure, excites the transformer cavity resonantly. Due to an impedance transformation, a high acceleration gradient is generated on the axis of the transformer cavity. After the main central beam has passed the transformer, the remaining energy is recuperated into the next superconducting driver section by a second train of hollow beam bunches. The longitudinal multibunch dynamics of the hollow beam in the driver and the transformer cavity is studied. Results concerning the interdependencies of the essential design parameters are presented.

1 Introduction

The Resonant Wake Field Transformer (RWT) [1] is a special cavity, which is excited by a train of many bunches in a hollow driver beam. The combination of the resonant superposition of the wake fields of many driver bunches with the transformer idea may be called another kind of Relativistic Klystron. [2] A colinear two-beam system based on the Resonant Wake Field Transformer, the RWT-collider, can be regarded as a candidate for the next generation of linear colliders with center of mass energies up to 2 TeV.

It was originally proposed [3] to use the transient wake fields of a hollow beam with a high charge of 1 μC to generate high accelerating gradients of 100 MV/m on the axis of the transformer. Stimulated by first experimental results [4] a new concept with a Resonant Wake Field Transformer excited by a train of 5 hollow beam bunches has been tested in an experiment at DESY. A gradient per total hollow beam charge of 20.67MV/mμC has been achieved in a 20 cm long Wake Field Transformer [5].

For the experiment at DESY a new Wake Field Transformer has been designed [6]. The long range wake potential on axis produced by a hollow driver bunch in the Wake Field Transformer is shown in figure 1 (TBCI calculation). As can be seen, a 4 GHz mode is excited. Thus 5 hollow beam bunches running subsequently through the transformer (60 cm distance from bunch to bunch) produce an almost linear increase of the single bunch wake potential by a factor of 5. Based on this proof of principle experiment at DESY the longitudinal beam dynamics of an RWT - Linear Collider is investigated in the following section.

*now at SLAC

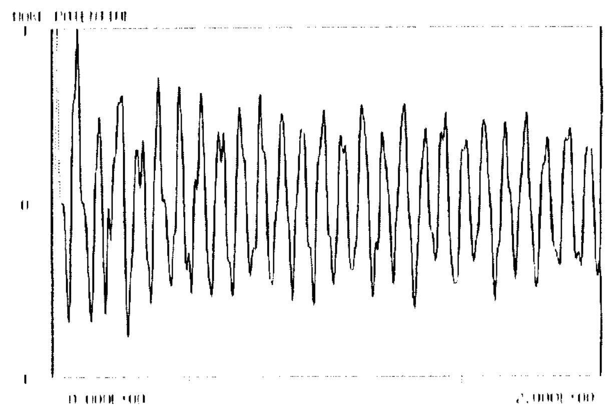

Figure 1: *Long range wake potential (2 m) on axis of the Resonant Wake Field Transformer used in the experiment at DESY. A 4 GHz mode is excited by an gaussian hollow beam bunch with* $\sigma = 4$ *mm*

2 The RWT - Collider

One section of the RWT - Collider consisting of a superconducting cw structure and a Resonant Wake Field Transformer is shown in figure 2. Between the sections special magnetic lenses are used to focus the hollow beam [7, 8].

A train of N hollow beam driving bunches is accelerated in a superconducting cavity with frequency f_1, quality factor Q_1 and loss parameter per unit length k_1'. Then the driver beam is decelerated in the Resonant Wake Field Transformer with parameters f_2, Q_2, k_2' (on axis) and transformer ratio t. The frequency f_2 is choosen as an higher harmonic of $f_0 = 1/\Delta t$ the frequency of the hollow driver bunches. The main central beam is accelerated by a linear superposition of the wake fields generated by the N driver bunches. Due to an impedance transformation the gradient on axis of the Wake Field Transformer is t times the deceleration voltages seen by the last hollow beam bunch.

The decelerating voltage for the n-th hollow driver bunch is given by:

$$V_2(n) = -L_2 \frac{2k_2'}{t^2} q \left(\frac{1}{2} + \sum_{m=1}^{n-1} \exp(-m\,2\pi\, h/(2Q_2))\right)$$

Where h is the harmonic number, i.e. $f_2 = h\, f_1$

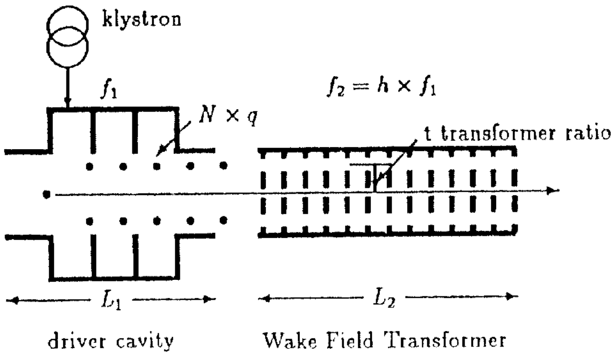

Figure 2: *One section of the RWT - Linear Collider.*

In order to keep the energy spread from bunch to bunch small a special injection scheme is used in the superconducting driver cavity. The n-th hollow driver beam bunch is injected at phase:

$$\varphi_n = \varphi_0 + n\,\Delta\varphi, \qquad \text{i.e. } f_1 = (1 + \frac{\Delta\varphi}{2\pi})\,f_0.$$

In figure 3 the injection phases for $N = 10$ bunches are marked.

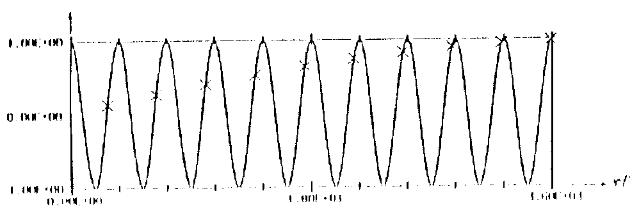

Figure 3: *Normalized driver cavity voltage. The injection phases for $N = 10$ hollow beam bunches are marked.*

The acceleration voltage for the n-th bunch in the superconducting driver cavity is given by:

$$\begin{aligned} V_1(n) &= V_0' L_1 \cos(\varphi_0 + n\,\Delta\varphi) \\ &\quad -2k_1' q \left(\frac{1}{2} + \sum_{m=1}^{n-1} \cos(m\,\Delta\varphi) \exp(-m\,\Delta\varphi/(2Q_1)) \right) \end{aligned}$$

V_0' is the driver cavity gradient.
Conservation of energy requires:

$$V_1(n) \geq -V_2(n) \;\; \forall n$$

Figure 4 shows the acceleration and deceleration voltages $V_1(n)$ and $-V_2(n)$ as a function of n for the example with parameters given in table 1. The first bunch is injected at phase $\varphi_0 = 272°$. The total phase advanced is $\Phi = N\,\Delta\varphi = 60°$ modulo 360°. As can be seen, only the energy really needed for the excitation of the wake field transformer is taken out of the superconducting driver cavity.

3 The Energy Recuperation Mechanism

Typically, the energy exstraction efficiency of the main central beam is lower then 5 %. The efficiency of the whole two-beam

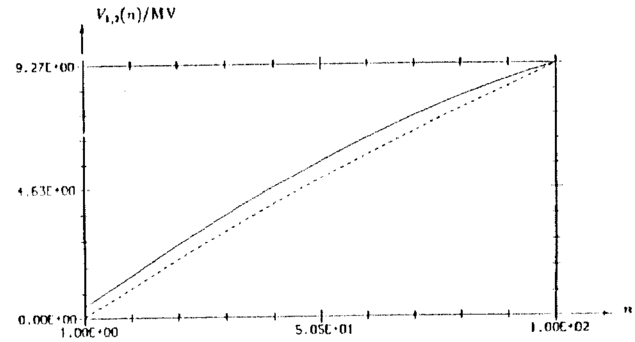

Figure 4: *Acceleration and deceleration voltages of the hollow beam bunches as functions of the bunch number n.*

system can be increased recuperating the energy left in the transformer cavity. A second train of hollow beam bunches takes properly phased the energy out of the transformer and stores it in the superconducting driver cavity of the next section of the RWT - Collider. Figure 5 shows the accelerating and decelerating voltages of the hollow beam bunches used for the energy recuperation.

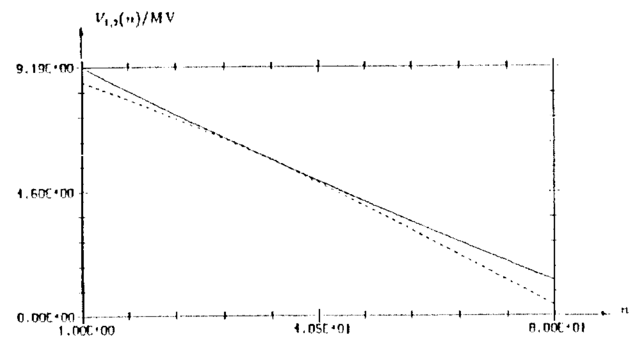

Figure 5: *Acceleration and deceleration voltages of the second train of hollow beam bunches used for energy recuperation as functions of the bunch number n.*

In Table 1 an example parameter list obtained by numerical calculations is presented. assuming a driver gradient V_0' of 20 MV/m an average gradient for the main central beam of 42 MV/m is achieved. The length ratio of the driver cavity length L_1 to the Wake Field Transformer length L_2 is 5.0. So only an active total driver cavity length of 4 km is needed for a 1 TeV RWT - Collider. Let η_m the extraction efficiency of the main central beam. With energy recuperation an total efficiency of

$$\eta_{tot} = g\,\eta_m, \qquad g = \frac{\eta_1}{1 - \eta_1\,\eta_2\,\eta_3}$$

is obtained. g is the gain factor. η_1, η_2 and η_3 are the efficiencies of the energy transport processes from the driver beam into the transformer, from the transformer into the energy recuperation beam and from the energy recuperation beam into the driver cavity of the next section of the RWT - Collider.
The important system parameters for the RWT - Collider are the harmonic number h, the transformer ratio t, the charge per hollow

cavity parameters			
	driver		transformer
f_1	500 MHz	f_2	6 GHz
Q_1	$3\ 10^9$	Q_2	12000
k_1'	0.32 V/(m pC)	k_2'	53.2 V/(m pC) (on axis)
V_0'	20 MV/m	t	25
bunch parameters			
first beam		recuperation beam	
N_1	100	N_2	80
$q_{bun\,1}$	153 nC	$q_{bun\,2}$	118 nC
gradient,length ratio and efficiencies			
G_{ave}	42 MV/m	Average Gradient	
L_2/L_1	5.0	length ratio	
efficiencies			
η_1	73%	hollow beam to transformer	
η_2	79%	transformer to recuperation beam	
η_3	91%	recuperation beam to driver	
g	2.15	energy gain	
The whole calculation includes parasitic losses			
In η_1 and η_2 wall losses are included			

Table 1: *Results for a 500 GHz driver linac and a 6 GHz Wake Field Transformer*

beam bunch, the lenght ratio L_2/L_1 and the driver gradient V_0'. The choice of parameters for the hollow beam is oriented by already experimentally achieved results. The requirements for the superconducting driver cavity should be reachable in the near future.

4 Longitudinal Multibunch Dynamics

Since not all bunches are decelerated in the Wake Field Transformer at the same amount as they are accelerated in the driver cavity (see figure 3) a energy distribution from bunch to bunch in the hollow beam is generated after several sections. In figure 6 the distribution of the energy of the center of each hollow beam bunch is show at the beginning of 10 driver cavity sections. All hollow beam bunches are injected with the same energy of 200 MeV into the first section. It was assumed that one section consist out of a 4 cell, 1.2 m long superconducting driver cavity and a 6 m long Wake Field Transformer. While the energy spread from bunch to bunch is relativly moderate the single bunch energy spread due to the injection on the flank of the rf driver cavity field is the really import dynamic process. Accepting an energy spread of 10 % in one hollow driver bunch the driver beam can be used for 10 sections. Thus after 72 m a new hollow beam has to be created.

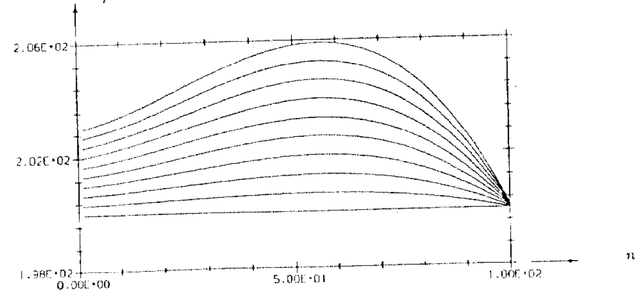

Figure 6: *Multibunch energy distribution at the begining of 10 driver cavity sections.*

5 Concluding Remarks

A Resonant Wake Field Transformer, designed for the proof of principle experiment at DESY, has been succesfully tested. A4 GHz mode was excited by a train of 5 hollow beam bunches. Based on the idea of a Resonant Wake Field Transformer the longitudinal beam dynamics of a 1 TeV RWT - Collider is studied. The example parameter list makes things clear where future research and development work should be done. Firstly, a new hollow beam gun for long high charged pulses has to be developed [9]. Compared to now commonly used superconducting cavities our requirements are rather high but certainly not unfulfillable. Major advantages of the RWT - Collider are the relatively low charge density in the hollow driver beam and the filling of the transformer with a group velocity at the speed of light. The charge density in one bunchlet of the CLIC [10, 11] driver beam is 35 times higher as the charge density in our hollow beam bunch. Therefore the RWT - Collider can be regarded as a candidate for the next generation of 2×1 TeV linear colliders.

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